

fellingdater: a toolkit to estimate, report and combine felling dates derived from historical tree-ring series.

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Summary

Tree-ring dating, or dendrochronology, allows to assign calendar-year dates to growth rings that can be observed on an old piece of timber. Once a tree-ring series is securely anchored to a calendar year time-scale, the end date of the outermost ring can be used to estimate the year when the tree was felled.

The **fellingdater** package offers a suite of functions that can assist dendrochronologists to infer, combine and report felling date estimates from dated tree-ring series, based on the presence of partially preserved sapwood or waney edge (Fig. 1).



Figure 1: A cross-section of a historical timber from a medieval roof construction. All ring boundaries are marked, as well as the heartwood and the partially preserved sapwood.

Background

Dendrochronology is the most precise chronometric dating technique for (pre-)historical wooden constructions and objects (Baillie 1995). It involves recording the ring-width pattern on a cross-section of an ancient wooden element and matching this pattern to absolutely dated reference chronologies. This allows to anchor the recorded tree-ring pattern to an absolute time scale. In archaeological, architectural or art-historical studies, the primary objective of a dendrochronological survey is to ascertain an accurate estimate of the

felling date (or dying-off) of the parent tree from which the timber originates [Haneca, Cufar, and Beeckman (2009); (Domínguez-Delmás 2020); Tegel et al. (2022)]. This felling date is the closest related and datable event to the creation of the wooden object or construction.

The exact felling date can be inferred from the most recently formed tree ring prior to the felling or death of the tree. Often, the wood of the felled tree has undergone processing, trimming, or biological deterioration leading to the irreversible loss of wood tissue. In such cases, the timing of the felling date can only be estimated. The most challenging situation is when neither sapwood, nor the transition between heartwood and sapwood, remains on the object or timber (Fig. 1, HW/SW boundary). Then, an untraceable amount of wood and growth layers has been removed and the last measured ring only provides an earliest possible felling date or *terminus post quem*.

The **fellingdate** package aims to facilitate the process to infer, combine and report felling date estimates from dated tree-ring series, based on the presence of (partially) preserved sapwood or waney edge.

Statement of need

Many descriptive statistics and statistical models have been published to establish accurate estimates of the expected number of sapwood ring (Edvardsson et al. 2022; Bleicher et al. 2020; Rybnicek, Vavrik, and Hubeny 2006; Pilcher 1987; Hollstein 1965, 1980; Wazny 1990; Miles 1997; Sohar, Vitas, and Läänelaid 2012; Bräthen 1982; Haneca, Cufar, and Beeckman 2009; Hughes, Milsom, and Leggett 1981; Jevšenak et al. 2019; Hillam, Morgan, and Tyers 1987; Gjerdum 2013; Shindo et al. 2024). These models often rely on log-transformation of the original counts of sapwood numbers from living and historical timbers, or use regression models that include additional variables such as mean ring width, the cambial age of the tree or a combination of both. A standardized methodology is hampered by this variety in methodology and reporting.

A Bayesian method to improve the procedures to model sapwood data, compute lower and upper limits for the felling date based upon the selected sapwood model and a given credible interval have been introduced by Millard (2002). This procedure was then further refined by Miles (2006), and critically reviewed with real-life examples by Tyers (2008). This workflow has been incorporated in OxCal, the routine software for radiocarbon dating and modelling (Bronk Ramsey 2009). Tree-ring analysis, on the other hand, relies on a growing set of R-packages, with the '*Dendrochronology Program Library in R*' (Bunn 2008, 2010; Bunn et al. 2022), at its core (opendendro.org; (Bunn, Anchukaitis, and Swetnam 2022)). Yet, the reporting of felling dates is currently not a standardized procedure incorporated in an R-package.

The **fellingdate** package allows to fully document the methodology to establish a felling date – for a single timber or a group of timbers – making the whole procedure reproducible and assists in building standardized workflows when applied to large datasets (e.g. (Haneca, Debonne, and Hoffsummer 2020)). The package includes functions related to each step in the (generalized) workflow when analysing historical tree-ring series (Fig. 2).

Data within the package

The package comes with published datasets of sapwood counts, retrieved from their original publication (Haneca and Debonne 2012). This was only possible for a limited number of datasets as many have been published as histograms with wide bins (>1), what does not allow to retrieve the underlying data points. An overview of all included sapwood datasets is generated by `sw_data_overview()`.

More information on the datasets, such as the bibliographic reference to the original publication, the wood species and some basic descriptive statistics can be accessed by `sw_data_info(<name_of_dataset>)`.

`sw_model()` fits a density distribution to the original data, and returns the output of the modelling process. With `sw_model_plot()` the model is visualized as a ggplot-style graph (Wickham 2016) (Fig. 3).

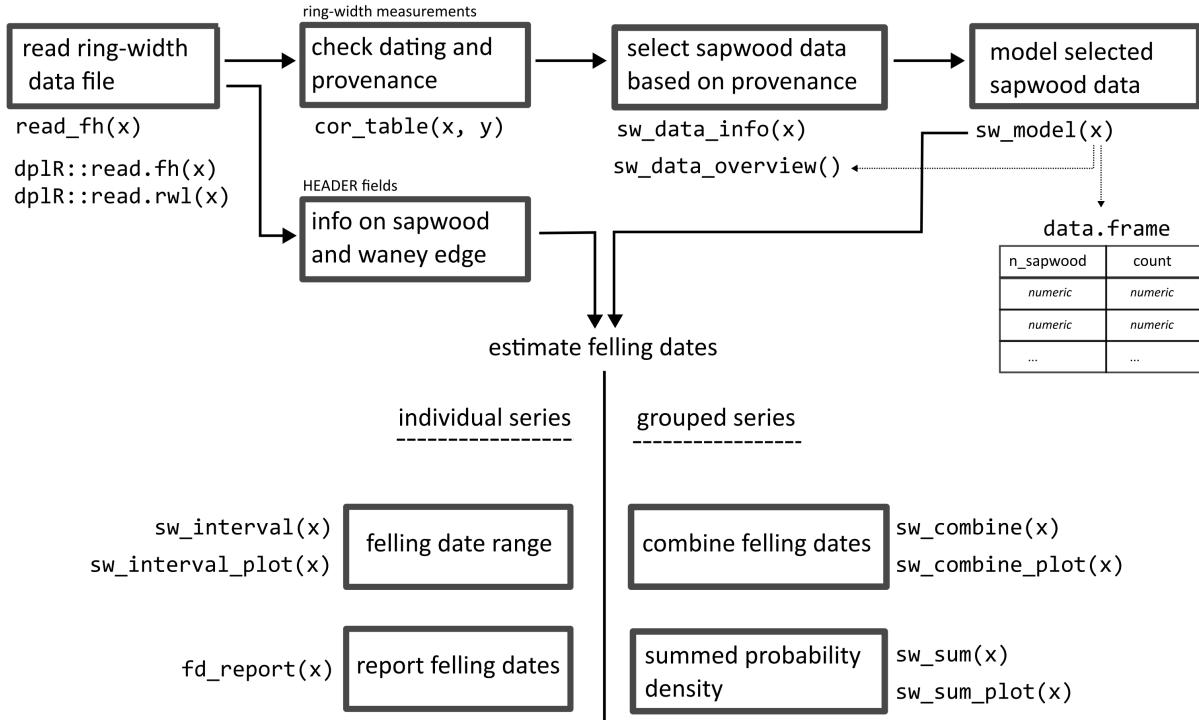


Figure 2: A generalized workflow and related functions, for inferring felling dates from tree-ring dated historical timbers.

```

library(fellingdater)

sw_data_overview()
#> [1] "Brathen_1982"      "Hollstein_1980"     "Miles_1997_NM"    "Miles_1997_SC"
#> [5] "Miles_1997_WBC"   "Pilcher_1987"     "Sohar_2012_ELL_c" "Sohar_2012_ELL_t"
#> [9] "Sohar_2012_FWE_c" "Sohar_2012_FWE_t" "Wazny_1990"       "vanDaalen_NLBE"
#> [13] "vanDaalen_Norway"

model <- sw_model("Hollstein_1980", plot = FALSE)
sw_model_plot(model)

```

Example of use

Installation

The latest version is hosted on GitHub and R-universe.

```

pak::pak("ropensci/fellingdater")

# or

install.packages("fellingdater", repos = "https://ropensci.r-universe.dev")

```

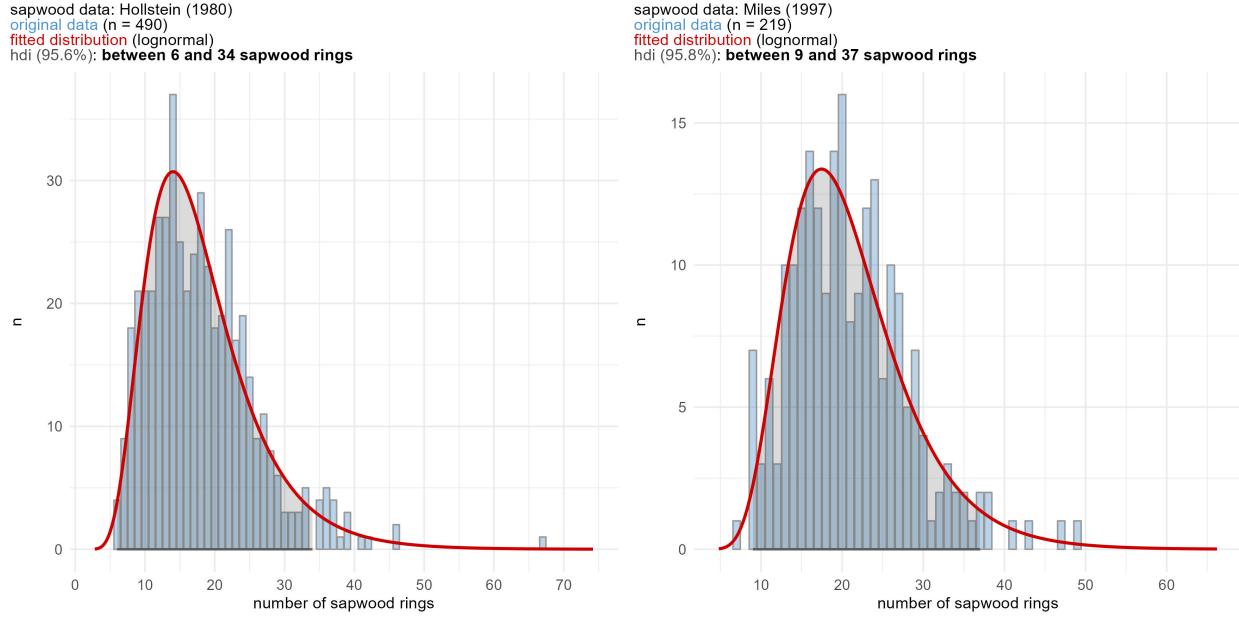


Figure 3: Two sapwood datasets with a density function modeled to the raw data.

Reading tree-ring files

The function `read_fh()` is an extension to the `dplyR::read.fh()` function and allows to read .fh (format Heidelberg) files of ring widths (both in decadal, half-chrono and chrono format) (Brewer and Murphy 2011). The function is focused on retrieving information found in the HEADER fields of the .fh files, that often harbour essential information necessary to establish a well informed estimate of the felling date. The `read_fh()` function retrieves the information from the HEADER fields and lists the items as attributes to the ring-width measurements. The `fh_header()` function facilitates easy conversion to a `data.frame`.

Crossdating

The function `cor_table()` computes commonly used correlation values between dated tree-ring series and reference chronologies. This function helps to check the assigned end date of the series by comparing the measurements against absolutely dated reference chronologies, and thereby provide information on timber provenance. The latter allows to select the most appropriate sapwood model for the tree-ring data.

The correlation values computed are:

- `glk`: ‘Gleichläufigkeit’ or ‘percentage of parallel variation’ (Buras and Wilmking 2015; Eckstein and Bauch 1969; Huber 1943; Visser 2021).
- `glk_p`: significance level associated with the `glk`-value (Jansma 1995).
- `r_pearson`: the Pearson’s correlation coefficient
- `t_St`: Student’s t-value based on `r_pearson`
- `t_BP`: t-values according to the Baillie and Pilcher (1973) algorithm
- `t_Ho`: t-values according to the Hollstein (1980) algorithm

```

Doel1_trs <- read_fh(Doel1, header = FALSE)
Hollstein_crn <- read_fh("Hollstein80.fh", header = FALSE)

cor_table(x = Doel1_trs,
          y = Hollstein_crn,
          min_overlap = 80,
          output = "table",
          sort_by = "t_BP")

```

Felling date interval

After selecting the appropriate sapwood model (e.g. , one of Fig. 2) one can use the model to estimate the upper and lower limits of the number of missing sapwood rings. The function `sw_interval()` calculates the probability density function (PDF) and highest probability density interval (HDI) of the felling date range based on the observed number of sapwood rings (`n_sapwood = ...`), their chronological dating (`last = ...`) and the selected sapwood data (`sw_data = ...`) and model (`densfun = ...`).

In the example below, 10 sapwood rings were observed on a historical timber (last ring dated to 1234 CE) that is supposed to have a provenance in the Southern Baltic region (sapwood model published by (Wazny 1990)). The HDI delineates an interval in which the actual felling date is most likely situated (Fig. 4).

Note that the more sapwood rings that have been measured, the more probability mass is assigned to the tails of the sapwood model.

```
# 10 sapwood rings observed and the Wazny 1990 sapwood model:
```

```

interval <- sw_interval(
  n_sapwood = 10,
  last = 1234,
  hdi = TRUE,
  cred_mass = .95,
  sw_data = "Wazny_1990",
  densfun = "lognormal",
  plot = TRUE)

```

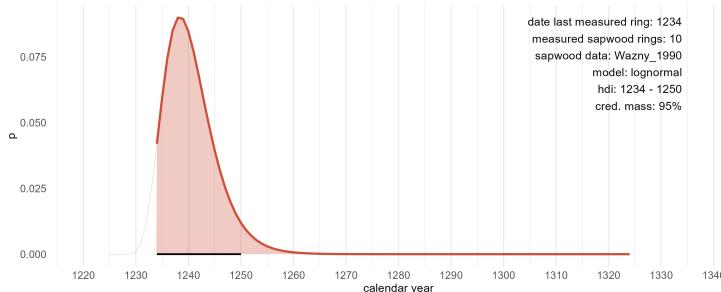


Figure 4: A truncated lognormal distribution, representing the sapwood model for a tree-ring series with 10 sapwood rings. The black line delineates the 95% credible interval for the felling date.

Combine felling dates

sw_combine

The procedure to combine felling dates of a group of related tree-ring series with (partially) preserved sapwood, in order to narrow down the range of a common felling date, is provided by the function **sw_combine()**. This function returns a **list** with:

- the probability density function (PDF) for the felling date of the individual series and the PDF of the model that combines these individual series (**\$data_raw**),
- the HDI for the combined estimate of the common felling date (**\$hdi_model**),
- the *Agreement index* (**\$A_model**) of the model, expressing how well the individual series fit into the model ,
- an overview of the felling date range for the individual series (**\$individual_series**), and their *Agreement index* (A_i) to the combined model.

The function **sw_combine_plot()** allows to visualize the output.

The rationale and mathematical background of the *Agreement index* (A_i) was introduced and developed by Bronk Ramsey (1995, 2017). Both the A_i of the individual series as for the whole model (A_{model}) should ideally be around 100%, and not lower than the critical threshold $A_c = 60\%$.

The example dataset below consists of 5 dated tree-ring series of which one has an exact felling date (Fig. 5, left). The proposed combined felling date equals the felling date of the series with an exact felling date (trs_15), but now it can be assessed that this falls within the felling date ranges for three other individual series (trs_11, trs_12 and trs_14). One other series (trs_13) has no remaining sapwood and therefore only an earliest possible felling date can be given (arrow pointing away from last measured ring). The agreement indexes of all individual series and the overall model are high and above the critical threshold of 60%.

```
trs_example2
#>   series last n_sapwood waneyedge
#> 1 trs_11 1000      5    FALSE
#> 2 trs_12 1005     10    FALSE
#> 3 trs_13 1008     NA    FALSE
#> 4 trs_14 1000      1    FALSE
#> 5 trs_15 1010      3    TRUE

p1 <- sw_combine(trs_example2, plot = TRUE)
```

In the next example, an attempt to compute a common felling date for a group of 5 tree-ring series fails. All but one of the series include partially preserved sapwood, but these tree-ring series do not share a common timing for their estimated felling date (Fig. 5, right). The agreement index of the model is far below 60%, as is the case for most of the individual series.

```
trs_example4
#>   series last n_sapwood waneyedge
#> 1 trs_21 1000      5    FALSE
#> 2 trs_22 1005     10    FALSE
#> 3 trs_23 1005     NA    FALSE
#> 4 trs_24 1020      1    FALSE
#> 5 trs_25 1040      0    FALSE

p2 <- sw_combine(trs_example4, plot = TRUE)
```

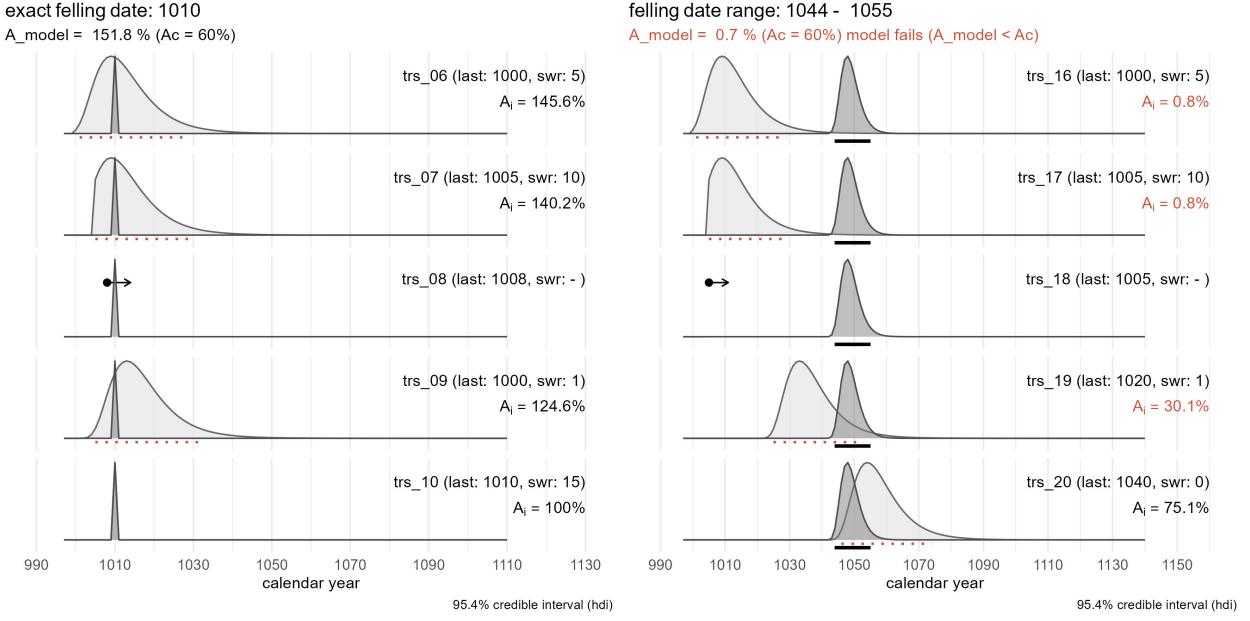


Figure 5: Graphical output of `sw_combine()`. The sapwood model for the individual series in light grey, the probability density function of the combined felling in dark grey tone. The credible interval for the felling date of individual series is shown as a dashed red line and a black line for the combined estimate. The dataset in the left graph includes an exact felling date that matches with the estimates for the other series. The graph on the right shows a model that fails to group all series around a common felling date.

Sum felling dates

For large datasets of dated tree-ring series, it is not always straightforward to assess temporal trends in the frequency of felling dates. The individual series each have their own probability density function based on a chosen sapwood model and the number of observed sapwood rings. To make another reference to radiocarbon dating, it is common practice in the analysis of large volumes of calibrated radiocarbon dates to compute the *summed probability densities* (SPD) of the calibrated radiocarbon dates. Summed probabilities are used to determine the temporal density of ages (events), where there is no clear prior information on their distribution (Bronk Ramsey 2017). This procedure is implemented in OxCal and the R-package `rcarbon` (Crema and Bevan 2020). The function `sw_sum()` makes this procedure available for tree-ring analyses. The summed probability distribution (SPD) of the individual probability densities of felling dates of single tree-ring series with incomplete sapwood allows to visualize fluctuations in the incidence of potential felling dates through time. Exact felling dates derived from tree-ring series with waney edge are not included in the computational process of the SPD as they would result in anomalous spikes in the SPD, as their associated probability ($p = 1$) would be assigned to a single calendar year. Therefore exact felling dates are plotted separately on top of the SPD (Fig. 6).

```
sum <- sw_sum(trs_example7)

sw_sum_plot(sum, dot_size = 2, dot_shape = 25)
```

Future work

In its current version the package `fellingdater` is tailored to the general workflow for analyzing tree-ring datasets from wooden cultural heritage objects and constructions, made of European oak (*Quercus* sp.). The

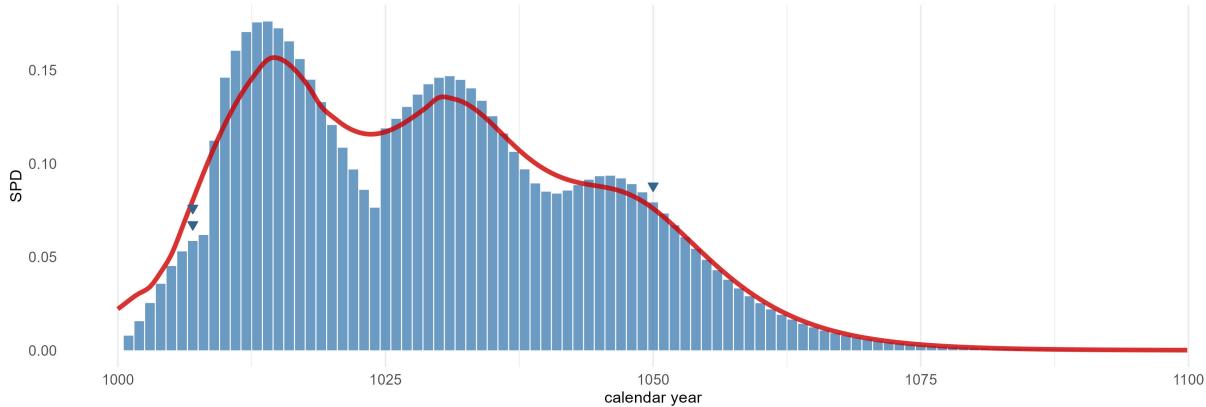


Figure 6: Graphical representation of the output of `sw_sum()`. The blue bars represent the summed probability density (SPD) of the individual series with partial sapwood. The red line is a rectangular filter applied to the SPD to highlight the general trend. Series with exact felling dates are plotted as triangles.

sapwood data included in the current version reflect this focus on oak. But all functions can also work with a custom sapwood dataset, provided as a `data.frame`. As such, sapwood data from other regions and wood species can also be explored, modeled and used to report felling dates.

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References

- Baillie, M. G. L. 1995. *A Slice Through Time. Dendrochronology and Precision Dating*. London: B.T. Batsford Ltd.
- Baillie, M. G. L., and J. R. Pilcher. 1973. “A Simple Crossdating Program for Tree-Ring Research.” *Tree-Ring Bulletin* 33: 7–14.
- Bleicher, N., F. Walder, U. Gut, and M. Bolliger. 2020. “The Zurich Method for Sapwood Estimation.” *Dendrochronologia* 64 (December): 125776. <https://doi.org/10.1016/j.dendro.2020.125776>.
- Bräthen, A. 1982. “A Tree-Ring Chronology from the Western Part of Sweden. Sapwood and a Dating Problem.” In *Second Nordic Conference on the Application of Scientific Methods in Archaeology, PACT 7(1)*, edited by T. Hackens and V. Mejdhahl, 27–35.
- Brewer, P., and D. Murphy. 2011. “Summary of Dendro Data Formats (Published as Supplementary Material for Brewer, Murphy & Jansma, 2011. TRiCYCLE: A Universal Conversion Tool for Digital Tree-Ring Data).” *Tree-Ring Research*, no. 67: 60. <https://doi.org/10.3959/2010-12.1>.
- Bronk Ramsey, C. 1995. “Radiocarbon Calibration and Analysis of Stratigraphy: The OxCal Program.” *Radiocarbon* 37 (2): 425–30. <https://doi.org/10.1017/S003382200030903>.
- . 2009. “Bayesian Analysis of Radiocarbon Dates.” *Radiocarbon* 51 (1): 337–60. <https://doi.org/10.2458/rc.v51i1.3494>.
- . 2017. “Methods for Summarizing Radiocarbon Datasets.” *Radiocarbon* 59 (6): 1809–33. <https://doi.org/10.1017/RDC.2017.108>.
- Bunn, A. G. 2008. “A Dendrochronology Program Library in R (dplR).” *Dendrochronologia* 26 (2): 115–24. <https://doi.org/10.1016/j.dendro.2008.01.002>.

- . 2010. “Statistical and Visual Crossdating in R Using the dplR Library.” *Dendrochronologia* 28 (4): 251–58. <https://doi.org/10.1016/j.dendro.2009.12.001>.
- Bunn, A. G., K. Anchukaitis, and T. L. Swetnam. 2022. *OpenDendro Webpages & Code*. Zenodo. <https://doi.org/10.5281/ZENODO.6110786>.
- Bunn, A. G., M. Korpela, F. Biondi, F. Campelo, P. Mérain, F. Qeadan, and C. Zang. 2022. *dplR: Dendrochronology Program Library in r. R Package Version 1.7.4.* <https://CRAN.R-project.org/package=dplR>.
- Buras, A., and M. Wilmking. 2015. “Correcting the Calculation of Gleichl äufigkeit.” *Dendrochronologia* 34: 29–30. <https://doi.org/10.1016/j.dendro.2015.03.003>.
- Crema, E. R., and A. Bevan. 2020. “Inference from Large Sets of Radiocarbon Dates: Software and Methods.” *Radiocarbon*, October, 1–17. <https://doi.org/10.1017/RDC.2020.95>.
- Domínguez-Delmás, M. 2020. “Seeing the Forest for the Trees: New Approaches and Challenges for Dendroarchaeology in the 21st Century.” *Dendrochronologia* 62: 125731. <https://doi.org/10.1016/j.dendro.2020.125731>.
- Eckstein, D., and J. Bauch. 1969. “Beitrag Zur Rationalisierung Eines Dendrochronologischen Verfahrens Und Zur Analyse Seiner Aussagesicherheit.” *Forstwissenschaftliches Centralblatt* 88: 230–50. <https://doi.org/10.1007/BF02741777>.
- Edvardsson, J., K. Rögnvaldsson, E. D. Helgadóttir, H. Linderson, and B. Hrafnkelsson. 2022. “A Statistical Model for the Prediction of the Number of Sapwood Rings in Scots Pine (*Pinus Sylvestris L.*).” *Dendrochronologia* 74: 125963. <https://doi.org/10.1016/j.dendro.2022.125963>.
- Gjerdrum, P. 2013. “Estimating Missing Sapwood Rings in Three European Gymnosperm Species by the Heartwood Age Rule.” *Dendrochronologia* 31 (3): 228–31. <https://doi.org/10.1016/j.dendro.2013.03.001>.
- Haneca, K., K. Cufar, and H. Beeckman. 2009. “Oaks, Tree-Rings and Wooden Cultural Heritage: A Review of the Main Characteristics and Applications of Oak Dendrochronology in Europe.” *Journal of Archaeological Science* 36 (1): 1–11. <https://doi.org/10.1016/j.jas.2008.07.005>.
- Haneca, K., and V. Debonne. 2012. “Precise Tree-Ring Dating of Building Activities Despite the Absence of Bark: A Case-Study on Medieval Church Roofs in Damme, Belgium.” *Dendrochronologia* 30 (1): 23–34. <https://doi.org/10.1016/j.dendro.2011.06.002>.
- Haneca, K., V. Debonne, and P. Hoffsummer. 2020. “The Ups and Downs of the Building Trade in a Medieval City: Tree-Ring Data as Proxies for Economic, Social and Demographic Dynamics in Bruges (c. 1200–1500).” *Dendrochronologia* 64: 125773. <https://doi.org/10.1016/j.dendro.2020.125773>.
- Hillam, J., R. A. Morgan, and I. Tyers. 1987. “Sapwood Estimates and the Dating of Short Ring Sequences.” *BAR International Series* 333: 165–85.
- Hollstein, E. 1965. “Jahrringchronologische Datierung von Eichenhölzern Ohne Waldkante.” *Bonner Jahrbücher* 165: 12–27.
- . 1980. *Mitteleuropäische Eichenchronologie: Trierer Dendrochronologische Forschungen Zur Archäologie Und Kunstgeschichte*. Trierer Grabungen Und Forschungen 11. Mainz am Rhein: Verlag Philipp von Zabern.
- Huber, B. 1943. “Über Die Sicherheit Jahrringchronologische Datierung.” *Holz Als Roh Und Werkstoff* 6 (10-12): 263–68. <https://doi.org/10.1007/BF02603303>.
- Hughes, M. K., S. J. Milsom, and P. A. Leggett. 1981. “Sapwood Estimates in the Interpretation of Tree-Ring Dates.” *Journal of Archaeological Science* 8: 381–90. [https://doi.org/10.1016/0305-4403\(81\)90037-6](https://doi.org/10.1016/0305-4403(81)90037-6).
- Jansma, E. 1995. *RemembeRINGS. The Development and Application of Local and Regional Tree-Ring Chronologies of Oak for the Purposes of Archaeological and Historical Research in the Netherlands*. Nederlandse Archeologische Rapporten 19. Amersfoort: ROB. <https://dspace.library.uu.nl/handle/1874/45149>.
- Jevšenak, J., E. Goršić, D. B. Stojanović, B. Matović, and T. Levanić. 2019. “Sapwood Characteristics of *Quercus Robur* Species from the South-Western Part of the Pannonian Basin.” *Dendrochronologia* 54: 64–70. <https://doi.org/10.1016/j.dendro.2019.02.006>.
- Miles, D. 1997. “The Interpretation, Presentation and Use of Tree-Ring Dates.” *Vernacular Architecture* 28: 40–56. <https://doi.org/10.1179/030554797786050563>.
- . 2006. “Refinements in the Interpretation of Tree-Ring Dates for Oak Building Timbers in England and Wales.” *Vernacular Architecture* 37: 84–96. <https://doi.org/10.1179/174962906X158291>.
- Millard, A. 2002. “A Bayesian Approach to Sapwood Estimates and Felling Dates in Dendrochronology.”

- Archaeometry* 44 (1): 137–43. <https://doi.org/10.1111/1475-4754.00048>.
- Pilcher, J. R. 1987. “A 700 Year Dating Chronology for Northern France. Applications of Tree-Ring Studies. Current Research in Dendrochronology and Related Subjects.” *BAR International Series* 333: 127–39.
- Rybniček, M., H. Vavrik, and R. Hubeny. 2006. “Determination of the Number of Sapwood Annual Rings in Oak in the Region of Southern Moravia.” *Journal of Forest Science* 52 (3): 141–46. <https://doi.org/10.17221/4496-JFS>.
- Shindo, L., M. Saulnier, H. Raese, F. Guibal, J.-L. Edouard, M. Bolka, M. Carrer, et al. 2024. “European Larch Sapwood: A Model for Predicting the Cambial Age and for a More Accurate Dating.” *Dendrochronologia* 83: 126150. <https://doi.org/10.1016/j.dendro.2023.126150>.
- Sohar, K., A. Vitas, and A. Läänelaid. 2012. “Sapwood Estimates of Pedunculate Oak (*Quercus Robur L.*) in Eastern Baltic.” *Dendrochronologia* 30 (1): 49–56. <https://doi.org/10.1016/j.dendro.2011.08.001>.
- Tegel, W., B. Muigg, G. Skiadaresis, J. Vanmoerkerke, and A. Seim. 2022. “Dendroarchaeology in Europe.” *Frontiers in Ecology and Evolution* 10 (February): 823622. <https://doi.org/10.3389/fevo.2022.823622>.
- Tyers, C. 2008. “Bayesian Interpretation of Tree-Ring Dates in Practice.” *Vernacular Architecture* 39 (1): 91106. <https://doi.org/10.1179/174962908X365082>.
- Visser, R. M. 2021. “On the Similarity of Tree-Ring Patterns: Assessing the Influence of Semi-Synchronous Growth Changes on the *Gleichläufigkeitskoeffizient* for Big Tree-Ring Data Sets.” *Archaeometry* 63 (1): 204–15. <https://doi.org/10.1111/arcm.12600>.
- Wazny, T. 1990. “Aufbau Und Anwendung Der Dendrochronologie Für Eichenholz in Polen.” PhD thesis, Hamburg.
- Wickham, H. 2016. *ggplot2: elegant graphics for data analysis*. Use R! New York: Springer-Verlag. <https://ggplot2.tidyverse.org>.