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

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Software

- Review
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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).

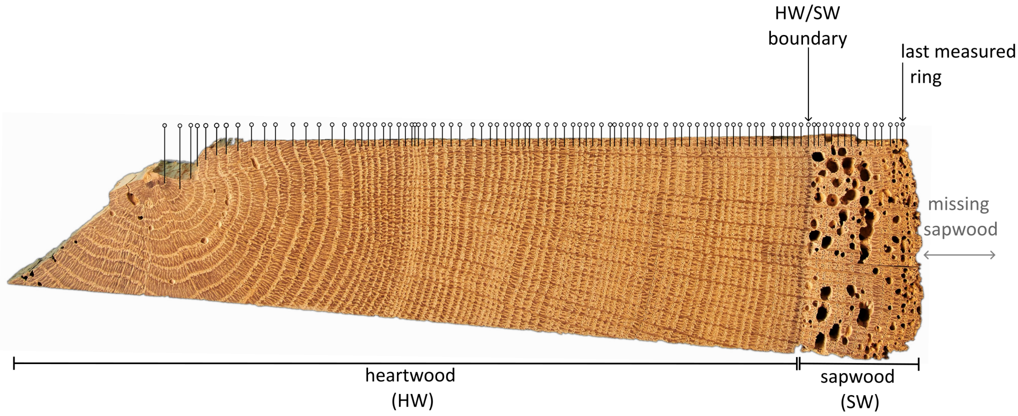

Figure 1: A cross-section of a historical timber from a medieval roof construction. All ring boundaries are marked, as well as the heartwood and the partially preserved sapwood.

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 anchoring 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 (Domínguez-Delmás, 2020; Haneca et al., 2009; 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 `fellingdater` 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 rings (Bleicher et al., 2020; Bräthen, 1982; Edvardsson et al., 2022; Gjerdrum, 2013; Haneca et al., 2009; Hillam et al., 1987; Hollstein, 1965, 1980; Hughes et al., 1981; Jevšenak et al., 2019; Miles, 1997; Pilcher, 1987; Rybnicek et al., 2006; Shindo et al., 2024; Sohar et al., 2012; Wazny, 1990). These models are based on counts of sapwood rings from living and historical timbers and often rely on log-transformation of the original data, or use regression models including additional variables such as mean ring width, the cambial age of the tree or a combination of both. A standardized methodology for reporting felling dates is therefore hampered by this variety in statistical approaches.

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 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, Korpela, et al., 2022), at it's core (https://opendendro.org/, Bunn, Anchukaitis, et al., 2022). Yet, the reporting of felling dates is currently not a standardized procedure incorporated in an R-package.

The `fellingdater` 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 et al., 2020). The package includes functions related to each step in the (generalized) workflow when analysing historical tree-ring series (Fig. 2).

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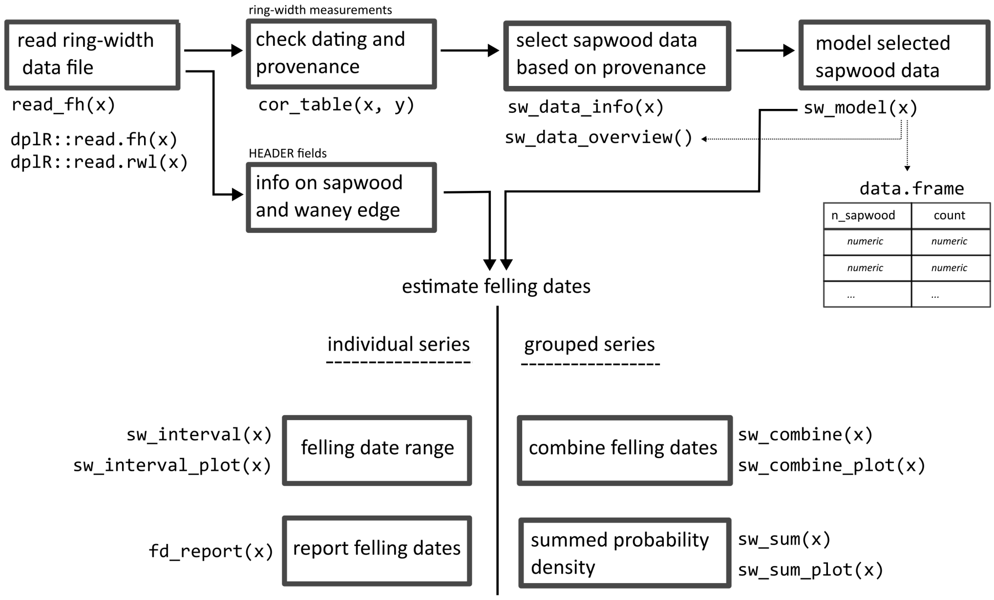

Figure 2: A generalized workflow and related functions, for inferring felling dates from tree-ring dated historical timbers.

Data within the package

The package comes with published datasets of sapwood counts, retrieved from their original publication (e.g. Haneca & 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 do 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 chosen 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).

```
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)
```

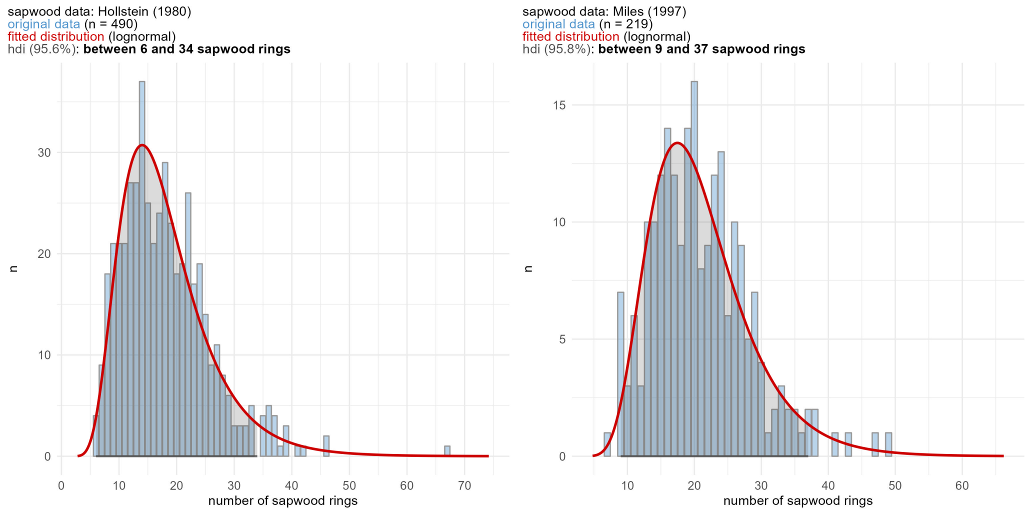

Figure 3: Two sapwood datasets with a fitted density function to the raw data.

Example of use

Installation

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

```r
pak::pak("ropensci/fellingdater")

# or

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

Reading tree-ring files

The function `read_fh()` is an extension to the `dplR::read.fh()` function and allows to read .fh (format Heidelberg) files of ring widths (in decadal, half-chrono or chrono format) (Brewer & Murphy, 2011). The function is focused on extracting information found in the HEADER fields of the .fh files, which often harbour essential information necessary for establishing 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 verify the assigned end date of the series by comparing the measurements against absolutely dated reference chronologies, thereby providing information on timber provenance. The latter enables the selection of the most appropriate sapwood model for the tree-ring data.

The correlation values computed are:

- glk: 'Gleichläufigkeit' or 'percentage of parallel variation' (Buras & Wilmking, 2015; Eckstein & 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 algorithm proposed by Baillie & Pilcher (1973).
- t_Ho: *t*-values according to the algorithm proposed by Hollstein (1980).

```
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. 3) 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 (with the last ring dated to 1234 CE) that is supposed to have a provenance in the Southern Baltic region (covered by the 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)
```

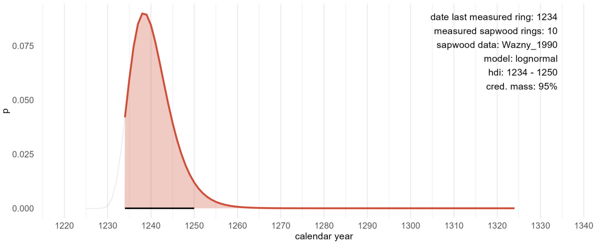

Figure 4: A truncated lognormal distribution, representing the sapwood model for a tree-ring series with 10 sapwood rings. The black line delineates the 95% credible interval for the felling date.

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 shared 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 and 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, one of which 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)
```

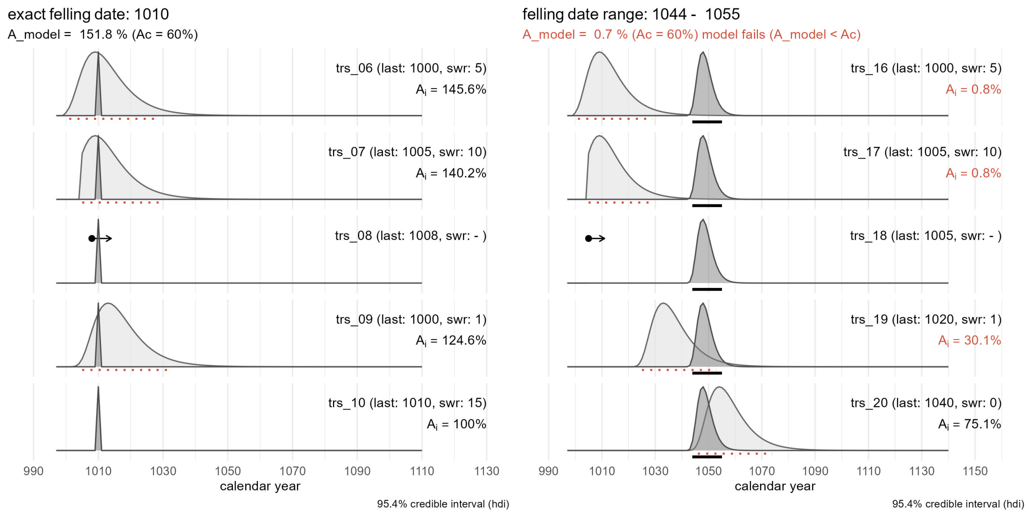

Figure 5: Graphical output of `sw_combine()`. The sapwood model for the individual series in light grey, the probability density function of the combined felling in dark grey tone. The credible interval for the felling date of individual series is shown as a dashed red line and a black line for the combined 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.

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)
```

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 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) in situations 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 & Bevan, 2020). The function `sw_sum()` makes his 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 visualizing of fluctuations in the incidence of potential felling dates over 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, since 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)
```

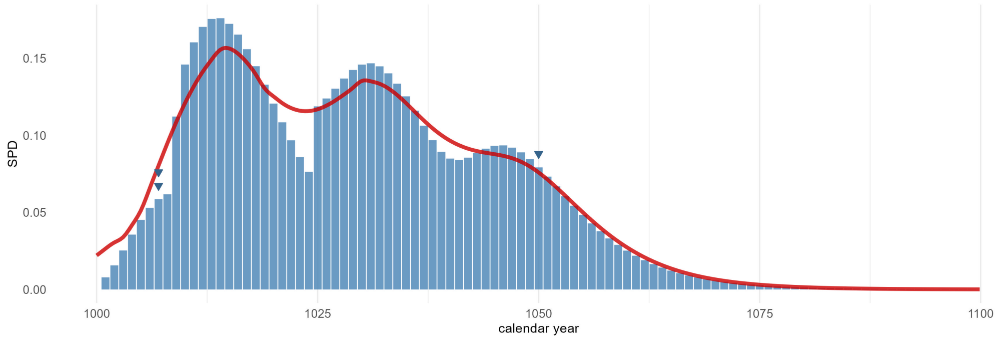

Figure 6: Graphical representation of the out put of `sw_sum()`. The blue bars represent the summed probability density (SPD) of the individual series with partial sapwood. The red line is a rectangular filter applied to the SPD to highlight the general trend. Series with exact felling dates are plotted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

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 sapwood data included in the current version reflect this focus on oak. However, 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 determine felling dates.

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