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Technical note

dendrometeR: Analyzing the pulse of trees in R

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ABSTRACT

Dendrometers are measurement devices proven to be useful to analyze tree water relations and growth responses in relation to environmental variability. To analyze dendrometer data, two analytical methods prevail: (1) *daily approaches* that calculate or extract single values per day, and (2) *stem-cycle approaches* that separate high-resolution dendrometer records into distinct phases of contraction, expansion and stem-radius increment. Especially the stem-cycle approach requires complex algorithms to disentangle cyclic phases. Here, we present an R package, named dendrometeR, that facilitates the analysis of dendrometer data using both analytical methods. By making the package freely available, we make a first step towards comparable and reproducible methods to analyze dendrometer data. The package contains customizable functions to prepare, verify, process and plot dendrometer series, as well as functions that facilitate the analysis of dendrometer data (i.e. daily statistics or extracted phases) in relation to environmental data. The functionality of dendrometeR is illustrated in this note.

1. Introduction

Dendrometers are measurement devices used in plant sciences that can monitor size variation of plant organs like stems, roots, branches and fruits with high temporal and spatial resolution. In forest ecological and tree physiological research, these tools are increasingly used to study seasonal growth dynamics of trees (e.g., Duchesne et al., 2012; van der Maaten, 2013), to gain insights in environmental parameters driving tree growth (Biondi and Hartsough, 2010; Deslauriers et al., 2003; Köcher et al., 2012), and to monitor the water balance of trees (Giovannelli et al., 2007; Turcotte et al., 2011; Zweifel et al., 2005). Dendrometers continuously record stem-size variations without invasive sampling of the cambium (Drew and Downes, 2009), making them particularly suitable for long-term monitoring. Recorded signals comprise irreversible stem growth and reversible cycles of stem water depletion and replenishment (Herzog et al., 1995; Kozlowski and Winget, 1964; Tardif et al., 2001). Several approaches have been proposed to analyze the different components of these data (e.g., Deslauriers et al., 2003; Downes et al., 1999; Drew and Downes, 2009; Herzog et al., 1995; King et al., 2013). Among them, two major approaches can be identified: (1) *daily*, and (2) *stem-cycle approaches*. The daily approach characterizes the properties of the circadian cycle by calculating or extracting summary metrics per day (i.e. daily mean, minimum or maximum) (Bouriaud et al., 2005; King et al., 2013; van der Maaten et al., 2013), whereas the stem-cycle approach separates stem-size changes into the distinct phases of contraction, expansion and stem-radius increment (Deslauriers et al., 2003; Downes et al., 1999; Herzog et al., 1995). Although time series from daily and stem-cycle approaches are highly correlated (Deslauriers et al., 2007), only stem-cycle approaches can consider cycles that last longer than one day.

To disentangle the different cyclic phases from dendrometer data, Deslauriers et al. (2011) presented an algorithm for the proprietary software SAS. For the free and open-source statistical software environment R (R Development Core Team, 2016) no such routine is available, yet. A steadily increasing offer and use

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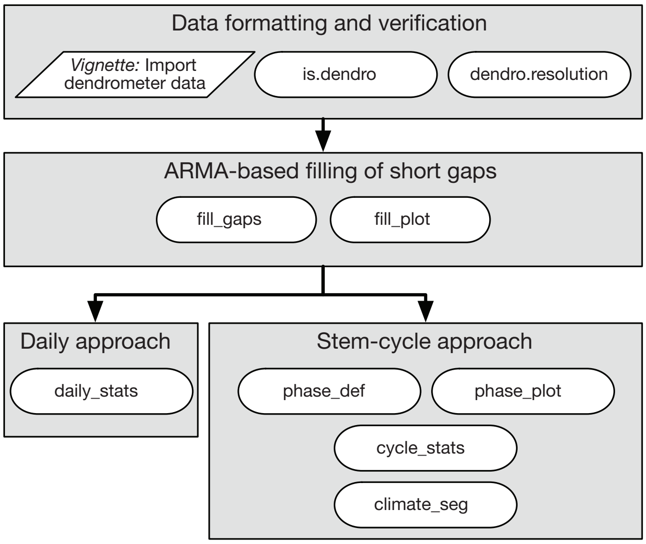

Fig. 1. Schematic overview of the functions included in dendrometeR.

of dendro-related R-packages like 'dplR' (Bunn, 2008), 'treeclim' (Zang and Biondi, 2015) and 'pointRes' (van der Maaten-Theunissen et al., 2015) are clearly highlighting the appreciation of the research community to make use of the extremely versatile R environment. Hence, a new R package was developed, named dendrometeR, that facilitates the analysis of sub-daily dendrometer data. Rather than a simple translation of the original SAS code (Deslauriers et al., 2011), dendrometeR presents an innovative and more comprehensive suite of customizable functions including functions for both daily and stem-cycle approaches. In this note, we describe and illustrate the functionality of the package.

2. Package functionality

The package dendrometeR contains functions (1) to prepare and verify dendrometer and environmental data formats for further processing in the package, (2) to perform gap-filling of dendrometer data, and to sequentially process dendrometer and environmental data for (3) daily statistics and (4) stem-cycle analysis (Fig. 1). Appropriate plotting functions allow to easily visualize gap-filled time series and the stem-cycle assignments.

2.1. *Data formatting and verification*

The package dendrometeR requests the input data to be formatted as a data frame with a timestamp as row names (in date-time format: %Y-%m-%d %H:%M:%S without daylight savings, e.g., time zone GMT), and dendrometer series (or environmental data) in columns; missing values should be indicated with NA. To facilitate a possibly needed transformation of raw dendrometer data, the package includes a vignette called 'Import dendrometer data'. It is highly recommended to consult this vignette, as it illustrates the transformation process for diverse raw data formats. The functions `is.dendro` and `dendro.resolution` can be used to verify the correct formatting and the time resolution of the input data. The function `is.dendro` returns `TRUE` when the data is in the required format, and `FALSE` if not. In the latter case, specific error messages on the nature of the problem (e.g., problems with timestamp, non-numeric data etc.) are returned as well. The temporal resolution of the data, which needs to be constant within a time series, can be obtained using `dendro.resolution`.

2.2. *Gap filling*

As there may be missing values in the dendrometer data, a function named `fill_gaps` is provided. This function employs an ARIMA model (cf. Deslauriers et al., 2011) to fill gaps of short duration (i.e. several hours). The ARIMA model cannot sensibly handle long gaps, i.e. lasting over more than a day. Optimal models are selected using the `auto.arima` function from the 'forecast' package (Hyndman and Khandakar, 2008). Optionally, seasonal components of ARIMA models can be included. In that case, AR-, I- and MA-components are checked across the seasonal oscillations within the data (for dendrometer data most likely to be daily). Although the inclusion of a seasonal component might increase the robustness and precision of the ARIMA model, it will also demand more computation resources, thereby slowing down the execution of `fill_gaps`. The output of the model can be smoothed using a user-defined smoothing parameter. As the ARIMA parameters, and thus the gap-filling, might be distinct for individual growing seasons, we deliberately designed `fill_gaps` for single growing seasons. Consequently, long dendrometer series should be splitted in individual growing seasons prior to gap-filling. To allow the usage of the function for datasets from the Southern Hemisphere, the input data may contain two consecutive calendar years at maximum. `fill_gaps` can work on multiple series simultaneously and returns a data frame with gap-filled dendrometer series. The output can be conveniently displayed for specified time windows using the `fill_plot` function.

2.3. *Daily approach*

For daily analyses, the function `daily_stats` can be applied on both dendrometer and environmental datasets. The function returns, depending upon the entry for argument `sensor` (i.e. a `numeric` or `"ALL"`), multiple statistics (mean, minimum, maximum, amplitude, and timing of minimum/maximum) for a specified sensor, or a single statistic (daily mean, minimum, maximum, or sum) for all sensors in a data frame. The option to calculate daily sums is included in `daily_stats` as it is relevant for environmental parameters like precipitation. An optional smoothing argument is included (`smooth.param`) to handle noisy datasets; it requires gap-free (or -filled) series.

2.4. *Stem-cycle approach*

The stem-cycle processing includes three functions that need to be sequentially performed, i.e. `phase_def`, `cycle_stats` and `climate_seg`. The function `phase_def` identifies and assigns each timestamp to the three distinct phases of contraction, expansion and stem-radius increment for dendrometer series from a data frame with gap-free (or -filled) dendrometer data. Thereby, the function first searches for minimum and maximum points within a specified daily time window. Then, the original dendrometer series are offset back- and forward to make sure that the identified extrema are indeed extrema of the cyclic phases. A comparison between the original and offset series finally allows selecting all appropriate minimum and maximum values. The `phase_def` function can be customized in many different ways. For example, the minimum temporal distance and the minimum difference between consecutive minimum and maximum points (i.e. in *x* and *y* direction) can be specified using the arguments `minmaxDist` and `minmaxSD`, respectively. The argument `radialIncrease` allows to determine from which moment on data points should be assigned to the stem-radius increment phase: when data points are continuously above the previous maximum (`"max"`), when a single data point is above the previous maximum (`"min"`), or right in between `"min"` and `"max"` (`"mid"`). This highly flexible architec-