Dendrochronologia 48 (2018) 32–39

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

dendroTools: R package for studying linear and nonlinear responses between tree-rings and daily environmental data

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ARTICLE INFO

Keywords:
Dendroclimatology
Daily climate data
Running window
Nonlinear modelling
Tree-ring proxies
Climate reconstruction

ABSTRACT

We introduce in this paper the *dendroTools* R package for studying the statistical relationships between tree-ring parameters and daily environmental data. The core function of the package is *daily_response()*, which works by sliding a moving window through daily environmental data and calculating statistical metrics with one or more tree ring proxies. Possible metrics are correlation coefficient, coefficient of determination and adjusted coefficient of determination. In addition to linear regression, it is possible to use a nonlinear artificial neural network with the Bayesian regularization training algorithm (*brnn*). *dendroTools* provides the opportunity to use daily climate data and robust nonlinear functions for the analysis of climate-growth relationships. Models should thus be better adapted to the real (continuous) growth of trees and should gain in predictive capabilities. The *dendroTools* R package is freely available in the CRAN repository. The functionality of the package is demonstrated on two examples, one using a mean vessel area (MVA) chronology and one a traditional tree-ring width (TRW).

1. Introduction

R computer language (R Core Team, 2017) is one of the most powerful platforms for analysing tree-ring data. Many useful packages have been developed in recent decades that are freely available to the tree-ring community. The *dplR* package (Bunn, 2008, 2010) is widely used to perform several standard analyses, including interactive detrending, chronology building and the calculation of standard descriptive statistics, and is slowly replacing the traditional software for tree-ring standardisation ARSTAN. The R package *treeclim* (Zang and Biondi, 2015) provides a unified and fast compilation of established methods, while adding novel functions, such as static and moving bootstrapped response and correlation functions, seasonal correlation analysis, a test for spurious temporal changes in proxy-climate relations, and the evaluation of reconstruction skills. Some other useful R packages developed for tree-ring analysis are *dendrometeR* (van der Maaten et al., 2016), *CAVIAR* (Rathgeber et al., 2011), *pointRes* (van der Maaten-Theunissen et al., 2015), *measuRing* (Lara et al., 2015), *TRADER* (Altman et al., 2014) and tracheideR (Campelo et al., 2016). These R packages are of significant importance and provide the opportunity to analyse tree-ring data more effectively. In addition to R packages, there are also other types of software that are commonly used for identifying climate signal in an annual tree-ring time series. Two of them are Seascorr (Meko et al., 2011), which runs in MATLAB; and DENDROCLIM2002 (Biondi and Waikul, 2004), a C++ programme.

The CLIMTREG programme was developed by Beck et al. (2013) and provides the possibility of calculating climate–growth correlations based on daily climate data using variable temporal width together with moving correlations to accommodate short term as well as long term influences. The programme has been used in several studies (e.g. Liang et al., 2013; Castagneri et al., 2015), but unfortunately has not been further developed, since the company that produced the GfaBasic32 programming language no longer exists. Despite the great potential of improving understanding of the climate-growth relationship, there is currently no similar function available in R. The identified methodological gap could be filled by our newly developed R package *dendroTools* (Jevšenak and Levanič, 2018), especially with its core function *daily_response()*. This function provides the possibility of analysing linear and nonlinear relationships between tree-ring and daily environmental data, and could therefore be important to help researchers identify tree-climate relationships. With the proposed methodology, models should be better adapted to the real (continuous) growth of trees and should gain predictive capabilities, which should result in more accurate climate reconstructions and better understanding of climate-growth relationships.

Common practice in dendroclimatology is to correlate one or more tree-ring proxies (predictors) to monthly or seasonal climate data (predictands). By using monthly data, some climate signal is inevitably

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https://doi.org/10.1016/j.dendro.2018.01.005
Received 25 October 2017; Received in revised form 22 January 2018; Accepted 24 January 2018
Available online 31 January 2018
1125-7865/

lost, mainly because months are invented categories not based on any of the laws of nature. Growth is a continuous process and should not be limited by artificially set monthly borders. With the *daily_response()* function from the *dendroTools* R package, temporal changes in climate-growth response are analysed and results can be later used for various dendroclimatological applications. It is not new for daily environmental data to be used in combination with tree-ring proxies. The process-based Vaganov-Shashkin model uses daily temperature and precipitation data to simulate tree-ring chronologies (e.g. Touchan et al., 2012). Chun et al. (2017) used tree-ring width information to improve daily-scale reconstructions of rainfall extremes.

The aim of this article is to present the functionality of the *dendroTools* R package, with an emphasis on the *daily_response()* function. Two case studies have been used to do so, one using a mean vessel area (MVA) and one using a tree-ring width (TRW) parameter.

2. *dendroTools* description

2.1. Package requirements, installation and dependences

The *dendroTools* R package will run on R version 3.4 or higher, simply because it depends on certain other packages that do not work in older versions of R. After installing the right version of R, *dendroTools* can be installed from the Comprehensive R Archive Network (CRAN) with the following command: install.packages("dendroTools") and loaded with: library ("dendroTools"). The current version (0.0.5) relies on 15 other R packages. Those that are important for the functionality of the *daily_response()* function are: *ggplot2* (Wickham, 2009), *oce* (Kelley and Richards, 2017), *brnn* (Pérez-Rodríguez and Gianola, 2016), *reshape2* (Wickham, 2007), *scales* (Wickham, 2016), *stats* (R Core Team, 2017), *reshape* (Wickham, 2007), *MLmetrics* (Yan, 2016), *dplyr* (Wickham et al., 2017) and dcv (Li and Zhang, 2010). In addition, R users should have installed the appropriate Java, i.e., 32-bit Java for 32-bit R and 64-bit Java for the 64-bit R version.

2.2. Package functionality

The *daily_response()* function is the core function of the *dendroTools* R package. Although the name of this function suggests the connection to the response functions presented by Fritts (1976), this is not the case; they are two different concepts. The main purpose of the *daily_response ()* is to analyse temporal changes of relationships between tree-ring proxies and daily environmental data. The function calculates all possible statistical metrics between different ranges of daily data and one or more response variables. The key purpose is to find the optimal consecutive sequence of days that are linearly or nonlinearly related to one or more response variable (i.e., tree-ring proxies).

The function *daily_response()* works by sliding a moving window through daily environmental data, aggregating daily environmental data within each window and calculating its averages (Fig. 1A), which are then used to calculate the selected statistical metric – i.e., correlation coefficient, coefficient of determination or adjusted coefficient of determination (Fig. 1B). Two data frames have to be passed to *daily_response()*, i.e., *response* and *env_data*. *response* are data frames with one or more tree-ring proxy variables. Rows represent years and columns represent proxy variables. Years should be included as row names of a data frame to avoid errors. *env_data* is a data frame with daily environmental data (e.g., temperature, precipitation or similar). Rows represent years and columns represent a day of a year, starting with day 1 of the year in column 1. Years should be included as row names of a data frame. The examples of *response* and *env_data* are given in Table 1.

To use *daily_response()*, the user should first decide whether to use a fixed or progressive window for calculations of moving averages. To use a fixed window, select its width by assigning an integer to the argument *fixed_width*. When the user is interested in many different windows, *lower_limit* and *upper_limit* arguments are available. In this case, all window widths between the lower and upper limits will be considered. In this context, window width representative of a specific day of the year (DOY) is defined as the values for this particular day and the number of subsequent days corresponding to window width. All calculated metrics are stored in a matrix (Fig. 1C). This matrix is available

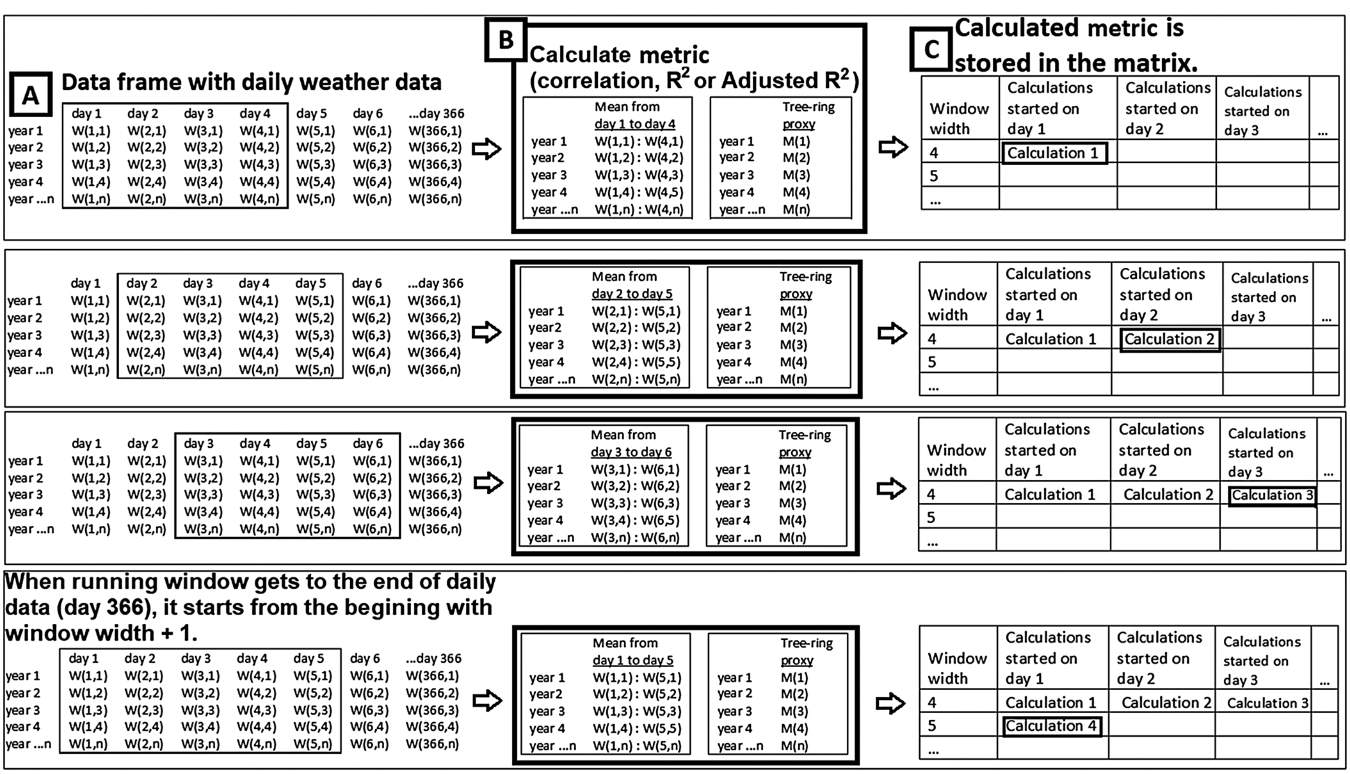

Fig. 1. Schematic presentation of the running window of the *daily_response()* function. In this example, the initial window width is set to 4.