WK 21 - Advanced Analyses of Tree Physiological Time Series in R and PhytoSim

ESA Virtual Meeting

Harnessing the ecological data revolution

Organizer

Richard L. Peters - Ghent University

Co-Organizers

Christoforos Pappas - Centre d’étude de la forêt, Université du Québec à Montréal & Téluq

Roman Zweifel - Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Kathy Steppe - Ghent University

Alexander G. Hurley - GFZ Potsdam

[03/08/2020 - 06/08/2020]

1. Course - Relevance of processing high-resolution tree physiological measurements

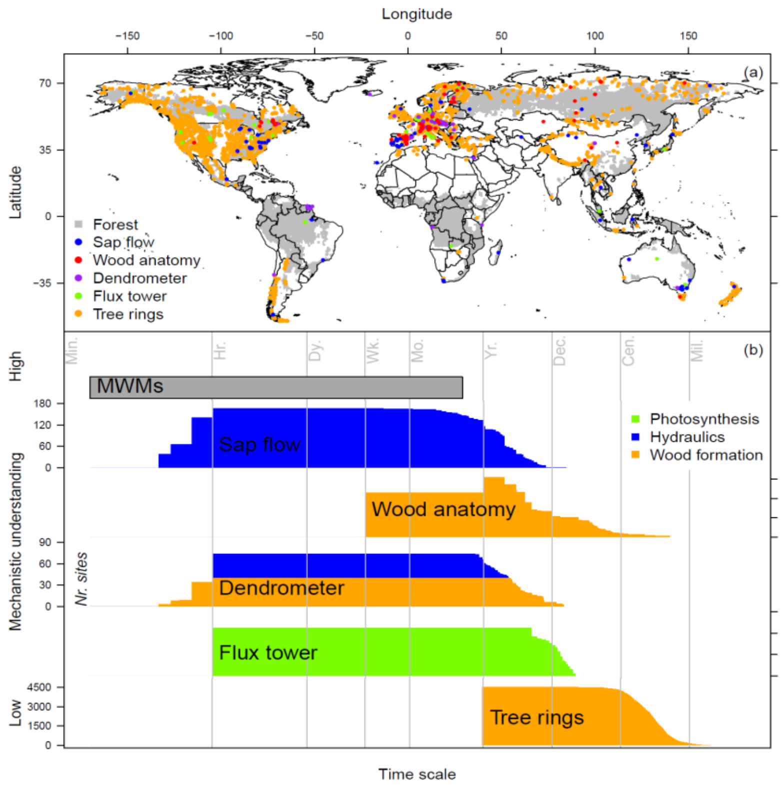


Fig. (a) Global distribution of sites where relevant tree physiological measurements were collected. (b) The temporal extend of the datasets presented spatially in (a). Additionally, the extend of simulations from mechanistic whole-tree models (MWMs) is provided.

Source: Peters (2018) doi:[10.5451/unibas-007085812](https://doi.org/10.5451/unibas-007085812)

Time-series measurements

Increasing availability of tree physiological time series on tree growth and water use [Fig.] provide unique opportunities for exploring tree and forest function, health, and resilience to ongoing environmental changes. However, processing such time series data is challenging, due to data quantity and quality, varying time steps, labor-intensive data cleaning, and assumptions for converting raw measurements to physiologically meaningful quantities. To resolve such issues, software tools should be utilized for facilitating data pre- and post-processing in a fast, efficient and reproducible way.

1. Course - Target of the Advanced Analyses of Tree Physiological Time Series workshop

Sapflow

Dendrometer

TREX

treenetproc

PhytoSim

Dynamic Plant Modelling and Simulation

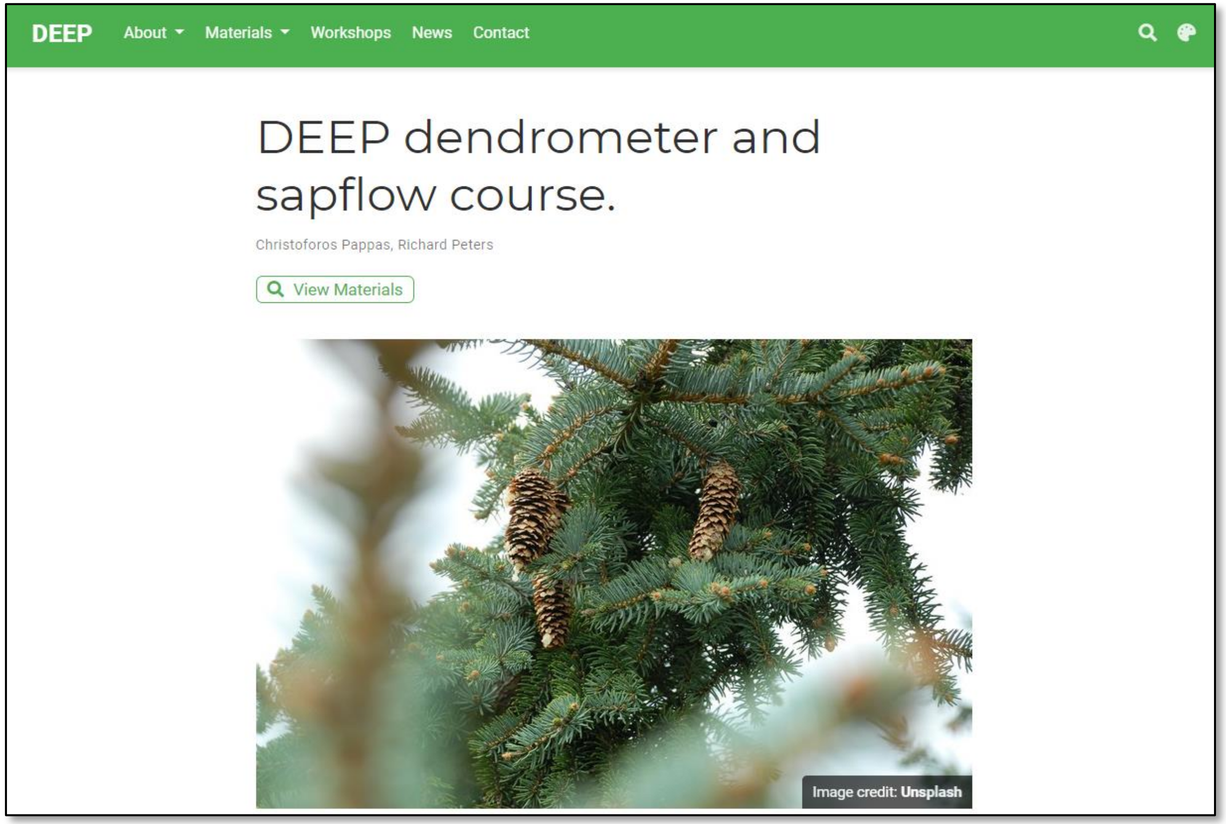
Aim

Within this workshop we aim at providing participants hands-on training on novel software tools: R packages to process dendrometer and sap flow data, and PhytoSim models to integrate data and unravel underlying mechanisms.

Practice

Guided by example datasets (within dedicated tutorials), this interactive workshop presents a benchmark for dendrometer and sap flow data processing methods [Fig.] and facilitates greater potential for improving comparability between datasets.

1. Course - Logistics for software and code availability



Infrastructure

Participants should use their own laptops with pre-installed copies of R/RStudio and/or PhytoSim. Data files and codes for this workshop are available via the below provided link.

DEEP tools Link [Fig.]

https://deep-tools.netlify.app/talk/esa-2020-rpeters-cpappas/

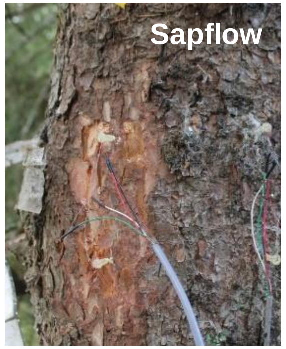
R software

Install R and R studio.
https://www.r-project.org/; https://rstudio.com/

PhytoSim software

Install a trial version of PhytoSim.
https://www.phyto-it.com/

1. **Course** - Content and structure of the workshop



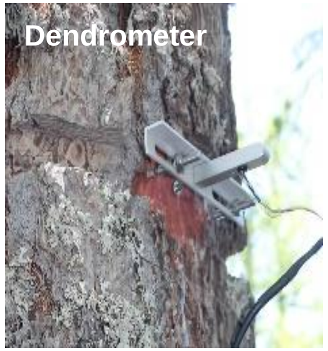


Fig. Example tree used within the workshop. This *Picea abies* grows in the Swiss Lötschental. Metadata;
Diameter at breast height = 30.7 cm,
stem length = 2.8 m,
phloem thickness = 0.48 cm,
bark thickness = 0.68 cm,
sapwood thickness = 2.5 cm,
and age = 90 years.

Source: Pappas *et al*. (2020)
doi:10.1111/ecog.04968

2. Dendrometer

Dendrometer functionalities include the option to align measurements to regular time intervals, remove outliers and correct for data-jumps. Additionally, parameters such as yearly growth or maximum daily shrinkage are provided.

3. Sapflow

For sap flow data processing, we present functionalities for importing and homogenizing raw sap flow measurements, conducting various data-processing approaches, calculating sap flux density and crown conductance to water, and quantify their uncertainties.

4. Mechanistic modelling

For the dendrometer-sap flow combination, we focus on turgor-driven growth and hydraulics.

2. Dendrometer - Utilizing the treenetproc R package (https://github.com/treenet/treenetproc)

Fig. Examples of band and point dendrometers

Introduction

Radial stem size changes measured with automated dendrometers [Fig.] at intra-daily resolution allow us to link environmental conditions with tree physiology (i.e., radial stem growth and tree water relations).
However, measured time series need to be cleaned of outliers and data shifts, and must be separated into the reversible (water related) and the irreversible (radial growth) components in order to conduct physiologically meaningful interpretations.
Here, we illustrate the utilities of the R package treenetproc to facilitate dendrometer data processing.

2. Dendrometer - Structure of the treenetproc R package and accessibility

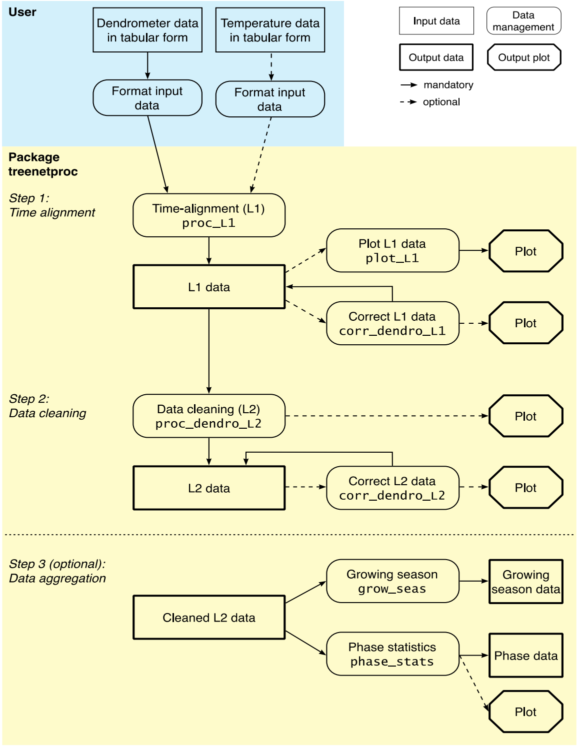


Fig. Workflow of treenetproc. Functions of the package are shown in rounded rectangles, including a description of the functionality (first line) and the name of the function (second line). Outputs of the functions are shown as rectangles (data output) and octagons (graphical output). Solid arrows indicate the regular workflow, dashed arrows indicate the optional, user-induced workflow.

Source: Knüsel *et al.* (in Rev.)

Availability

The R package treenetproc and all source code is available on GitHub (https://github.com/treenet/treenetproc). In the R software (Team, 2019), the package can be installed with the following commands:

```
# install.packages("devtools")
library(devtools)
devtools::install_github("treenet/treenetproc")
```

Link

An R tutorial on the use of treenetproc is accessible via this link: https://deep-tools.netlify.app/docs-workshops/esa-workshop2020/01_treenetproc

Structure

The general workflow of treenetproc is composed of three main steps including multiple functions [Fig.]. In step 1 (time alignment), the raw data of dendrometer is aligned to user-defined, regular time steps (L1 data). In step 2 (data cleaning), outliers and shifts in the L1 data are detected and corrected. In step 3, the L2 data is analysed and several derived variables are calculated (Table 1).

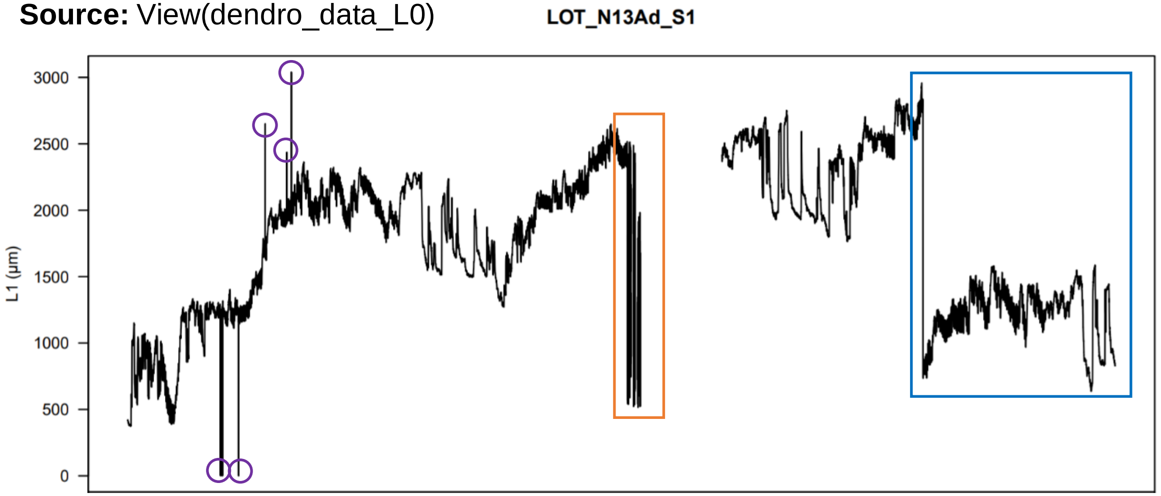
References

Zweifel *et al.* (2016) doi: 10.1111/nph.13995
https://github.com/treenet/treenetproc

2. Dendrometer - Raw dendrometer series and common issues

Fig. Example data of point dendrometer measurements from LOT_N13Ad_S1. Here we plotted all three years of raw dendrometer data (L0; radial variability in µm) collected from a Picea abies tree (S1) growing in the valley bottom (N13Ad) in the Lötschental (LOT; Switzerland). Multiple data issues are present within the data, including; outliers in 2008 (purple circles), sensor failure in 2009 (orange square) and a measurement jump due to reinstalling the sensor in 2010 (blue square).

Source: View(dendro_data_L0)



Common data issues

Within this tutorial we will present the treenetproc functionalities on LOT_N13Ad_S1 [Fig.]. The analysis of dendrometer measurements can be challenging, as raw measurements often contain outliers, errors, shifts or jumps in the data due to adjustments of the device in the field, electronic failures or external mechanical disturbances. Therefore, data cleaning is often a manually performed, time-consuming, and usually a poorly reported part of the data treatment.

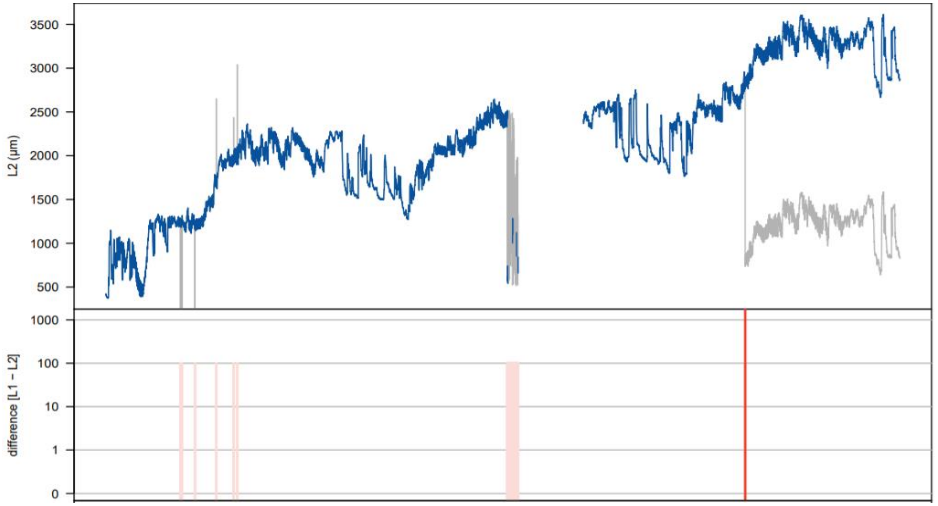
Code

See section: #0. Import data (L0)

2. Dendrometer - Removing outliers and correcting for data jumps

Fig. Example of data cleaning of the point dendrometer measurements from LOT_N13Ad_S1, using the function proc_dendro_L2. The first panel shows cleaned L2 data. The grey lines show the raw measurements, while the blue lines indicate the cleaned time-series. The second panel shows the data jump correction-induced differences between L1 and L2 data (red) on a logarithmic scale.

Source: proc_dendro_L2()



Step 1: Time alignment

Key to the following processing steps is the proper time alignment of dendrometer and temperature data to a user-defined, regular time step with the function proc_L1.

Code

See: ?treenetproc::proc_dendro_L1

Step 2: Data cleaning

Automatic outlier error detection of the dendrometer data is based on first order differences of the L1 data (diff) and the respective frequency analysis of the function proc_dendro_L2. Since the density distribution of diff is typically very narrow (most values of diff are close to zero) the most frequent values within the 30% and 70% percentiles are removed before calculating thresholds for data outliers and shifts. To increase the quality of error detection, time-aligned temperature data is provided to temp_data_L1.Cleaned data series are gap-filled according to the custom-set parameter interpol (in min.) which defines the maximum gap size that is linearly interpolated. The cleaned and gap-filled data is used to compute timeseries of tree water deficit (twd) and annually accumulated growth (gro_yr) which are returned as csv-files [Fig.].

Code

See: ?treenetproc::proc_dendro_L2

2. Dendrometer - Manual cleaning of time-series when automatic detection fails

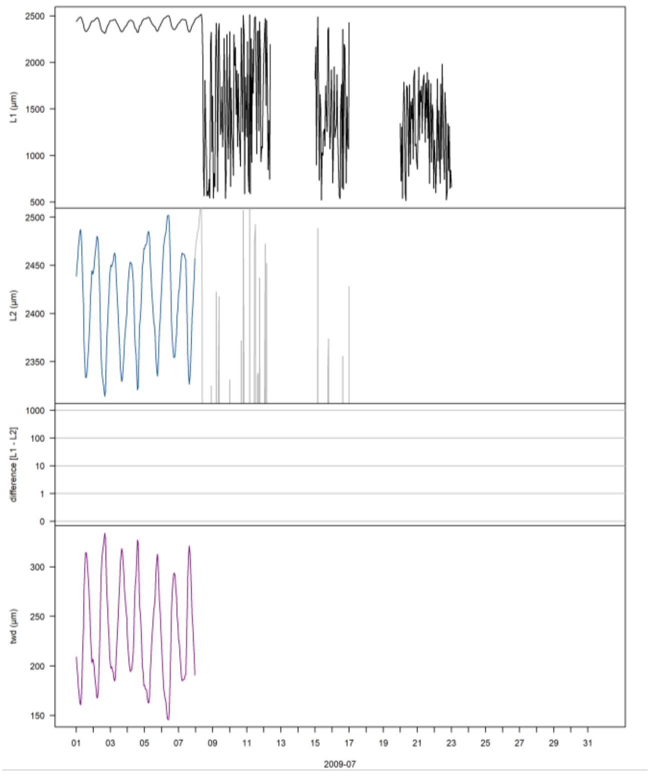


Fig. Example of data cleaning of the point dendrometer measurements from LOT_N13Ad_S1, using the function corr_dendro_L2. When isolating July 2009 (2009-07), one can see that although most of the errors (induced by sensor failure) have been removed some manual removing is still required. With the manual editing all erroneous data is removed in July 2009. Now the data is ready for extracting relevant physiological measurements.

Source: corr_dendro_L2()

Manual editing

The processed L2 data can be exported and visually inspected in user-defined plots to identify remaining errors and inconsistencies due to an inaccurate parameter setting. For example, a too flexible value of tol_jump (too high value) will not correct all jumps in the dataset. In contrast, a too rigid one (too low value) may, in the worst case, lead to an attenuation of the shape of the stem size curve over time. For remaining errors treenetproc offers functions to overrule introduced changes or force changes that were not automatically made. Generally, it is advisable to remove periods of obvious erroneous data already after time-alignment with the function corr_dendro_L1. This function can be used to reverse erroneous changes or force changes that were not automatically made. All corrections are also reflected in the returned data.frame and all changes are documented in the column flags

There are three possibilities to manually correct remaining errors:
1) Reverse: specify the ID numbers of the changes that should be reversed. Remaining changes are renumbered starting at 1;
2) Force: force a shift in the data that was not corrected for by specifying a date up to five days prior to where the shift should occur;
3) Delete: delete an entire period of erroneous data by specifying a date range. This can also be done for L1 data with the function corr_dendro_L1().

Code

See: ?treenetproc::corr_dendro_data_L2

2. Dendrometer - Workflow to obtain physiologically relevant parameters

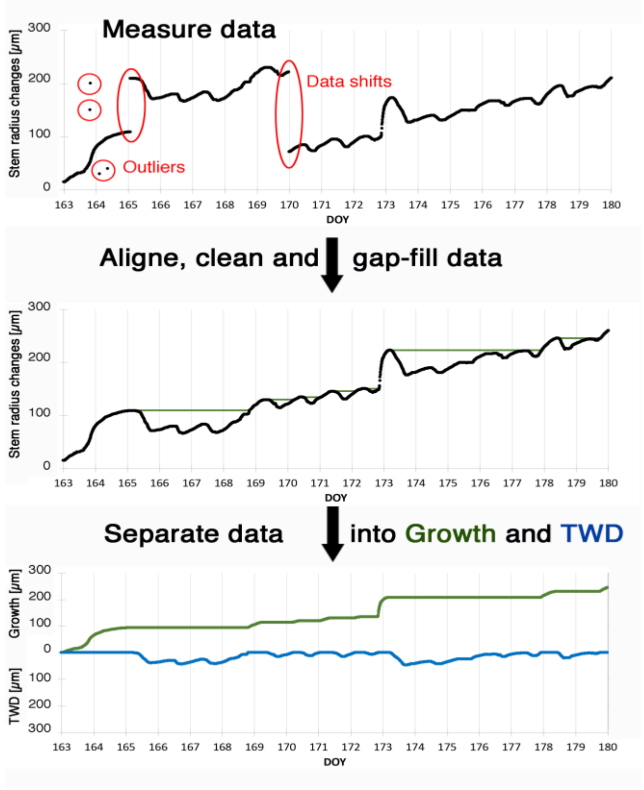


Fig. From raw stem radius measurements on trees to valuable growth and tree water relations data. The automated point dendrometer mounted on a tree stem measures highly resolved stem size changes in a micrometre resolution. Stem radius changes origin in the cambium due to newly built cells (growth), and in the bark due to hydraulically induced pressure changes and the tree water deficit-induced tissue shrinkage and swelling (TWD). Measured raw data needs to be aligned, cleaned for data outliers and shifts, and gap filled before being separated into the growth- and the TWD-induced fractions of the size changes.

Source: Knüsel *et al.* (in Rev.)

Physiological parameters

After error detection and processing and the manual removal of remaining errors, the package offers functions to calculate additional physiological parameters that may be of use for later analyses [Fig.].

The cleaned dendrometer time series is partitioned into growth and water-related components according to the zero growth (ZG) concept. The ZG concept assumes that growth starts once the previous stem diameter maximum is exceeded and ends as soon as stem shrinkage occurs. Consequently, the ZG concept only considers growth to occur during periods without stem shrinkage.

Moreover, treenetproc calculates a number of characteristics such as the start and end of stem growth for the years measured or the timing and rate of change in phases of stem shrinkage and expansion offering a wide range of opportunities to better set stem radius data into value.

Source

Zweifel *et al.* (2016) doi: 10.1111/nph.13995

2. Dendrometer - Tree water deficit patterns provide information on drought stress

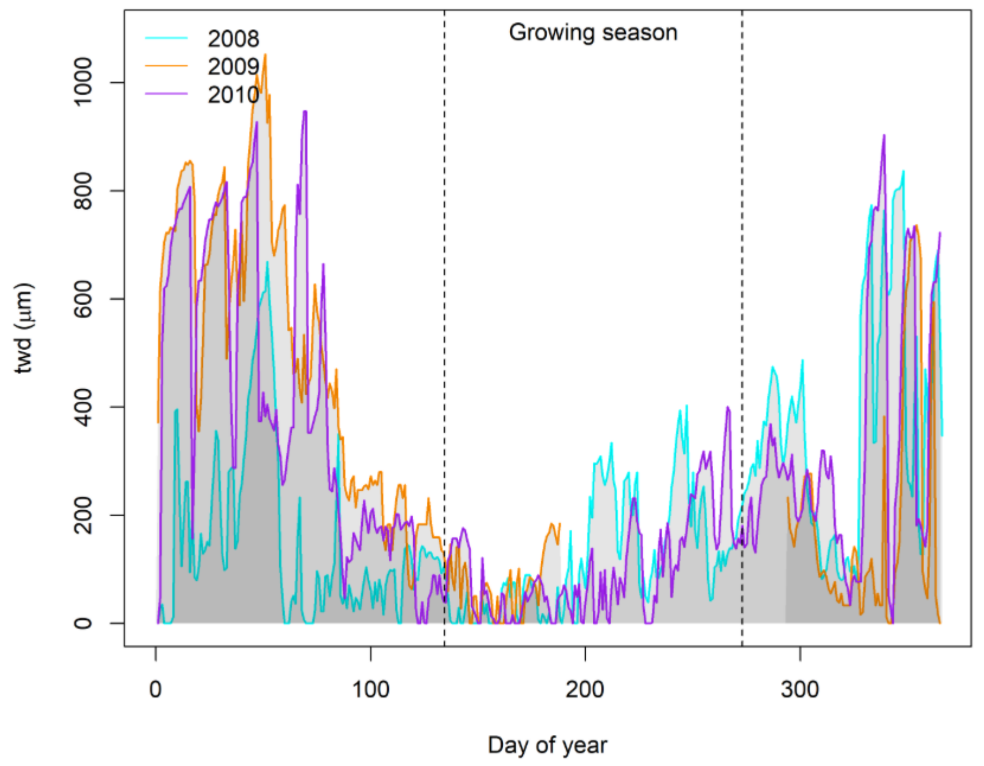


Fig. Example of tree water deficit (twd) time-series.

Tree water deficit and drought stress

High-resolution dendrometers capture reversible elastic reductions in stem diameter following capacitive water release, most often referred to as tree water deficit (twd). This physiological parameter can be used as an indicator of drought stress, as larger shrinkage indicates higher depletion of the water storage pools within the stem. Particularly the minimum daily twd highlights the capability of a tree to fully refill their storage pools during drought events and prevent drought induced damage to their hydraulic architecture.

Interpretation

Tree water deficit (twd) dynamics [Fig.] reveal that the tree mainly shrinks during the night in winter. Besides the temperature (frost) induced winter shrinkage, drought impacts are detectable within the growing season. During the growing season 2008 showed more shrinkage compared to 2010, revealing the tree was experience stronger water limitation during growth within this period.

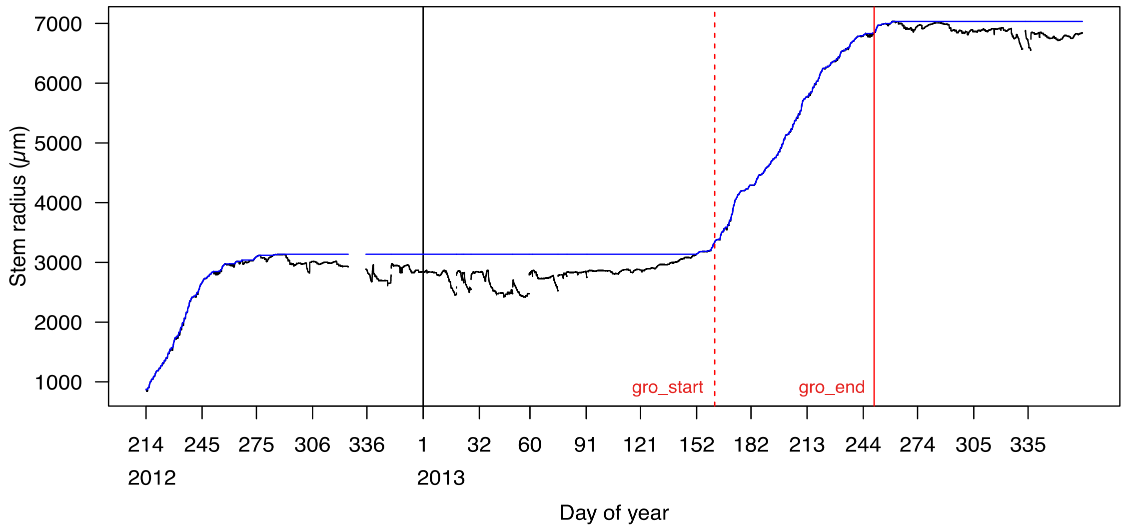
Code

See section: #3. Data aggregation (L3)

2. Dendrometer - Extracting growth for determining the start and end of radial growth

Fig. Example on how the calculation of start (gro_start, red dashed line) and cessation (gro_end, red solid line) of the growing season are performed and how these are influenced by the function grow_seas with a 5% uncertainty tolerance (tol_seas = 0.05).

Source: Knüsel *et al.* (in Rev.)



Determining the growing season

The function grow_seas returns the day of year of growth onset and growth cessation [Fig.] for clean L2 dendrometer data. Growth onset (gro_start) is defined as the day of year at which the maximum value of the past year is crossed, based on the ZG concept. Growth cessation (gro_end) is defined as the day of year at which the maximum value is reached.

Interpretation

The function returns a data.frame containing the day of year (doy) of the start and end of the growing season. Values are returned starting from the second year only, since gro_start and gro_end depend on the values from the previous year. The results generate in the R markdown illustrate that the tree growth starts around the end of May, which is realistic for these species growing in the Alps. The asymptotic nature of the growth curves makes the definition of the end of the growing season more sensitive to tol_seas. Make sure to validate these numbers for rationality.

Code

See: ?treenetproc::grow_seas

2. Dendrometer - Diurnal cyclic patterns to extract hydraulic activity

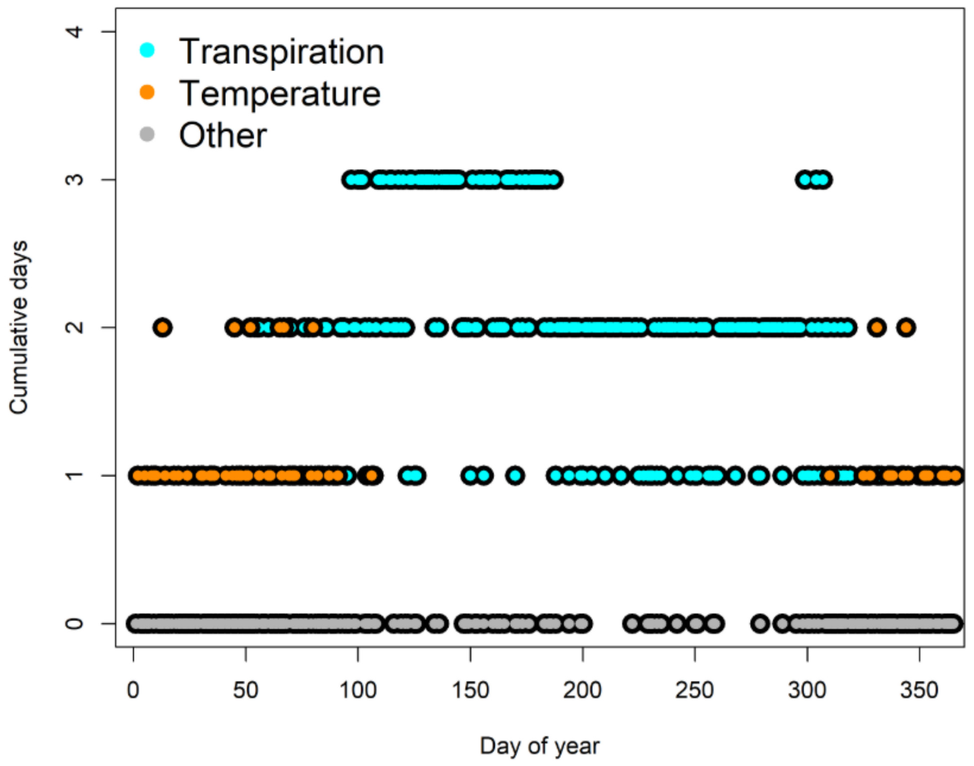


Fig. Example of phase statistics.

Phase statistics

Several characteristics of the diurnal shrinkage and expansion phases can be calculated with the function phase_stats. The function phase_stats calculates the timing, duration, amplitude and the rate of change of shrinkage and expansion phases. The function returns the timing, duration, amplitude and slope of the shrinkage and expansion phases. This information can be plotted daily for visual inspection.

Interpretation

The information on the diurnal phases could be used to identifies days on which radial change is likely driven by transpiration (phase_class = 1) or temperature (phase_class = -1). This plot [Fig.] shows the cumulative days of the three years (2008, 2009 and 2010) of LOT_N13Ad_S1 where the daily cycle is likely explained by transpiration, temperature or something else (other). These results show that transpiration for this individual tree is starting around day of year 50 and continues until day of year 325.

Code

See: ?treenetproc::phase_stats

3. Sap flow - Utilizing the TREX R package (https://the-hull.github.io/TREX)

Fig. Example of custom-made thermal dissipation sap flow sensors and their field installations.

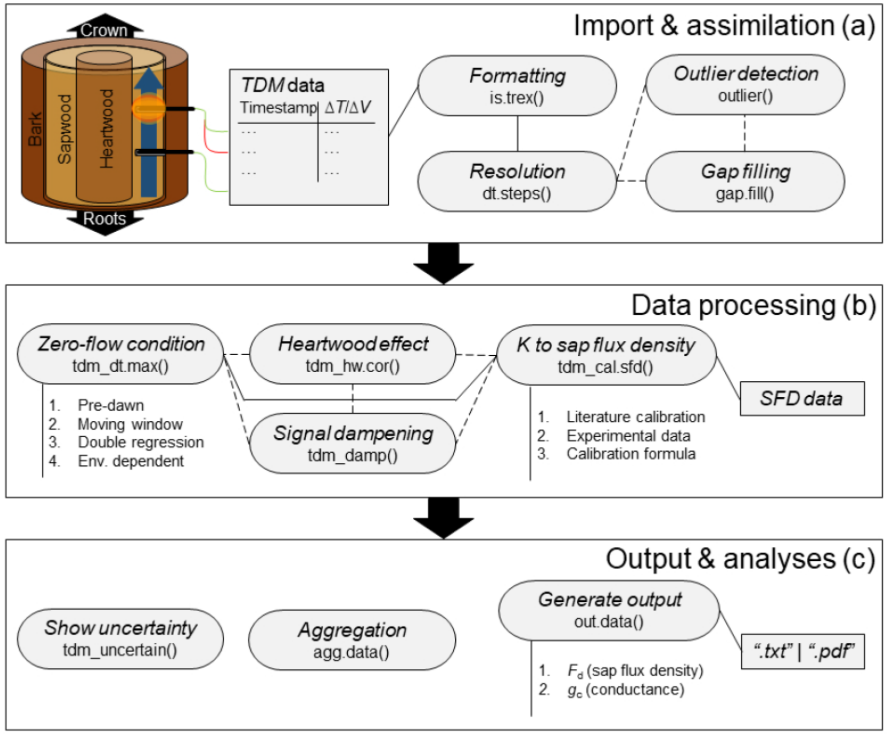
Source: Pappas *et al*. (2018) doi:doi.org/10.1093/treephys/tpy043

Introduction

Sap flow measurements provide semi-continuous (e.g., hourly) monitoring of stem water use and can provide unique insights into tree water use strategies. Sap flow data can be also upscaled at the stand level and quantify the transpiration, a major component of the terrestrial water balance. One of the most widespread technique for measuring sap flow in tree stems is the thermal dissipation method.

Here, we illustrate the functionalities of the R package TREX to facilitate thermal dissipation sap flow data processing and interpretation.

3. Sap flow - Structure of the TREX R package and accessibility



Source: Peters *et al.* (in Rev.)

Availability

The R package TREX and all source code is available on GitHub (https://the-hull.github.io/TREX). In the R software (Team, 2019), the package can be installed with the following commands:

```
# install.packages("devtools")
library(devtools)
devtools::install_github("the-Hull/TREX")
```

Link

An R tutorial on the use of treenetproc is accessible via this link:
https://deep-tools.netlify.app/docs-workshops/esa-workshop2020/02_trex/

Structure

The general workflow of TREX is composed of three main steps including multiple functions [Fig.]. In step 1 (import & assimilation), the raw sap flow data and the associated auxiliary meteorological data are imported in R and the consistency of the time series object is tested and if necessary corrected (i.e., regular time steps of time series objects, outlier detection, gap filling). In step 2 (data processing), zero-flow conditions can be derived with several approaches, and corrections can be applied (i.e., to heartwood correction and dampening). Then, sap flux density can be estimated using user-specific or literature values of the calibration parameters. In step 3 (output & analyses), the uncertainties associated with the sap flow pre-processing assumptions can be quantified with state-of-the-art statistical methods, the temporal resolution of the generated data can be adjusted, and the crown conductance to water can be estimated

References

Peters *et al.* 2018 doi: 10.1111/nph.15241

3. Sap flow - TREX-compatible time-series objects

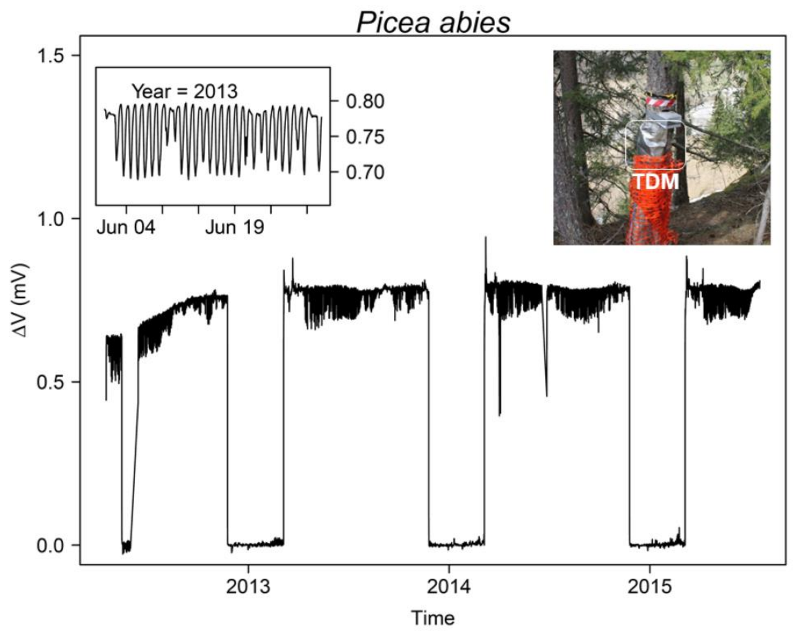


Fig. Example of a thermal dissipation time series from a mature Norway spruce (*Picea abies*) growing in an alpine valley (Lötschental, Switzerland) at 1300 m a.s.l..

Source: Peters *et al.* (in Rev.)

Step 1a: Data import & assimilation

The initial module of the TREX package deals with importing and assimilating the data. This includes check for time zone, define the temporal output resolution, data cleaning and gap filling. More specifically:

- The ***is.trex*** function tests if the structure of the input matches the requirements of TREX functions and specifies the time zone;
- The ***dt.steps*** function performs minimum time step standardization, gap filling and start/end time selection;
- The ***gap.fill*** function fills gaps by linear interpolation between observations.

Code

?is.trex
?dt.steps
?gap.fill

3. Sap flow - Outlier detection and interactive data cleaning

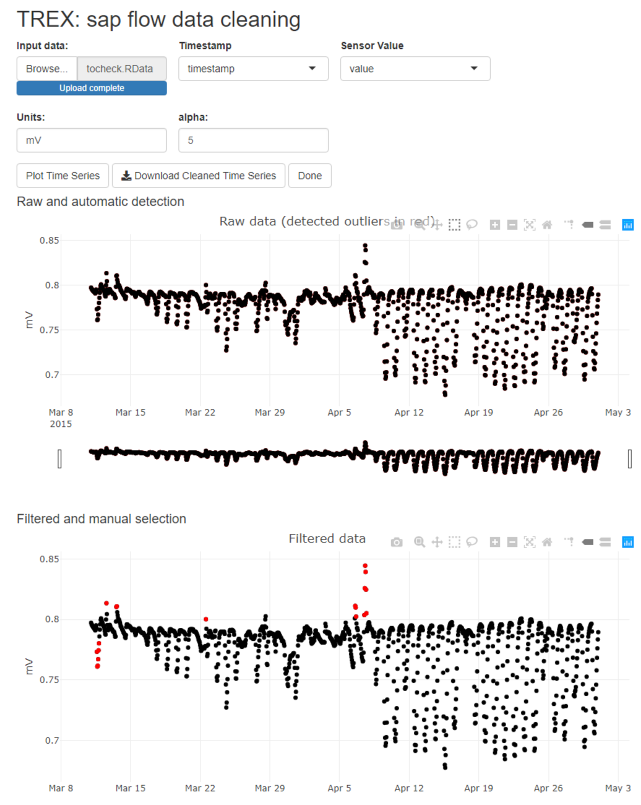


Fig. An example of the ***outlier*** functionalities. An.RData file is loaded in the Shiny app, the columns to be plotted in x- and y-axes are selected, as well as the units of the data and the parameter 'alpha' for the automatic outlier detection. Then the time series is plotted and the automatically detected outliers (if any) are highlighted in the upper panel. Parameter 'alpha' can be adjusted to better detect automatically outliers. Further, the lower panel allows the user to thoroughly inspect the time series and select manually outliers. Once the selection is finished, the user can export an .rds file with the outlier-free data that can be next imported in R and continue processing with the TREX package.

Step 1b: interactive data cleaning

The second part of the initial TREX module includes the interactive data inspection and outlier detection [Fig.]. The ***outlier*** function launches a Shiny application that; 1) visualizes raw and outlier-free time series interactively (using plotly), 2) highlights automatically detected outliers, 3) allows the user to revise the automatically detected outliers and manually include data points, and 4) exports the original data, the automatically selected outliers, the manually selected outliers, and the outlier-free time series in an is.trex-compliant object that can be further processed.

Code

?outlier

3. Sap flow - Data processing of raw sap flow measurements

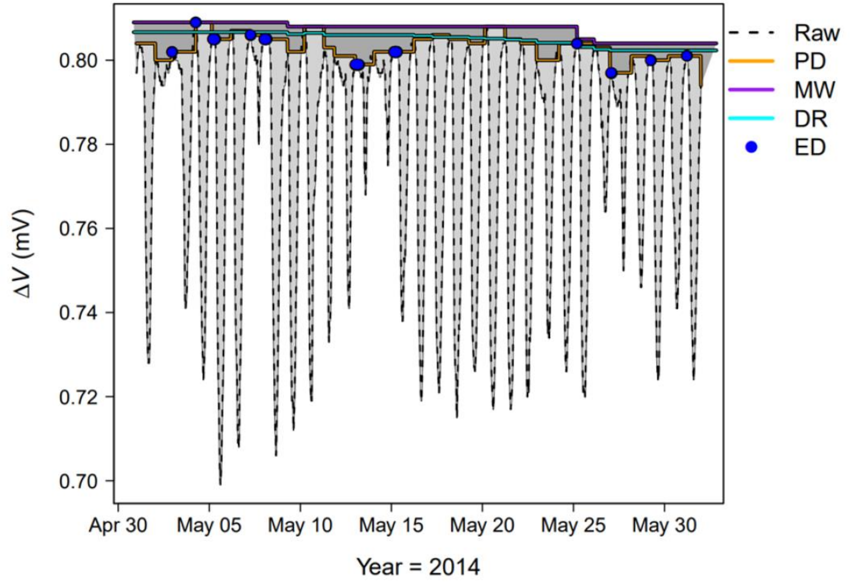


Fig. An illustration of the results obtained with the ***tdm_dt.max*** function. Raw sap flow measurements (mV) are processed with four methods implemented in TREX to determine the zero flow conditions.

Source: Peters *et al.* (in Rev.)

Step 2a: Zero flow conditions

The second TREX module includes the data processing, such as the determination of zero-flow conditions. In TREX four methods are implemented for determining the zero flow conditions, namely, 1) predawn (pd), 2) moving-window (mw), 3) double regression (dr), and 4) environmental-dependent (ed) as applied in Peters *et al.* (2018; doi: 10.1111/nph.15241). The ***tdm_dt.max*** function can provide ΔTmax (or ΔVmax) values and subsequent K values for all methods [Fig.].

Code

?tdm_dt.max

3. Sap flow - Data processing of raw sap flow measurements

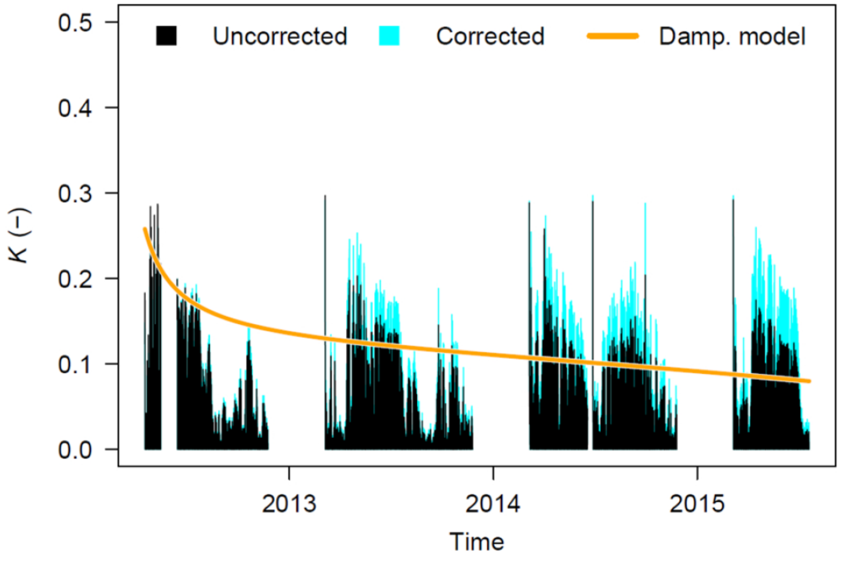


Fig. An illustration of the results obtained with the ***tdm_damp*** function. A non-liner model was fit to describe the signal dampening effect and then the raw sap flow data are corrected accordingly.

Source: Peters *et al.* (in Rev.)

Step 2b: Heartwood correction

Depending on the tree-specific sapwood allometry as well as the needle length of the deployed sap flow sensors, it might be necessary to apply a heartwood correction in the obtained raw sap flow data. The ***tdm_hw.cor*** function corrects for the proportion of the probe that is installed within the non-conductive heartwood according to Clearwater *et al.* (1999) doi: 10.1093/treephys/19.10.681. The function requires ΔTmax, the probe length and the sapwood thickness.

Code

?tdm_hw.cor

Step 2c: Signal dampening

When long-term K time series (~3 years) are provided, one can perform a signal dampening correction (when sensors were not re-installed; see Peters *et al.* 2018 doi: 10.1111/nph.15241). Applying the signal dampening correction requires visually inspecting the correction curve (see [Fig.]). The correction curve is constructed with the day since installation and the day of year (DOY) to account for seasonal changes in K values. The function returns corrected K values and the applied correction curve.

Code

?tdm_damp

3. Sap flow - Data processing of raw sap flow measurements

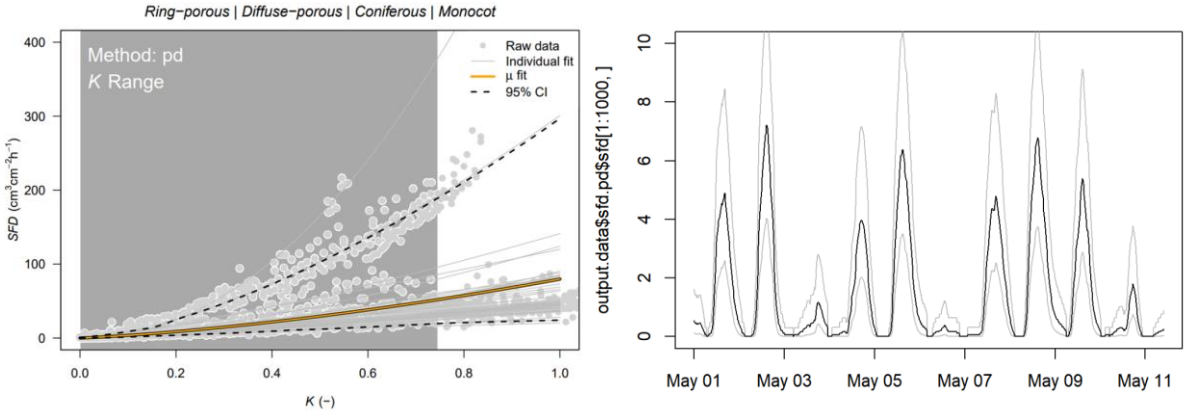


Fig. (left panel) Calibration curves obtained from literature, including all wood types, i.e., ring-porous, diffuse porous, coniferous and monocot. Power functions are fitted through each individual dataset. (right panel) Estimated sap flux density and 5 to 95% confidence intervals.

Source: Peters *et al.* (in Rev.)

Step 2d: Sap flux density

After having processed the raw sap flow data (K values) the next step is to calculate the sap flux density (SFD; $cm^3\ cm^{-2}\ h^{-1}$) with the ***tdm_cal.sfd*** function. This step requires some empirical (species-specific) parameters. As many calibration curves exist (see Peters *et al.* 2018 doi: 10.1111/nph.15241; Flo *et al.* 2019 doi: 10.1016/j.agrformet.2019.03.012), the function provides the option to calculate SFD using calibration experiment data from the meta-analyses by Flo *et al.* (2019); see ***cal.data*** function. Additionally, raw calibration data can be provided or directly the parameters *a* and *b* for a specific calibration function ($a\ K^b$). The algorithm determines for each calibration experiment the calibration curve ($SFD = a\ K^b$) and calculates SFD from either the mean of all curves and the 95% confidence interval of either all curves, or bootstrapped resampled uncertainty around the raw calibration experiment data when one calibration dataset is selected [Fig.].

Code

?tdm_cal.sfd
?cal.data

3. Sap flow - Output generation and data analyses

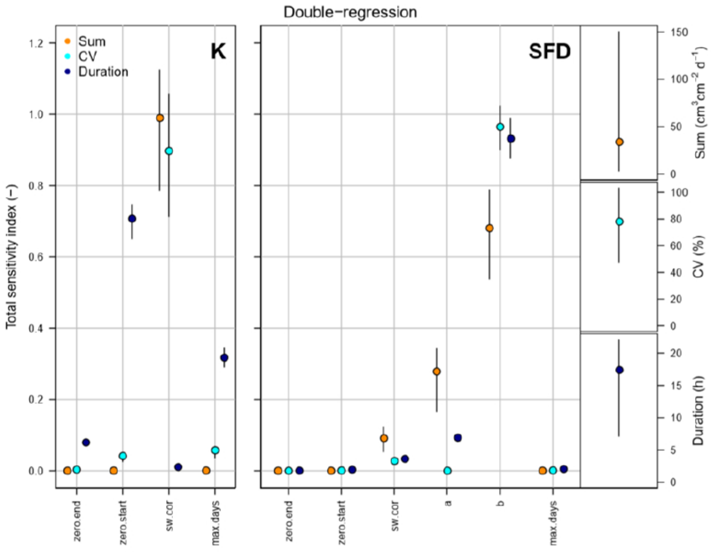


Fig. Visual output from the ***tdm_uncertain*** function when considering the double-regression ΔTmax method. Total Sobol' sensitivity indices of the investigated parameters with their mean (coloured dots) and 95% confidence intervals (vertical lines) are provided for K and SFD, respectively.

Source: tdm_uncertain() and Peters *et al.* (in Rev.)

Step 3a: Uncertainty quantification

Several of the previous steps include user-specific assumptions as well as empirical parameters. To assess the robustness of the obtained results (e.g., sap flux density), within the frame of TREX package, we provide functionalities for advanced global sensitivity and uncertainty analyses (Pappas et al. 2013 doi: 10.1002/jgrg.20035). The ***tdm_uncertain*** function quantifies the induced uncertainty on SFD and K time series due to the variability in input parameters applied during TDM data processing. Moreover, it applies a global sensitivity analysis to quantify the impact of each individual parameter on three relevant outputs derived from SFD and K, namely: i) the mean daily sum of water use, ii) the variability of maximum daily SFD or K values, iii) and the duration of daily sap flow. This function provides both the uncertainty and sensitivity indices, as time-series of SFD and K with the mean, standard deviation (sd) and confidence interval (CI) due to parameter uncertainty [Fig.].

Code

?tdm_uncertain

3. Sap flow - Output generation and data analyses

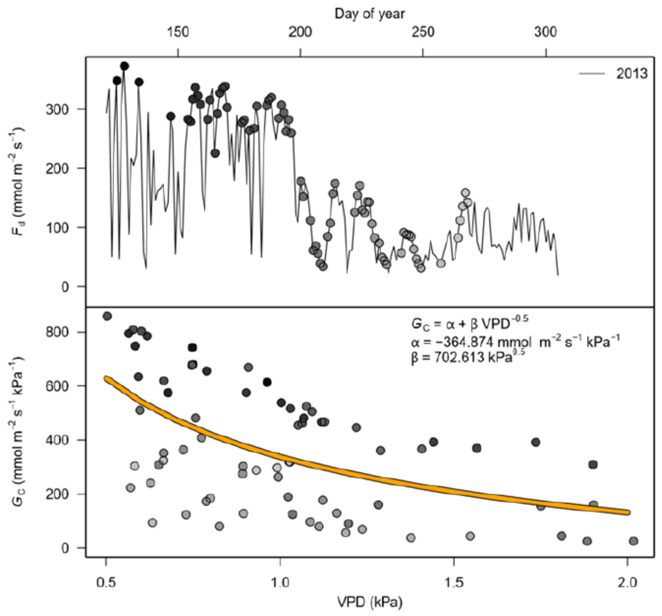


Fig. An illustration of the output from the ***out.data*** function. The upper panel shows the daily sap flux density, while the lower panel the estimated crown conductance to water.

Source: out.data() and Peters *et al.* (in Rev.)

Step 3b: Generate output

After having gone though the previous steps, the ***out.data*** function allows the user to generate relevant outputs from the sap flux density (SFD) values. This function provides both SFD expressed in mmol m^{-2} s^{-1} and crown conductance values (Gc; an analogue to stomatal conductance) in an easily exportable format. Additionally, the function can perform environmental filtering on Fd and Gc and model Gc sensitivity to vapor pressure deficit (VPD) [Fig.].

In addition, in the ***agg.data*** function allows the user to aggregate the variables of interest to specific temporal resolution and to select time periods of interest.

Code

?agg.data
?out.data

4. Mechanistic modelling - Modelling stem growth and internal stem hydraulics

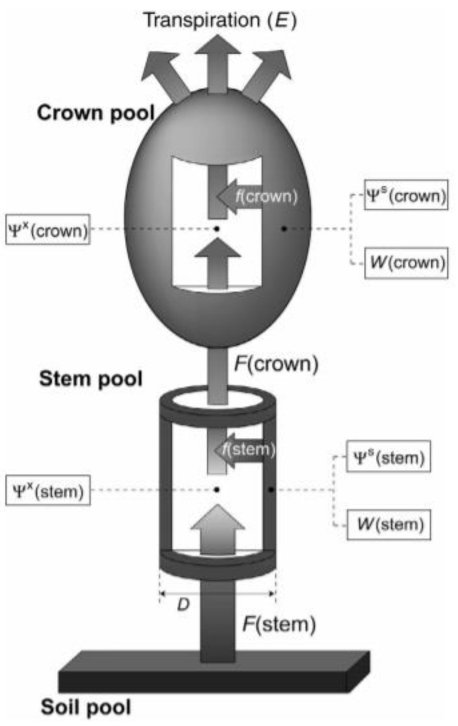


Fig. Schematic of the single-tree flow and storage model. The model is driven by transpiration. Flow rates into and out of the stem (i.e., bark) and the crown storage compartments are included. Such models can simulate pressure gradients within the tree and turgor-driven growth. A similar model will be presented within the PhytoSim software.

Source: Steppe *et al.* (2006) doi: 10.1093/treephys/26.3.257

PhytoSim
Dynamic Plant Modelling and Simulation

Introduction

State-of-the-art mechanistic models can simulate intra-daily stem growth (of both xylem and phloem) and internal stem hydraulics with an (sub-)hourly resolution by combining dendrometer and sap flow measurements.
PhytoSim was designed to apply such models, consisting of a set of dynamic algebraic and/or first order (ordinary) differential equations.

Availability

The software is available via this link:
https://www.phyto-it.com/

Link

A tutorial on the use of Phytosim is accessible via this link:
https://deep-tools.netlify.app/docs-workshops/esa-workshop2020/03_phytosim/

References

Steppe *et al.* (2006) doi: 10.1093/treephys/26.3.257
Steppe *et al.* (2008) doi: 10.1007/s00271-008-0111-6
De Pauw *et al*. (2008) doi: 10.1016/j.mbs.2007.08.007
De Pauw *et al*. (2008) doi: 10.1016/j.biosystemseng.2008.05.011

4. Mechanistic modelling - Using PhytoSim to model tree hydraulics and growth

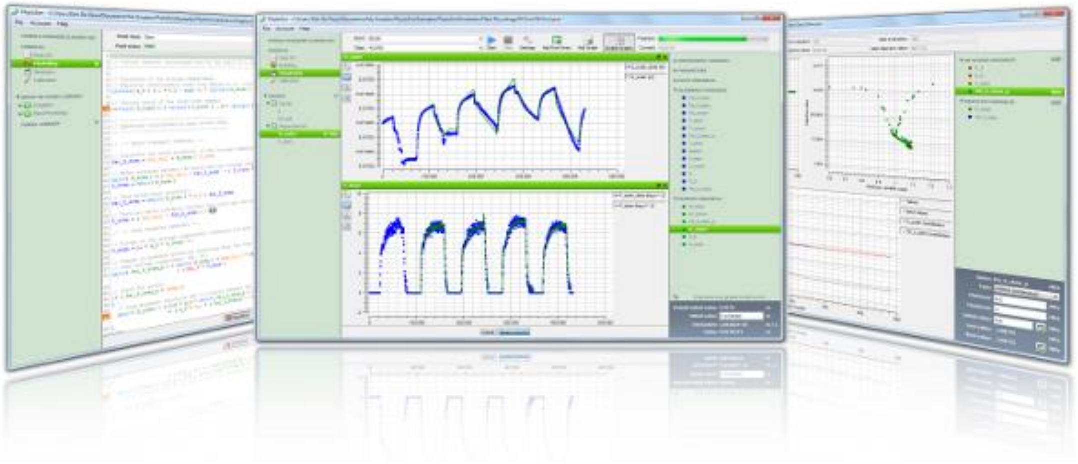


Fig. PhytoSim is a dynamic modelling and simulation software, and includes different modules which allow state-of-the-art mechanistic modelling. There is a module for Data I/O, Modelling, Simulation, Calibration, uncertainty and sensitivity analysis.

In the software, **Press F1** for help and to access the full PhytoSim User Guide.

PhytoSim introduction

PhytoSim is a dynamic plant modelling and simulation software, with several modules available:

- **Data I/O** for data exchange;
- **Modelling** to write dynamic models consisting of algebraic and/or (first order) differential equations;
- **Simulation** to simulate the written models;
- **Calibration** to automatically fit models to measured data;
- **Uncertainty** to propagate *uncertainties* in parameters, data variables and initial conditions through the model in order to obtain uncertainty on model variables;
- **Sensitivity** to determine the *sensitivity* of the model variables to changes in the parameters, data variables or initial conditions.

We will focus on the first three modules, but feel free to contact kathy.steppe@ugent.be for more information on the other modules.

Press F1 for help and to access the full PhytoSim User Guide.

4. Mechanistic modelling - an example of linking sap flow to turgor-driven growth using tree hydraulics

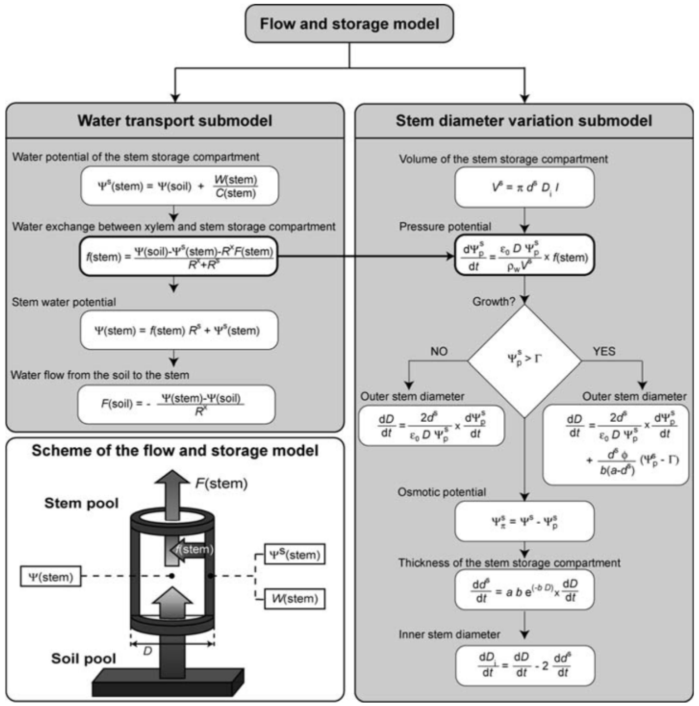


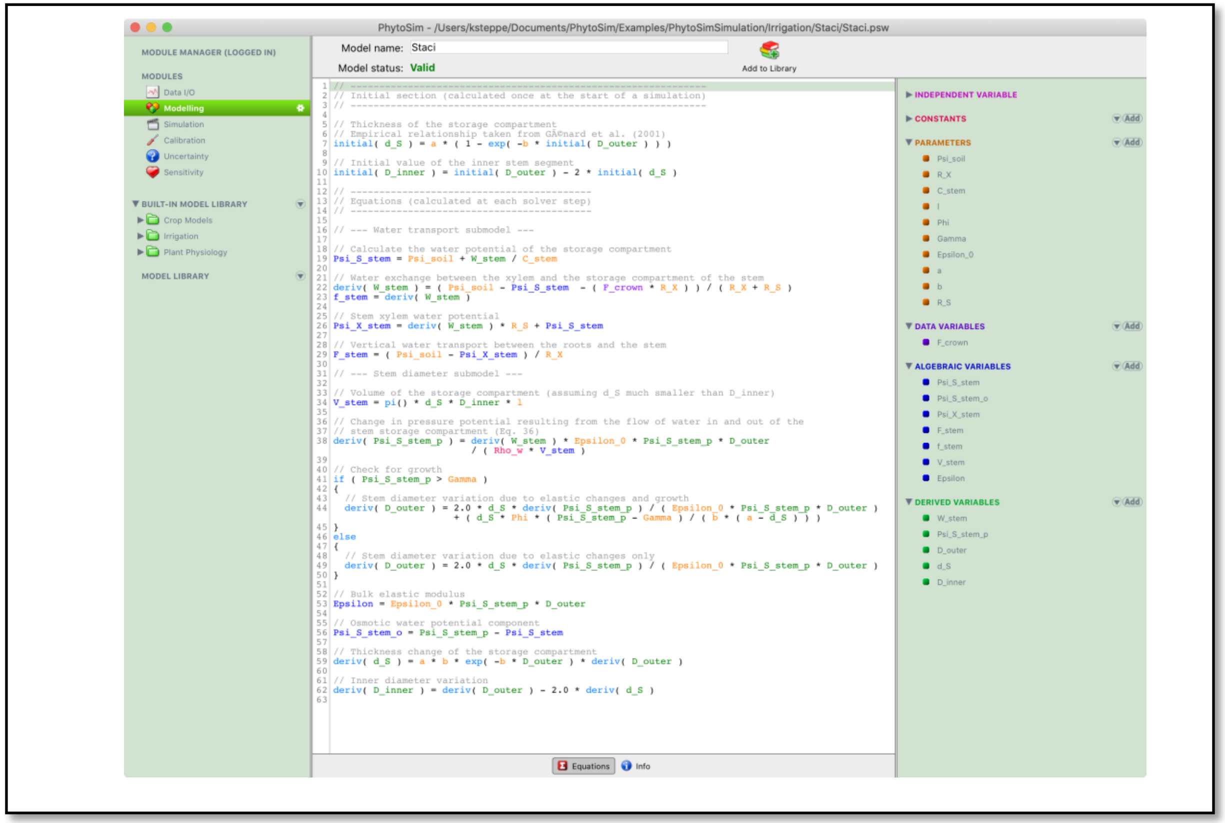
Fig. The scheme and mathematical equations of STACI.

Source: Steppe *et al.* (2006) doi: 10.1093/treephys/26.3.257
Steppe *et al.* (2008) doi: 10.1007/s00271-008-0111-6

STACI model description

The model is driven by the sap flow to the crown, *F*(stem). The stem of diameter *D* is modelled by two coaxial cylinders (xylem and stem storage compartment, respectively) separated by a membrane. The radial flow rate into and out of the stem storage compartment is represented by *f*(stem). This radial water flow (bold arrow) establishes the direct link between the sub-model for calculating dynamic water transport and the sub-model for predicting stem diameter variations. Depending on the value of the pressure potential in the stem storage compartment, the stem diameter variation resulting from turgor-driven growth is included.

4. Mechanistic modelling - an example of linking sap flow to turgor-driven growth using tree hydraulics



Getting started with the PhytoSim built-in plant models

PhytoSim includes a built-in plant model library with simulation examples for all models. To use and simulate these built-in models and have a look at the code you can open the simulation examples:

- File – Open – Examples – PhytoSimSimulation;
- Choose any model you like.

In this workshop, we will work with the STACI model. To load the model, go from the PhytoSimSimulation directory to Irrigation, then Staci and open the *staci.psw* file:

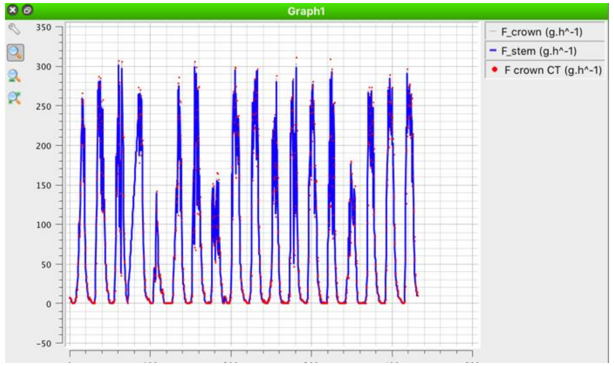
- The **data I/O** module shows the data files;
- The **modelling** module shows the dynamic model consisting of algebraic and differential equations [Fig.]. The info button at the bottom of the page shows the description of the model and references;.
- The **simulation** module enables you to simulate the STACI model written with the modelling module by pressing the Start button.

4. Mechanistic modelling - an example of linking sap flow to turgor-driven growth using tree hydraulics

Fig. *Picea abies* growing in the Swiss Lötschental.

Model parameters characterize the internal tree hydraulics (after model calibration):
- Hydraulic capacitance C_stem = 200 g MPa^{-1}
- Hydraulic resistance R_X = 0.003 MPa h g^{-1}
- Cell-wall yielding threshold for turgor-driven growth = 0.9 MPa

INPUT DATA – sap flow



Sap flow data is used as model input.

Getting started with the sample dataset

Copy the “ESA workshop modelling” directory from the link: https://deep-tools.netlify.app/docs-workshops/esa-workshop2020/03_phytosim/ into your PhytoSim Workspaces directory. This directory includes the esastaci.psw file and the required data .txt files.

- Open this **esastaci.psw** file in PhytoSim;
- The **data I/O** module shows the sample datasets. If you select a column and press the Quick View button (*top of screen*) you can view the sample data [Fig.];
- The **modelling** module shows the model equations of the STACI model (source: Steppe *et al*. (2008) doi: 10.1007/s00271-008-0111-6).

4. Mechanistic modelling - an example of linking sap flow to turgor-driven growth using tree hydraulics

Sources: Steppe *et al*. (2006) doi: 10.1093/treephys/26.3.257
Steppe *et al*. (2015) doi: 10.1016/j.tplants.2015.03.015
Peters *et al*. (in Press) New Phytologist

Model simulation and interpretation

With the **simulation** module [Fig.] you can simulate the calibrated model (see https://deep-tools.netlify.app/docs-workshops/esa-workshop2020/03_phytosim/ for more details). The model parameters (see previous slide) and the model variables enable you to unravel the underlying mechanisms (e.g. hydraulic resistance and capacitance, turgor-driven growth, and water potential dynamics).

The model is able to simulate the measured stem diameter variations (*top* in Fig.). Besides sub-daily fluctuations due to shrinkage and swelling of the stem, the tree stem grows (at night) when turgor pressure exceeds the cell-wall yielding threshold. The continuous sub-daily simulation of the stem water potential closely corresponds with the point measurements, and characterise the tree’s water status (*bottom* in Fig.). When applying such mechanistic tree models for several periods during the growing season, changes in hydraulic parameters can be investigated, and tree growth responses to changing climate can be explained from underlying mechanisms.

4. Mechanistic modelling - an example of linking sap flow to turgor-driven growth using tree hydraulics

Source: Steppe et al. (2016) doi: 10.3389/fpls.2016.00993
Steppe et al. (2015) doi: 10.1016/j.tplants.2015.03.015

Beyond the simulations

Dendrometer-sap flow combinations can be successfully used in monitoring networks, such as TreeWatch.net, which is a tree water and carbon monitoring network that has been developed to assess instant tree hydraulic functioning and stem growth via measurements and mechanistic modelling (source: Steppe *et al*. (2016) doi: 10.3389/fpls.2016.00993). In TreeWatch.net harmonized dendrometer and sap flow data can be used to parameterize in *real-time* mechanistic tree models (as the one demonstrated in this workshop). This approach can then be used to demonstrate the sensitivity of trees to changing weather conditions, such as drought, heat waves, or heavy rain showers from the underlying mechanisms. In addition, TreeWatch.net also envisions a broader societal application to teach youngsters and create public awareness on the effects of changing weather conditions on trees and forests in this era of climate change.

WK 21 - Advanced Analyses of Tree Physiological Time Series in R and PhytoSim

ESA Virtual Meeting
Harnessing the ecological data revolution

Organizer
Richard L. Peters
[richard.peters@ugent.be]

Co-Organizers
Christoforos Pappas
[christoforos.pappas@umontreal.ca]
Roman Zweifel
[roman.zweifel@wsl.ch]
Kathy Steppe
[kathy.steppe@ugent.be]
Alexander G. Hurley
[hurley@gfz-potsdam.de]