Assimilate, process, and analyse thermal dissipation sap flow data using the TREX R package

Richard L. Peters^{a,b*}, Christoforos Pappas^{c,d,e}, Alexander G. Hurley^f, Rafael Poyatos^{g,h}, Victor Flo^g, Roman Zweifel^b, Willem Goossens^a, Kathy Steppe^a

^aLaboratory of Plant Ecology, Faculty of Bioscience Engineering, Ghent University, Coupure links 653, B-9000 Ghent, Belgium

^bForest Dynamics, Swiss Federal Research Institute for Forest, Snow and Landscape Research (WSL), Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

^cDépartement de géographie, Université de Montréal, Montréal, H2V 0B3, Montreal, QC, Canada

^dCentre d'étude de la forêt, Université du Québec à Montréal, C.P. 8888, Succursale Centre-ville, Montréal, QC, H3C 3P8, Canada

^eDépartement Science et Technologie, Télucq, Université du Québec, 5800 rue Saint-Denis, Bureau 1105, Montréal, QC, H2S 3L5, Canada

^fSchool of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham B15 2TT, United Kingdom

^gCREAF, E08193 Bellaterra (Cerdanyola del Vallès), Catalonia, Spain

^hUniversitat Autònoma de Barcelona, E08193 Bellaterra (Cerdanyola del Vallès), Catalonia, Spain

*Corresponding Author:

Tel: +32 9 264 61 12, Fax: +32 9 224 44 10, e-mail: Richard.Peters@UGent.be.

Abstract

1. A key ecophysiological measurement is the flow of water (or sap) along the tree's water-transport system, which is an essential process for maintaining the hydraulic connection within the soil-plant-atmosphere continuum. The thermal dissipation method (TDM) is widespread in the scientific community for measuring sap flow and has provided novel insights into water use and its environmental sensitivity, from the tree- to the forest-stand level. Yet, methodological approaches to determine sap flux density (SFD; in cm^3 of sap per cm^2 of sapwood area per h) from raw TDM measurements remains case-specific, introducing uncertainties and hampering data syntheses and meta-analyses.

2. Here, we introduce the R package TREX (TRee sap flow EXtractor), incorporating a wide range of sap flow data-processing procedures to quantify SFD from raw TDM measurements. TREX provides functions for: i) importing and assimilating raw measurements, ii) data quality control and filtering, and iii) calculating standardized SFD outputs and their associated uncertainties according to different data-processing methods.

3. A case study using a Norway spruce tree illustrates TREX's functionalities, featuring interactive data curation and generating outputs in a reproducible and transparent way. The calculations of SFD in TREX can, for instance, use the original TDM calibration coefficients, user-supplied calibrations or calibration data from a recently compiled database of 22 studies and 37 species. Moreover, the package includes an automatic procedure for quantifying the sensitivity and uncertainty of the obtained results to user-defined assumptions and parameter values, by means of a state-of-the-art global sensitivity analysis.

4. Time series of plant ecophysiological measurements are becoming increasingly available and enhance our understanding of climate change impacts on tree functioning. TREX allows for establishing a baseline for data processing of TDM measurements and supports comparability between case studies, facilitating robust, transparent, and reproducible large-scale syntheses of sap flow patterns. Moreover, TREX facilitates the simultaneous application of multiple common data-processing approaches from raw data to physiological relevant measurements. This allows for robust quantification of the impact (i.e., sensitivity and uncertainty) of user-specific choices and methodological differences, which is necessary for process understanding and policy making.

52 **Keywords:** thermal dissipation method, transpiration, sap flux density, calibration, uncertainty
53 analysis, global sensitivity analysis, whole-tree water use

1 | Introduction

A key ecophysiological measurement is tree water transport, as terrestrial plant transpiration plays a key role in the local, regional and global water cycle (e.g., Reyes-Acosta & Lubczynski 2013; Schlesinger & Jasechko 2014; Fatichi & Pappas 2017). More specifically, sap flow (SF; total flow of water, often expressed in kg H₂O per h) attracts large interest across several scientific disciplines, as it is essential for maintaining the soil-plant-atmosphere continuum (e.g., Zweifel, Item & Häslar 2001; Steppe, Vandegehuchte, Tognetti & Mencuccini 2015). SF can be measured in different plant organs, although it is typically measured in stems. For decades, heat-based SF measurements have been used to quantify whole-tree water use for partitioning ecosystem-level water fluxes into transpiration and evaporation (e.g., Poyatos *et al.* 2016). In addition, species comparisons on stomatal regulation in mature trees have been performed using SF, revealing species-specific environmental responses to drought and heat waves (e.g., Brinkmann, Eugster, Zweifel, Buchmann & Kahmen 2016; Dietrich, Delzon, Hoch & Kahmen 2019).

A large variety of heat-based SF methods exist (as reviewed by Smith & Allen 1996; Peters *et al.* 2018), yet no method suits all needs for tree ecophysiological research. The thermal dissipation method (TDM) is the most widely applied for measuring SF in trees, due to its simplicity and low cost to measure environmental responses of tree water use (Flo, Martinez-Vilalta, Steppe, Schuldt & Poyatos 2019). In short, the TDM measures how moving sap within the tree's water conducting xylem (i.e. sapwood) affects the dissipation of heat supplied by a continuous heater (Granier 1985). The TDM is applied by installing two axially aligned probes into the xylem and measuring the temperature difference between a continuously heated probe and the non-heated reference probe (in ΔT or as voltage difference in ΔV), where ΔT decreases due to the convective cooling of SF over the heating probe with moving sap.

The range of user-specific choices (e.g., parameter values, calculation procedures) applied during data processing between studies represents a key challenge for homogenising and synthesising SF measurements obtained from TDM (Peters *et al.* 2018). A large variety of TDM data-processing steps are applied to convert raw data into physiologically meaningful variables, namely sap flux density (SFD in cm³ of sap per cm² of sapwood area per h), yet often only a single data-processing path is utilized. Typically suggested data-processing steps include: i) determining time periods of zero flow (Rabbel, Dieckkrüger, Voigt & Neuwirth 2016), ii) correcting for the partial insertion of the probe into non-conducting heartwood (Clearwater, Meinzer, Andrade, Goldstein & Holbrook 1999), iii) accounting for signal

dampening due to wound response (Peters *et al.* 2018), and iv) sensor calibration (Fuchs, Leuschner, Link, Coners & Schuldt 2018). Yet, although data-processing steps can impact the quantification of SFD (Köstner, Granier & Cermák 1998; Peters *et al.* 2018), no consensus exists on a standardized method.

The lack of a standardize method of TDM data processing has stimulated the recent development of software tools for specific TDM data-processing steps (i.e., Oishi, Hawthorne & Oren 2016; Speckman, Ewers & Beverly 2018). Although such tools provide an array of data cleaning procedures with a graphical interface and a fixed chain of data-processing options, they do not facilitate the exploration of multiple approaches and parameter values (i.e., multi-method ensemble for SFD data analyses). Moreover, although there are techniques to identify parameters which critically impact the output of interest (e.g., De Pauw, Steppe & De Baets 2008; Pappas, Fatichi, Leuzinger, Wolf & Burlando 2013), such systematic sensitivity analyses have yet to be considered for TDM data-processing. The consequence is that SFD data from TDM studies may still be difficult to compare or to apply in broader ecological research questions.

Here we present the R package TREX (TRee sap flow Extractor; R Core Team 2017) freely accessible via the Comprehensive R Archive Network (CRAN: <http://cran.r-project.org>). TREX imports and assimilates raw TDM measurements, provides a complete multi-modular data-processing workflow and facilitates SFD-related outputs and analyses. TREX provides functionalities for interactive data curation, quantification of the sensitivity and uncertainty of the obtained results to user-defined assumptions and parameter values, and produces outputs in a reproducible and transparent way. Notwithstanding, a multitude of the TREX functionalities are also applicable to other heat-based SF measurements.

2 | TREX functionalities

We demonstrate the functionalities of TREX using an example dataset (Figure 1) from a mature Norway spruce (*Picea abies* (L.) Karst.; see *tdm.data()*). TREX functionalities are structured in three modules (Figure 2), where each module contains multiple functions which can be used separately or in a processing chain (short descriptions of the functions are provided in Table S1). The first module “Import & assimilation” guides users to import data, adjust time-step-related issues and perform outlier detection and gap filling. The second module “Data processing” provides a chain of functions which apply different TDM data-processing procedures. The final module “Output & analyses” generates standardized data output and

quantifies the output sensitivity and uncertainty associated to variations in selected parameters. Some functions from the “Import & assimilation” and “Output & analyses” modules can also be used with other SF methods (Figure 2).

TREX functions for data import and assimilation

TREX utilizes TDM time series of ΔT (or ΔV) provided for each individual sensor in text file format, with ΔT (or ΔV) data recorded for a specified timestamp, providing information on time zone and daylight savings time (see *example.data()*). It is crucial to know the time zone in which the data were logged and whether day-time-saving was applied. The input can be presented in a *Timestamp* format: including a timestamp of the measurements column, and value of ΔT (or ΔV) of a specific sensor (Table 1; but also see *DOY* format in *?TREX::example.data*). Multiple reference probes used to correct for natural temperature gradients in the sapwood (Lindén, Fonti & Esper 2016) can also be added as additional columns (labelled as *ref1*, *ref2*, ..., *refn*). The user can verify whether the imported dataset fits the requirements for TREX data format by calling the function *is.trex()*. After specifying the timestamp format and time zone, the users can select whether the time series should be standardized to solar time (i.e., mid-day corresponding to solar noon which enhances comparability across sites) by providing the longitude (in decimal degrees) of the location of the sensor. Although TREX functionalities are applied per individual sensor, a looping procedure could allow for their application on multiple individual trees or sensors.

The *dt.steps()* function manipulates the temporal extent and resolution (indicated with *time.int* in minutes) of an *is.trex* object (i.e., to facilitate comparison with other time series). Outliers in ΔT (or ΔV) time series need to be identified and removed before proceeding with data processing (Figure 3). This task is addressed in the TREX package with an accompanying Shiny application that is launched with the *outlier()* function and i) visualizes raw and outlier-free time series interactively (Sievert 2018), ii) highlights automatically detected outliers (see *?TREX::outlier()* for method specifications), iii) allows the user to revise the automatically detected outliers and manually include data points interactively, and iv) exports the original data and the outlier-free time series in a *is.trex()* object that can be further processed. The cleaned or raw time series can additionally be fed to the *gap.fill()* function to interpolate sporadic gaps of a user-defined length (using *max.gaps* defined in minutes).

SFD is estimated by first determining the relative thermal difference (known as the heat index and denoted as K , unitless) between ΔT and zero-flow conditions (denoted as $\Delta T_{\max}$ or $\Delta V_{\max}$ in equation 1; Granier 1985). Multiple methods exist to determine $\Delta T_{\max}$ (equation 1; Rabbel, Diekkrüger, Voigt & Neuwirth 2016). Four classes of methods (as reviewed by Peters *et al.* 2018) are incorporated in the function `tdm_dt.max()`, including: i) the pre-dawn $\Delta T_{\max}$ (*pd*), where zero-flow is assumed to occur each night, ii) daily moving window (*mw*; e.g., 7 days, defined with *max.days*), in which the centred maximum pre-dawn $\Delta T_{\max}$ over a moving window is assumed to represent zero-flow conditions, iii) the double regression method (*dr*; Lu, Urban & Zhao 2004), determining the mean pre-dawn $\Delta T_{\max}$ over the *max.days* period and removes all points below this moving-window mean and calculates a second running mean moving window, and iv) the environmental dependent method (*ed*) assuming that one can find zero-flow conditions based on environmental conditions (Oishi, Hawthorne & Oren 2016; see `?TREX::tdm_dt.max` for details). As the selected parameters are likely site-, and even tree-specific, users should carefully inspect the selected nights of zero-flow conditions resulting from the selected criteria (e.g., Figure S1). Yet, when determining $\Delta T_{\max}$, users have to keep in mind that this is a subjective process where the four presented methods are surely not suitable for each region or tree species. For example, in some regions where zero-flow conditions do not occur over many weeks, an alternative approach will be required. Moreover, zero-flow conditions might not be homogeneous across the radial profile of the sapwood, requiring different $\Delta T_{\max}$ method for the inner- *versus* outer-sapwood.

Equation 1.

$$K = \frac{\Delta T_{\max} - \Delta T}{\Delta T}$$

The correction for the proportion of the probe that is inserted into the non-conducting heartwood is another important data-processing step (see Peters *et al.* 2018). This correction is incorporated in the `tdm_hw.cor()` function using the sapwood thickness (*sapwood.thickness* in mm). Together with the length of the probe (*probe.length* in mm), the proportion of the probe inserted into the sapwood (γ in mm mm⁻¹) *vs.* the proportion of the probe in the inactive heartwood is used to calculate ΔT_{sw} (Equation 2) which replaces ΔT (Equation 1; Clearwater, Meinzer, Andrade, Goldstein & Holbrook 1999).

179

Equation 2

$$\Delta T_{sw} = \frac{(\Delta T - (1 - \gamma) \cdot \Delta T_{max})}{\gamma}$$

180 When installing probes into living tissue for multiple years a dampening in K is
 181 commonly observed (see Wiedemann, Marañón-Jiménez, Rebmann, Herbst & Cuntz 2016).
 182 When probes are inserted into the xylem without reinstalling each year, one can correct for the
 183 dampening effect with the statistical method proposed by Peters *et al.* (2018) with the
 184 *tdm_damp()* function. Yet, it should be noted that no empirical evidence (i.e., gravimetric
 185 validation) exists to confirm the correction shape implemented within this functions and should
 186 thus be implemented with caution. Moreover, more evidence should be gathered to improve the
 187 accuracy of the approaches for corrected for signal dampening. For K values obtained from
 188 preceding functions, a dampening model can be fitted to calculate corrected K values (using
 189 *nls()*; equation 3 and see *?TREX::tdm_damp* for details). After careful visual inspection of the
 190 fitted model, the fitted parameters (a , b , c , and d) can be used to correct K and scaled to the
 191 maximum values within the first year since installation (Figure 4).

192

Equation 3

$$K_{res} = \frac{(a + b \cdot t)}{(1 + c \cdot t + d \cdot t^2)}$$

193

194 SFD is defined by the relationship between K and SFD using a power-type function
 195 (equation 4). Recent calibration studies and meta-analyses have urged the application of case-
 196 or species-specific calibration experiments (e.g., Steppe, De Pauw, Doody & Teskey 2010;
 197 Fuchs, Leuschner, Link, Coners & Schuldt 2018; Flo, Martinez-vilalta, Steppe, Schuldt &
 198 Poyatos 2019). Thus, within the *tdm_cal.sfd()* one can either supply raw calibration experiment
 199 data or provide a and b parameters from the obtained calibration (equation 4). Alternatively,
 200 the package also contains a database (see *cal.data*) of raw calibration measurements (from 22
 201 studies covering 37 species), representative of the main wood anatomy types, originating from
 202 Flo, Martinez-vilalta, Steppe, Schuldt & Poyatos (2019; Figure 5).

203

Equation 4.

$$SFD = a \cdot K^b$$

204

3 | TREX uncertainty and sensitivity analyses and output generation

Uncertainty and sensitivity analyses

Each parameter choice in TDM data-processing affects the SFD output. The uncertainty, i.e., variability in relevant SFD output caused by input parameters used in the data-processing cascade, could impact the level of confidence in tree water-use estimates which is relevant for both, mechanistic understanding of ecophysiological processes and environmental decision making (Maier, Ascough, Wattenbach, Renschler & Labiosa 2008). Besides providing a framework to quantifying uncertainty, assessing the contribution of specific input parameters to the overall output uncertainty could support the identification of key parameters, that could be better constrained with additional data collection reducing thus the final output uncertainty (e.g., Pappas, Fatichi, Leuzinger, Wolf & Burlando 2013).

The *tdm_uncertain()* function performs uncertainty and global sensitivity analysis of TDM time series (see Note S1 for details). For conducting sensitivity and uncertainty analyses of TDM data with TREX, the user needs to; i) select the output variable of interest, ii) identify the relevant input parameters (some of them are method-specific), and iii) determine their range and statistical distributions (Table 2). For a given time series three output variables are considered, calculated as the mean over the entire time period where data are available, namely: i) mean daily sum of water use (“Sum”, expressed as SFD or K), ii) the variability in maximum SFD or K values (“CV”, coefficient of variation in % as this alters climate response correlations), and iii) the duration of daily sap flow based on SFD or K below a user-defined threshold (“Duration”, expressed in hours per day dependent on a threshold, see *min.sfd* and *min.k*). The relevant input parameters are presented for each of the $\Delta T_{\max}$ methods in Table 2, (providing default values and sampling distributions; excluding *tdm_damp()* as its application demands detailed visual inspecting). Yet, users should note that parameter ranges and distributions represent an important critical component of any sensitivity analysis (Wallach & Genard 1998) and should be carefully assessed.

The *tdm_uncertain()* function provides both graphical (Figure 6) and tabular output (Table S2) depending on the $\Delta T_{\max}$ calculation method (Figure S2-S3). The sensitivity output for each $\Delta T_{\max}$ calculation method can be compared to identify key parameters which need to be constrained. In the Norway spruce example dataset, the total sensitivity indices for the Sum, CV and Duration based on K values illustrate that both the Sum and CV of K are highly sensitive to the sapwood correction, suggesting the need for carefully establishing sapwood depth at the

location of probe installation (Figure 6). For all outputs based on SFD the b parameter of the power-type calibration curve appears to strongly impact both absolute water flow as well as their variability, illustrating the need for robust calibration curves to constrain the output variables. High sensitivity of CV to some of the input parameters suggests potential alterations of SF environmental responses caused by methodological variability (Peters *et al.* 2018).

Relevant output generation

The package provides the functionality to temporarily aggregate the required SFD data into any user-defined interval (*agg.data()*; e.g., daily sap flow values in $\text{cm}^3 \text{ cm}^{-2} \text{ d}^{-1}$). Moreover, the package provides the *out.data()* function to generate either SFD (expressed as F_d in $\text{mmol m}^{-2} \text{ s}^{-1}$) or crown conductance estimates (G_c in $\text{cm}^3 \text{ cm}^{-2} \text{ h}^{-1} \text{ kPa}^{-1}$) outputs in an exportable format. Here, G_c is defined as the ratio of SFD to VPD and is analogue to stomatal conductance under conditions of negligible stem capacitance, but expressed per unit of sapwood area (Meinzer *et al.* 2013). The function *out.data()* offers the opportunity to decide about the conditions that fulfil these negligible capacitance assumptions (see Note S2 for details). A non-linear model of the form $G_c = \alpha + \beta \text{VPD}^{-0.5}$ can then be automatically fitted with the *out.data()* function to the selected peak-of-day mean values of G_c on VPD to quantitatively describe the observed patterns (Figure S4; as described in Pappas *et al.* 2018). This can be used to get preliminary insights into tree water use strategies, yet caution is needed for the interpretations of these values (i.e., capacitance assumptions need to be verified and G_c response models to VPD have statistical limitations due to estimation of G_c using VPD).

4 | Conclusion

The TREX package contains advanced functionalities to assimilate, process and analyse raw sap flow measurements obtained with the TDM. The package provides means for transparent and reproducible TDM data processing and for enhancing comparability of SFD estimates between studies. Moreover, to our knowledge, this is the first study to provide a state-of-the-art systematic quantification of sap flow uncertainty and sensitivity due to data-processing parameter inputs and assumptions. We believe that TREX provides a structured and transparent pathway for sap flow data processing, which will emphasize the utility of heat-based sap flow measurements for future research. The package structure eases the implementation of future processing methods when made available from the scientific community, facilitating thus multi-method comparisons and robust sensitivity and uncertainty analyses.

Acknowledgements

We thank Patrick Fonti for providing constructive comments on an earlier version of the manuscript and supplying the example dataset collected at the Lötschental transect. We thank Dirk J. W. De Pauw and Ana Stritih for their discussions on uncertainty analyses. We also thank all researchers and their funding agencies, whose work was essential for obtaining all the calibration experiment data. RLP acknowledges the support of the Swiss National Science Foundation (SNSF), Grant P2BSP3_184475. CP acknowledges the support of the SNSF (Grants P2EZP2_162293 and P300P2_174477), the Canada Research Chair in Atmospheric Biogeosciences in High Latitudes and the Global Water Futures project Northern Water Futures. RP acknowledges the support of the Spanish grant RTI2018-095297-J-I00 and of a Humboldt Research Fellowship for Experienced Researchers. Data collection was performed in the framework of the SNSF projects INTEGRAL (121859) and LOTFOR (150205). All authors declare that there is no conflict of interest,

Data availability statement

The TREX package is available as a package in R. The program R is freely available from the Comprehensive R Archive Network (CRAN; <http://cran.r-project.org/>). The package is also available for download and installation via a GitHub repository (<https://github.com/theHull/TREX>).

Authors' Contributions

RLP, CP and AGH initiated the concept of the R package TREX and developed the main functions. RLP and CP mainly wrote the manuscript and all authors contributed to the manuscript drafts. RP and VF aided in further developing the functionalities and AH mainly compiled the R package. RLP and KS raised the funding.

291 **References**

- 292 Brinkmann, N., Eugster, W., Zweifel, R., Buchmann, N., & Kahmen, A. (2016). Temperate
 293 tree species show identical response in tree water deficit but different sensitivities in sap
 294 flow to summer soil drying. *Tree Physiology*, 36(12), 1508–1519.
 295 doi:10.1093/treephys/tpw062
- 296 Clearwater, M. J., Meinzer, F. C., Andrade, J. L., Goldstein, G., & Holbrook, N. M. (1999).
 297 Potential errors in measurement of nonuniform sap flow using heat dissipation probes.
 298 *Tree Physiology*, 19(10), 681–687. doi:10.1093/treephys/19.10.681
- 299 De Pauw, D. J. W., Steppe, K., & De Baets, B. (2008). Identifiability analysis and
 300 improvement of a tree water flow and storage model. *Mathematical Biosciences*, 211,
 301 314–332. doi:10.1016/j.mbs.2007.08.007
- 302 Dietrich, L., Delzon, S., Hoch, G., & Kahmen, A. (2019). No role for xylem embolism or
 303 carbohydrate shortage in temperate trees during the severe 2015 drought. *Journal of*
 304 *Ecology*, 107(1), 334–349. doi:10.1111/1365-2745.13051
- 305 Fatichi, S., & Pappas, C. (2017). Constrained variability of modeled T:ET ratio across
 306 biomes. *Geophysical Research Letters*, 44, 6795–6803. doi:10.1002/2017GL074041
- 307 Flo, V., Martinez-vilalta, J., Steppe, K., Schuldt, B., & Poyatos, R. (2019). Agricultural and
 308 Forest Meteorology A synthesis of bias and uncertainty in sap flow methods.
 309 *Agricultural and Forest Meteorology*, 271, 362–374.
 310 doi:10.1016/j.agrformet.2019.03.012
- 311 Fuchs, S., Leuschner, C., Link, R., Coners, H., & Schuldt, B. (2017). Calibration and
 312 comparison of thermal dissipation, heat ratio and heat field deformation sap flow probes
 313 for diffuse-porous trees. *Agricultural and Forest Meteorology*, 244–245, 151–161.
 314 doi:10.1016/j.agrformet.2017.04.003
- 315 Granier, A. (1985). Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc
 316 des arbres. *Annals of Forest Science*, 42, 193–200.
- 317 Köstner, B., Granier, A., & Cermák, J. (1998). Sapflow measurements in forest stands:
 318 Methods and uncertainties. *Annales Des Sciences Forestieres*, 55(1–2), 13–27.
 319 doi:10.1051/forest:19980102
- 320 Lindén, J., Fonti, P., & Esper, J. (2016). Urban Forestry & Urban Greening Temporal
 321 variations in microclimate cooling induced by urban trees in Mainz , Germany. *Urban*
 322 *Forestry & Urban Greening*, 20, 198–209. doi:10.1016/j.ufug.2016.09.001
- 323 Lu, P., Urban, L., & Zhao, P. (2004). Granier’s Thermal Dissipation Probe (TDP) Method for
 324 Measuring Sap Flow in Trees: Theory and Practice. *Acta Botanica Sinica*, 46(6), 631–
 325 646.
- 326 Maier, H.R., Ascough, J.C., Wattenbach, M., Renschler, C.S., & Labiosa, W.B. (2008)
 327 Uncertainty in Environmental Decision Making: Issues, Challenges and Future
 328 Directions. Publ. from USDA-ARS/UNL Fac.

329 Meinzer, F. C., Woodruff, D. R., Eissenstat, D. M., Lin, H. S., Adams, T. S., & McCulloh, K.
330 A. (2013). Above-and belowground controls on water use by trees of different wood
331 types in an eastern US deciduous forest. *Tree Physiology*, 33(4), 345–356.
332 doi:10.1093/treephys/tpt012

333 Oishi, A. C., Hawthorne, D. A., & Oren, R. (2016). Baseline: An open-source, interactive
334 tool for processing sap flux data from thermal dissipation probes. *SoftwareX*, 5, 139–143.
335 doi:10.1016/j.softx.2016.07.003

336 Pappas, C., Fatichi, S., Leuzinger, S., Wolf, A., & Burlando, P. (2013). Sensitivity analysis of
337 a process-based ecosystem model: Pinpointing parameterization and structural issues.
338 *Journal of Geophysical Research: Biogeosciences*, 118(2), 505–528.
339 doi:10.1002/jgrg.20035

340 Pappas, C., Matheny, A. M., Baltzer, J. L., Barr, A. G., Black, T. A., Bohrer, G., ... Stephens,
341 J. (2018). Boreal tree hydrodynamics: Asynchronous, diverging, yet complementary.
342 *Tree Physiology*, 38(7), 953–964. doi:10.1093/treephys/tpy043

343 Peters, R. L., Fonti, P., Frank, D. C., Poyatos, R., Pappas, C., Kahmen, A., ... Steppe, K.
344 (2018). Quantification of uncertainties in conifer sap flow measured with the thermal
345 dissipation method. *New Phytologist*, 219, 1283–1299. doi:10.1111/nph.15241

346 Poyatos, R., Granda, V., Molowny-Horas, R., Mencuccini, M., Steppe, K., & Martínez-
347 Vilalta, J. (2016). SAPFLUXNET: Towards a global database of sap flow measurements.
348 *Tree Physiology*, 36(12), 1449–1455. doi:10.1093/treephys/tpw110

349 R Core Team (2017). R: A language and environment for statistical computing. R Foundation
350 for Statistical Computing, Vienna, Austria. Link: <https://www.R-project.org/>.

351 Rabbel, I., Dieckrüger, B., Voigt, H., & Neuwirth, B. (2016). Comparing ΔT_{max}
352 determination approaches for Granier-based sapflow estimations. *Sensors*, 16(1), 1–16.
353 doi:10.3390/s16122042

354 Reyes-Acosta, J. L., & Lubczynski, M. W. (2013). Mapping dry-season tree transpiration of
355 an oak woodland at the catchment scale, using object-attributes derived from satellite
356 imagery and sap flow measurements. *Agricultural and Forest Meteorology*, 174–175,
357 184–201. doi:10.1016/j.agrformet.2013.02.012

358 Schlesinger, W. H., & Jasechko, S. (2014). Agricultural and Forest Meteorology
359 Transpiration in the global water cycle. *Agricultural and Forest Meteorology*, 189–190,
360 115–117. doi:10.1016/j.agrformet.2014.01.011

361 Sievert, C. (2018) Interactive web-based data visualization with R, plotly, and shiny. Link:
362 <https://plotly-r.com>.

363 Smith, D.M., & Allen, S.J. (1996) Measurement of sap flow in plant stems. *Journal of*
364 *Experimental Botany* 47:1833–1844. doi: 10.1093/jxb/47.12.1833

- 365 Speckman, H. Ewers, B.E., & Beverly, D.P. (2018). AquaFlux : Rapid , transparent and
366 replicable analyses of plant transpiration. *Methods in Ecology and Evolution*, (11), 44–
367 50. doi:10.1111/2041-210X.13309
- 368 Steppe, K., De Pauw, D. J. W., Doody, T. M., & Teskey, R. O. (2010). A comparison of sap
369 flux density using thermal dissipation, heat pulse velocity and heat field deformation
370 methods. *Agricultural and Forest Meteorology*, 150(7–8), 1046–1056.
371 doi:10.1016/j.agrformet.2010.04.004
- 372 Steppe, K., Vandegehuchte, M. W., Tognetti, R., & Mencuccini, M. (2015). Sap flow as a key
373 trait in the understanding of plant hydraulic functioning. *Tree Physiology*, 35(4), 341–
374 345. doi:10.1093/treephys/tpv033
- 375 Wiedemann, A., Marañón-jiménez, S., Rebmann, C., Herbst, M., & Cuntz, M. (2016). An
376 empirical study of the wound effect on sap flux density measured with thermal
377 dissipation probes. *Tree Physiology*, (36), 1471–1484. doi:10.1093/treephys/tpw071
- 378 Zweifel, R., Item, H., & Häslér, R. (2001). Link between diurnal stem radius changes and tree
379 water relations. *Tree Physiology*, (21), 869–877.

381

382 **Figure 1.** Example of a thermal dissipation time series from a mature Norway spruce (*Picea*
 383 *abies* Karst.) growing in an alpine valley at 1300 m a.s.l. (Lötschental, Switzerland; Peters *et*
 384 *al.* 2019).

Figure 2. Schematic overview of the modules (a-c), functions and workflow of the TREX package. Functions which are specifically designed to work with thermal dissipation method data are indicated with “tdm...”, while other functions can be applied on any type of sap flow data.

TREX: sap flow data cleaning

Figure 3. An illustration of the *outlier()* function, launching a Shiny application for interactive time series visualization and inspection. Users can adjust the *alpha* parameter for the automatic detection of outliers. Red points in the upper panel highlight the automatically detected outliers, while red points in the lower panel are manually selected points.

Figure 4. Example of the dampening model function to correct K (using the *tdm_damp()* function) for the Norway spruce example dataset (see Figure 1). As a smooth curve is fitted and it shows good agreement with the maximum values over the years presented, we consider this an appropriate correction.

Figure 5. Calibration curves obtained from literature, including all wood types (using the `tdm_cal.sfd()` function; mean $[\mu]$ and confidence interval [CI] over studies). The grey background shows the K range of the specific zero flow method, which was provided as input for the function and provides insight into whether the uncertainty of the calibration curve (presented with CI) will impact the provided K time series.

Figure 6. Visual output from the *tdm_uncertain()* function when considering the double-regression $\Delta T_{\max}$ method for the Norway spruce example dataset (see Figure 1). 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 (see Note S1 for details). The sensitivity analysis was conducted on the example dataset considering May to November of 2013. Less input parameters are presented for *K* as the calibration parameters (*a* and *b* in equation 2) do not affect *K*. The smaller panels on the right present the uncertainty over the selected output variables. Sum indicates the daily sum of water use (expressed in cm³ cm⁻² d⁻¹ for SFD or unitless for *K*), CV indicates the variability of maximum SFD or *K* values (coefficient of variance in %), and Duration indicates the duration of daily transpiration based on SFD or *K* (expressed in hours per day dependent on a threshold).

Tables

Table 1. Example of TREX data format of a thermal dissipation time series *example.data(type= "timestamp")*. Data for an individual tree has to be provided with either ΔT or ΔV values (here ΔV).

timestamp	value
17-4-2012 15:00	0.444
17-4-2012 15:15	0.541
17-4-2012 15:30	0.560
17-4-2012 15:45	0.568
17-4-2012 16:00	0.572
17-4-2012 16:15	0.545
...	...

Table 2. Selection of data-processing parameters relevant for the uncertainty and sensitivity analyses. Each $\Delta T_{\max}$ method is considered with its unique set of parameters (indicated with square brackets). Default values incorporated into TREX, operating on the example dataset, are provided as a baseline and are based on expert judgement and existing literature. Incorporated data-processing functions include; *tdm_dt.max()* calculating zero-flow conditions, *tdm_hw.cor()* implementing the heartwood correction, and *tdm_cal.sfd()* quantifying the sap flux density. The $\Delta T_{\max}$ methods include; pre-dawn (pd), moving window (mw), double regression (dr) and environmental dependent (ed).

Data-processing [$\Delta T_{\max}$ method]	Parameter	Sampling distribution	Default values
tdm_dt.max[pd/mw/dr/ed]	zero.start	Integer sampling range	2 hours
	zero.end	Integer sampling range	2 hours
tdm_dt.max[mw/dr]	max.days	Integer fixed sampling range	5-15 days
tdm_dt.max[ed]	ed.window	Integer fixed sampling range	2-4 hours
	criteria[sr]	Dependent sampling range	30%
	criteria[vpd]	Fixed sampling range	0.05-0.5 kPa
	criteria[cv]	Fixed sampling range	0.5-1 %
tdm_hw.cor [pd/mw/dr/ed]	sapwood.thickness [sw.cor]	Normal distribution	$\sigma = 16$ mm
tdm_cal.sfd [pd/mw/dr/ed]	a	Normal distribution (Log)*	$\mu = 4.085$; $\sigma = 0.628$
	b	Normal distribution*	$\mu = 1.275$; $\sigma = 0.262$

*See *cal.sfd* with Use all; Coniferous in example