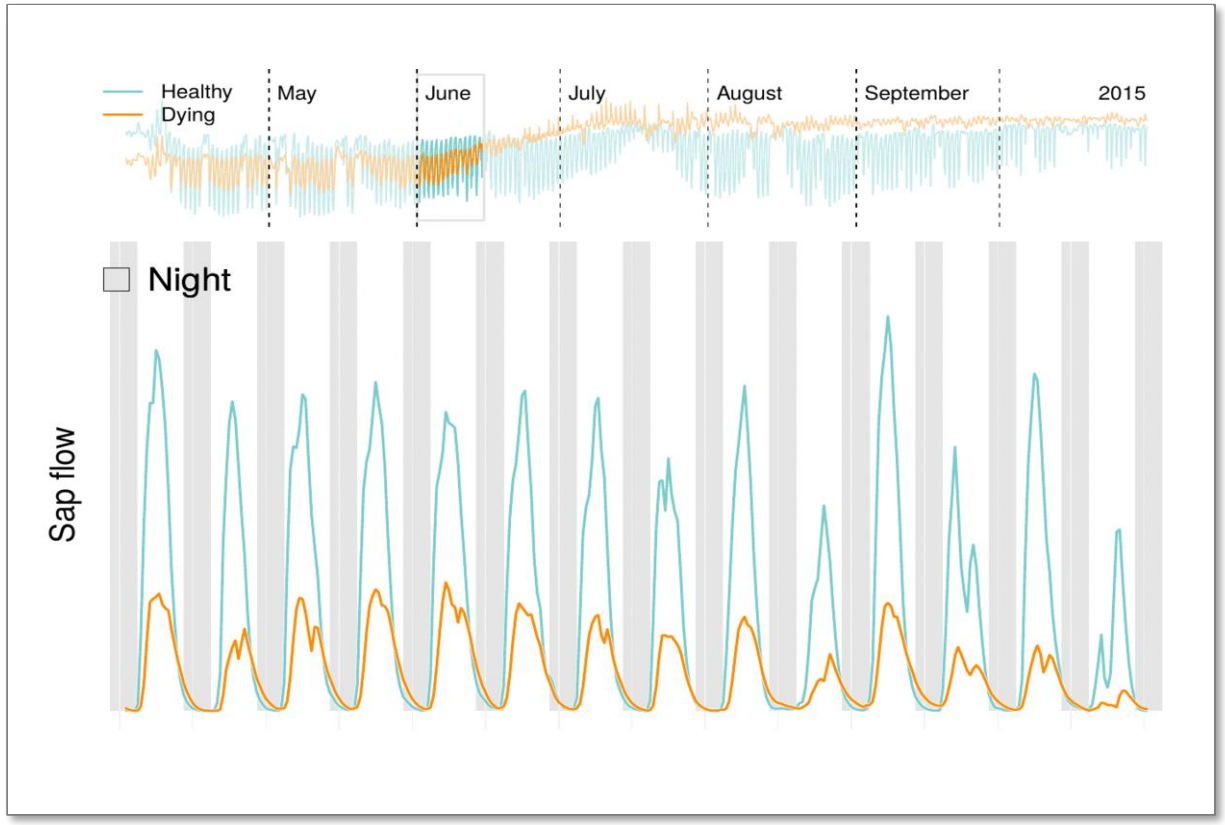
Time series processing in R

Goal

Facilitate the work with raw time series data and make methods for their processing accessible and reproducible



Christoforos Pappas

Richard L. Peters

Alexander G. Hurley

Time series processing in R

Outline

(1) Handling

(2) Cleaning

(3) Processing

(4) Interpreting

(5) Q/A

Christoforos Pappas

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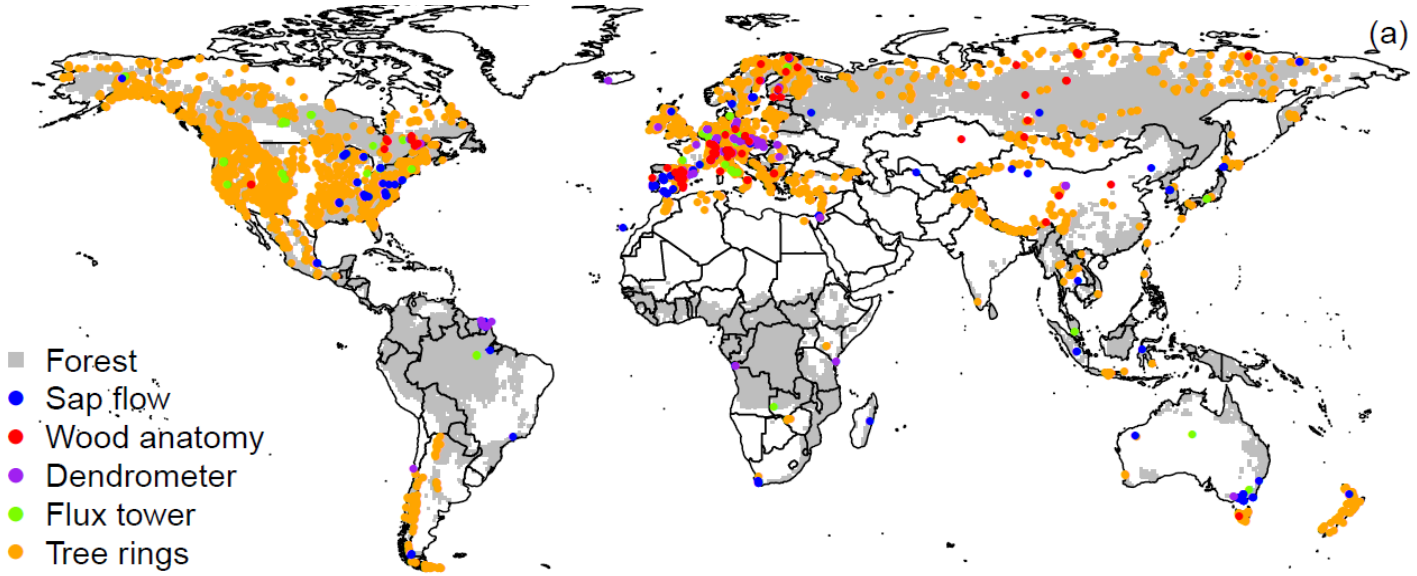
Relevance

Ecological research is becoming increasingly data-rich!



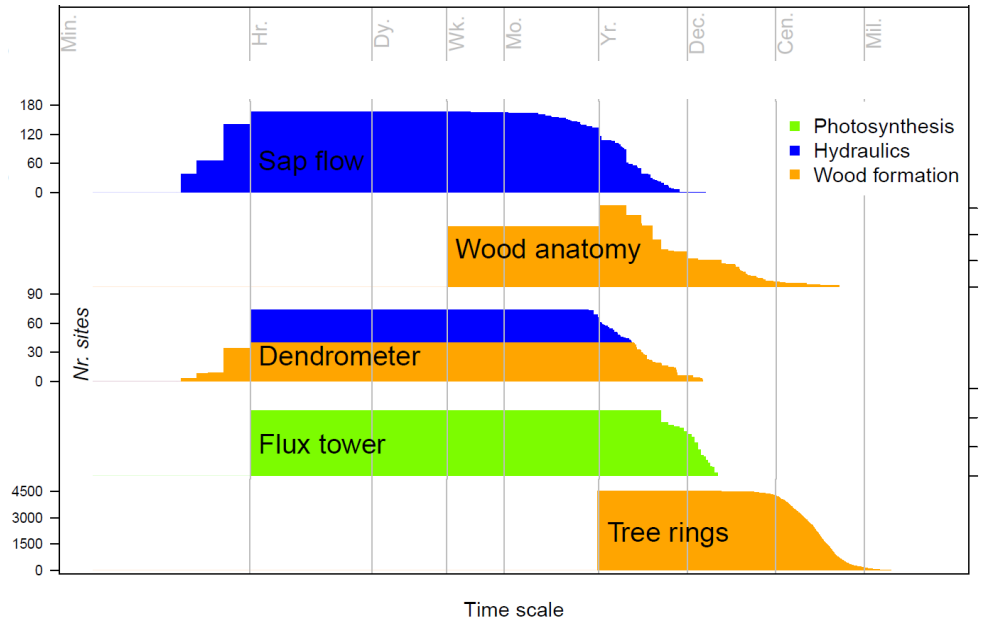


Fig. Global distribution of sites with relevant tree physiological measurements.
Source: Peters (2018) doi: https://doi.org/10.5451/unibas-007085812

Relevance

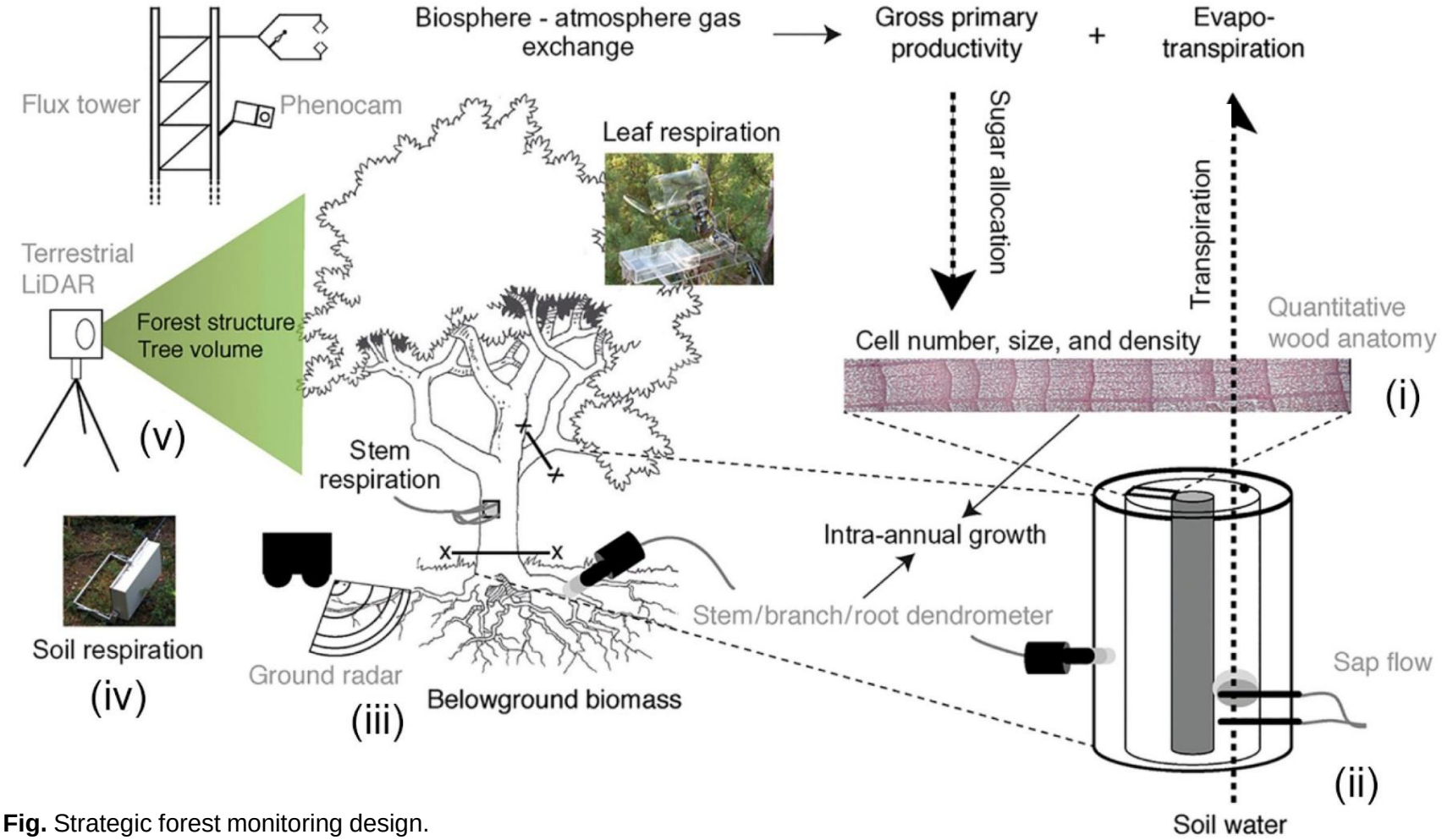
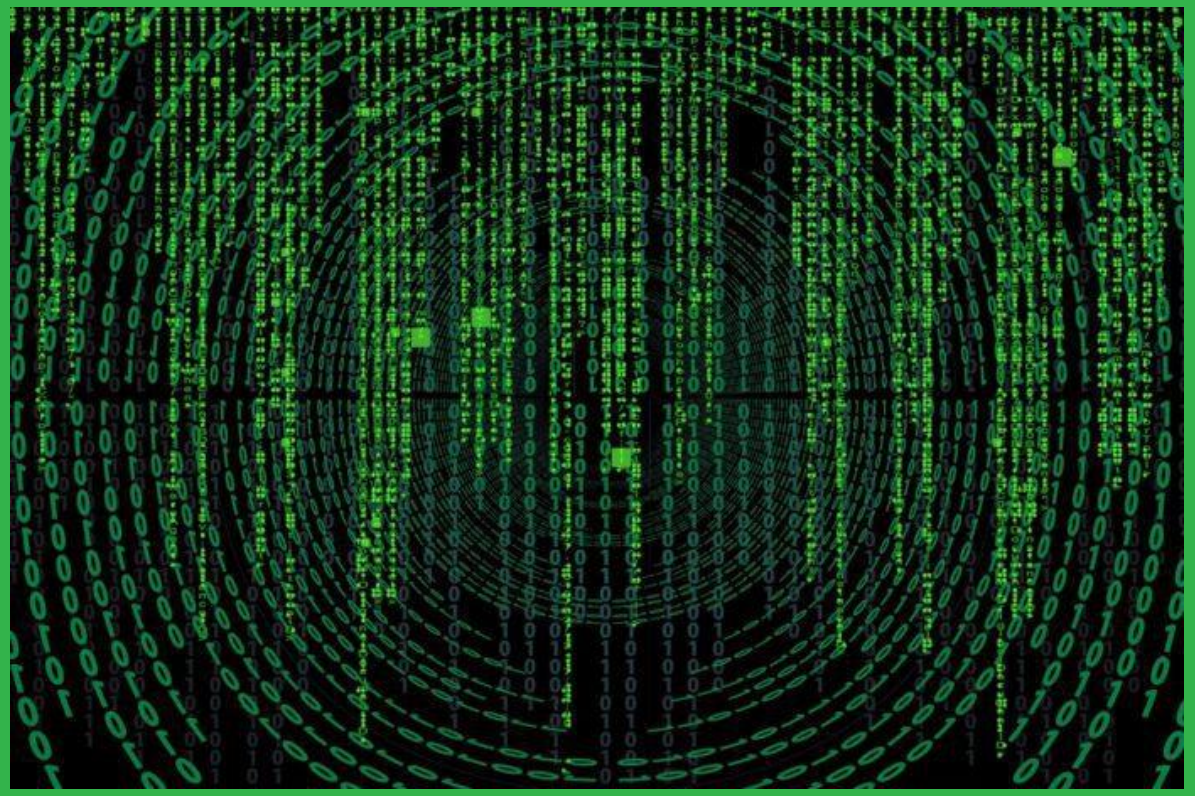


Fig. Strategic forest monitoring design.
Source: Babst et al. (2021) doi: https://doi.org/10.1016/j.tplants.2020.10.002

Data handling



Raw data

- Typically, text files/spreadsheets
- Delimited formats (tab, space, …), data types (numeric, strings, factors, …)
- Quick view with a text editor

TOA5_15475.Table1.dat

```
"TOA5","15475","CR1000X","15475","CR1000X.Std.04.01","CPU:STE_Site1_HRM_2020.CR1X","56661","Table1"
"TIMESTAMP","RECORD","BattV_Avg","deltaT1(1)","deltaT1(2)","deltaT1(3)","deltaT1(4)","deltaT1(5)","deltaT1(6)","deltaT2(1)","deltaT2(2)","deltaT2(3)","del
,"deltaT7(1)","deltaT7(2)","deltaT7(3)","deltaT7(4)","deltaT7(5)","deltaT7(6)","deltaT8(1)","deltaT8(2)","deltaT8(3)","deltaT8(4)","deltaT8(5)","deltaT8(6)
"TS","RN","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","",
"","","Avg","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp"
"2021-05-27 10:46:00",0,12.1,0.77,1.076,0.591,0.787,1.113,0.576,0.551,0.551,0.252,0.542,0.618,0.324,0.586,0.561,0.319,0.512,0.571,0.359,0.574,1.089,1.008,
"2021-05-27 11:16:00",1,12.1,0.779,1.077,0.593,0.798,1.116,0.577,0.557,0.554,0.255,0.544,0.625,0.326,0.588,0.567,0.321,0.508,0.572,0.36,0.587,1.102,1.019,
"2021-05-27 11:46:00",2,12.1,0.767,1.074,0.594,0.778,1.112,0.577,0.544,0.552,0.255,0.526,0.62,0.328,0.594,0.566,0.323,0.508,0.569,0.362,0.585,1.104,1.022,
"2021-05-27 12:16:00",3,12.11,0.774,1.074,0.595,0.788,1.114,0.58,0.552,0.555,0.255,0.532,0.62,0.327,0.594,0.568,0.325,0.508,0.574,0.362,0.587,1.105,1.025,
"2021-05-27 12:46:00",4,1
"2021-05-27 13:16:00",5,1
"2021-05-27 13:46:00",6,1
"2021-05-27 14:16:00",7,1
"2021-05-27 14:46:00",8,1
"2021-05-27 15:16:00",9,1
"2021-05-27 15:46:00",1
"2021-05-27 16:16:00",11,
"2021-05-27 16:46:00",12,
"2021-05-27 17:16:00",13,
"2021-05-27 17:46:00",14,
```

STE1_StationA_05112021.txt - Notepad

File Edit Format View Help

```
Date Time       D1_A04 (micrometer)     D2_A05 (micrometer)     D3_A06 (micrometer)
21/05/19 13:28:31.0     11134.75        11548.67        12510.31        10304.58
21/05/19 13:58:31.0     11134.75        11548.67        12510.31        10304.17
21/05/19 14:28:31.0     11140.24        11548.26        12511.43        10304.17
21/05/19 14:58:31.0     11151.01        11548.26        12519.56        10302.65
21/05/19 15:28:31.0     11151.01        11548.26        12519.56        10299.50
21/05/19 15:58:31.0     11151.01        11548.26        12519.56        10296.45
21/05/19 16:28:31.0     11151.01        11547.96        12519.96        10288.32
21/05/19 16:58:31.0     11151.01        11523.47        12519.56        10282.43
21/05/19 17:28:31.0     11151.01        11508.03        12519.96        10275.11
21/05/19 17:58:31.0     11151.01        11494.41        12519.96        10270.85
21/05/19 18:28:31.0     11146.03        11480.09        12519.96        10264.24
```

https://codersera.com/blog/best-text-editor/

Time series handling

North American Dendroecological Fieldweek

Data import in R

- base R
- tidyverse

```
read.table(file, header = FALSE, sep = "", quote = "\"'",
           dec = ".", numerals = c("allow.loss", "warn.loss", "no.loss"),
           row.names, col.names, as.is = !stringsAsFactors,
           na.strings = "NA", colClasses = NA, nrows = -1,
           skip = 0, check.names = TRUE, fill = !blank.lines.skip,
           strip.white = FALSE, blank.lines.skip = TRUE,
           comment.char = "#",
           allowEscapes = FALSE, flush = FALSE,
           stringsAsFactors = default.stringsAsFactors(),
           fileEncoding = "", encoding = "unknown", text, skipNul = FALSE)

read.csv(file, header = TRUE, sep = ",", quote = "\"",
         dec = ".", fill = TRUE, comment.char = "", …)

read.csv2(file, header = TRUE, sep = ";", quote = "\"",
          dec = ",", fill = TRUE, comment.char = "", …)

read.delim(file, header = TRUE, sep = "\t", quote = "\"",
           dec = ".", fill = TRUE, comment.char = "", …)

read.delim2(file, header = TRUE, sep = "\t", quote = "\"",
            dec = ",", fill = TRUE, comment.char = "", …)
```

https://www.rdocumentation.org/packages/utils/versions/3.6.2/topics/read.table

readr

- `read_csv()` : comma-separated values (CSV) files
- `read_tsv()` : tab-separated values (TSV) files
- `read_delim()` : delimited files (CSV and TSV are important special cases)
- `read_fwf()` : fixed-width files
- `read_table()` : whitespace-separated files
- `read_log()` : web log files

https://readr.tidyverse.org/

Time series handling

North American Dendroecological Fieldweek

STE1_TOA5_15475.Table1.dat

```
"TOA5","15475","CR1000X","15475","CR1000X.Std.04.01","CPU:STE_Site1_HRM_2020.CR1X","27479","Table1"
"TIMESTAMP","RECORD","BattV_Avg","deltaT1(1)","deltaT1(2)","deltaT1(3)","deltaT1(4)","deltaT1(5)","deltaT1(6)","deltaT2(1)","deltaT2(2)","deltaT2(3)","deltaT
,"deltaT7(1)","deltaT7(2)","deltaT7(3)","deltaT7(4)","deltaT7(5)","deltaT7(6)","deltaT8(1)","deltaT8(2)","deltaT8(3)","deltaT8(4)","deltaT8(5)","deltaT8(6)",
"TS","RN","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","","",
"","","Avg","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","
"2020-07-23 11:16:00",0,12.08,0.01,-0.011,-0.025,0.012,-0.007,-0.021,0.006,-0.013,-0.021,0.007,-0.011,-0.021,0,-0.011,-0.017,0.007,-0.01,-0.017,-0.009,0.003,
"2020-07-23 11:46:00",1,12.08,-0.001,-0.002,-0.008,-0.003,0.002,-0.001,0,-0.001,-0.004,0,-0.003,-0.003,-0.002,0,-0.002,-0.003,-0.033,-0.003,0.002,0.006,0.005
"2020-07-23 12:16:00",2,12.08,0.009,0.004,0,0.008,0.002,0,0.004,0.001,0.001,0.004,0,-0.001,0.006,0.001,-0.001,0.004,-0.002,0,0.006,0.006,0.004,0.007,0.004,0.
"2020-07-23 12:46:00",3,12.08,0.002,0.003,0.003,-0.003,-0.001,0,0.001,0.001,0.002,-0.001,-0.001,0,-0.003,-0.003,0,-0.003,0.01,-0.002,0.001,0.001,0.001,-0.001
"2020-07-23 13:16:00",4,12.08,-0.002,0.007,0.002,0.009,-0.001,0.001,0.002,0,0,0.002,0,0.001,0.006,0.003,0.002,0.007,0.011,0,0.002,0,-0.001,0.003,0.004,0,0.00
"2020-07-23 13:46:00",5,12.08,0.008,0.004,0.002,0.006,0.001,0.003,0.005,0.002,0.003,0.003,0.002,0.002,0.004,0.004,0.003,0.005,0.025,0.004,0.004,0.002,0.001,-
"2020-07-23 14:16:00",6,12.08,0.379,0.965,0.894,0.308,0.917,0.933,0.354,0.609,0.577,0.263,0.618,0.582,0.355,0.486,0.448,0.217,0.275,0.435,0.004,0.001,0.007,0
"2020-07-23 14:46:00",7,12.09,0.054,0.058,0.085,0.027,0.041,0.073,0.254,0.073,0.081,0.114,0.051,0.073,0.115,0.049,0.071,0.054,0.041,0.069,-0.003,-0.001,-0.00
"2020-07-23 15:16:00",8,12.08,-0.172,0.013,0.026,-0.082,0.012,0.022,0.319,0.028,0.031,0.149,0.005,0.031,0.021,0.04,0.034,0.01,0.038,0.026,-0.006,-0.003,-0.00
"2020-07-23 15:46:00",9,12.09,0.028,0.051,0.019,0.006,0.027,0.02,-0.17,-0.026,0.026,-0.017,0.012,0.02,-0.28,-0.018,0.015,-0.121,0.003,0.01,-0.001,0,-0.003,-0
"2020-07-23 16:16:00",10,12.09,-0.124,0,0.009,-0.052,0.009,0.005,-0.006,0.043,0.014,-0.057,0.015,0.005,0.157,0.04,0.011,0.092,0.007,0.01,-0.003,-0.001,-0.002
"2020-07-23 16:46:00",11,12.09,-0.049,-0.062,0,-0.017,-0.027,0.001,0.47,-0.008,-0.003,0.2,-0.028,0.001,0.033,0.007,0.009,0.004,-0.007,0.007,0.002,0.002,0.001
"2020-07-23 17:16:00",12,12.09,-0.546,-0.028,0.009,-0.263,0.001,0.004,-0.505,-0.115,0.007,-0.24,-0.029,0.01,-0.08,-0.046,0.007,-0.031,0.007,0.01,0.007,-0.001
"2020-07-23 17:46:00",13,12.09,-0.852,-0.01,-0.001,-0.447,0.031,-0.015,0.562,-0.039,0.001,0.272,-0.038,0.005,0.034,0.01,0.007,0.009,0.004,0.007,0.001,0,0.001
"2020-07-23 18:16:00",14,12.09,0.009,0.064,0.004,-0.011,0.034,0.004,0.056,0.072,0.013,-0.026,0.035,0.022,0.075,0.018,0.021,0.06,0.024,0.006,-0.001,-0.001,-0.
01,0.001,-0.00
004,0.002,0.00
,-0.004,0.01,-
,0.001,-0.002,
0,-0.003,-0.00
006,-0.003,-0.
```

	TIMESTAMP	RECORD	BattV_Avg	deltaT1(1)	deltaT1(2)	deltaT1(3)	deltaT1(4)	deltaT1(5)	deltaT1(6)	deltaT2(1)	deltaT2(2)	deltaT2(3)	deltaT2(4)
1	2020-07-23 11:16:00	0	12.08	0.010	-0.011	-0.025	0.012	-0.007	-0.021	0.006	-0.013	-0.021	0.007
2	2020-07-23 11:46:00	1	12.08	-0.001	-0.002	-0.008	-0.003	0.002	-0.001	0.000	-0.001	-0.004	0.000
3	2020-07-23 12:16:00	2	12.08	0.009	0.004	0.000	0.008	0.002	0.000	0.004	0.001	0.001	0.004
4	2020-07-23 12:46:00	3	12.08	0.002	0.003	0.003	-0.003	-0.001	0.000	0.001	0.001	0.002	-0.001
5	2020-07-23 13:16:00	4	12.08	-0.002	0.007	0.002	0.009	-0.001	0.001	0.002	0.000	0.000	0.002
6	2020-07-23 13:46:00	5	12.08	0.008	0.004	0.002	0.006	0.001	0.003	0.005	0.002	0.003	0.003
7	2020-07-23 14:16:00	6	12.08	0.379	0.965	0.894	0.308	0.917	0.933	0.354	0.609	0.577	0.263
8	2020-07-23 14:46:00	7	12.09	0.054	0.058	0.085	0.027	0.041	0.073	0.254	0.073	0.081	0.114
9	2020-07-23 15:16:00	8	12.08	-0.172	0.013	0.026	-0.082	0.012	0.022	0.319	0.028	0.031	0.149
10	2020-07-23 15:46:00	9	12.09	0.028	0.051	0.019	0.006	0.027	0.020	-0.170	-0.026	0.026	-0.017
11	2020-07-23 16:16:00	10	12.09	-0.124	0.000	0.009	-0.052	0.009	0.005	-0.006	0.043	0.014	-0.057
12	2020-07-23 16:46:00	11	12.09	-0.049	-0.062	0.000	-0.017	-0.027	0.001	0.470	-0.008	-0.003	0.200

```
data = read.table("datafile.dat",
                  header=F,
                  sep=",",
                  skip=4,
                  na.strings = "NAN")

data$TIMESTAMP = ymd_hms(data$TIMESTAMP, tz="America/Toronto")
```

Time series handling

Dates

- time stamps

https://rawgit.com/rstudio/cheatsheets/main/lubridate.pdf

2017-11-28T14:02:00	**ymd_hms(), ymd_hm(), ymd_h().** ymd_hms("2017-11-28T14:02:00")
2017-22-12 10:00:00	**ydm_hms(), ydm_hm(), ydm_h().** ydm_hms("2017-22-12 10:00:00")
11/28/2017 1:02:03	**mdy_hms(), mdy_hm(), mdy_h().** mdy_hms("11/28/2017 1:02:03")
1 Jan 2017 23:59:59	**dmy_hms(), dmy_hm(), dmy_h().** dmy_hms("1 Jan 2017 23:59:59")
20170131	**ymd(), ydm().** ymd(20170131)
July 4th, 2000	**mdy(), myd().** mdy("July 4th, 2000")
4th of July '99	**dmy(), dym().** dmy("4th of July '99")

2018-01-31 11:59:59	**day(x)** Day of month. day(dt) **wday(x, label, abbr)** Day of week. **qday(x)** Day of quarter.
2018-01-31 11:59:59	**hour(x)** Hour. hour(dt)
2018-01-31 11:59:59	**minute(x)** Minutes. minute(dt)
2018-01-31 11:59:59	**second(x)** Seconds. second(dt)

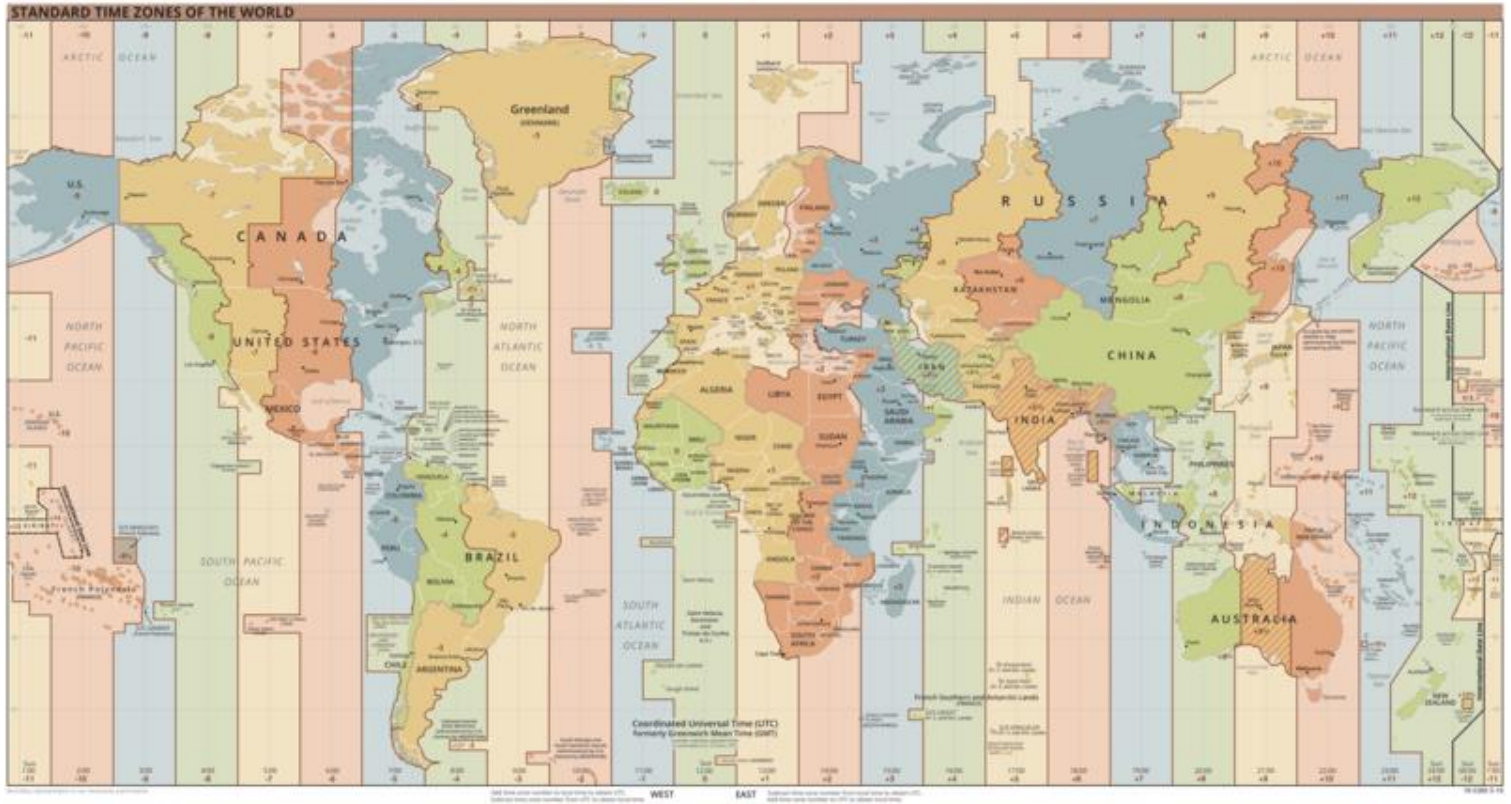
More examples

- base R: https://deep-tools.netlify.app/docs-workshops/uhelsinki-workshop2021/01_datacleanr/
- lubridate: https://lubridate.tidyverse.org/

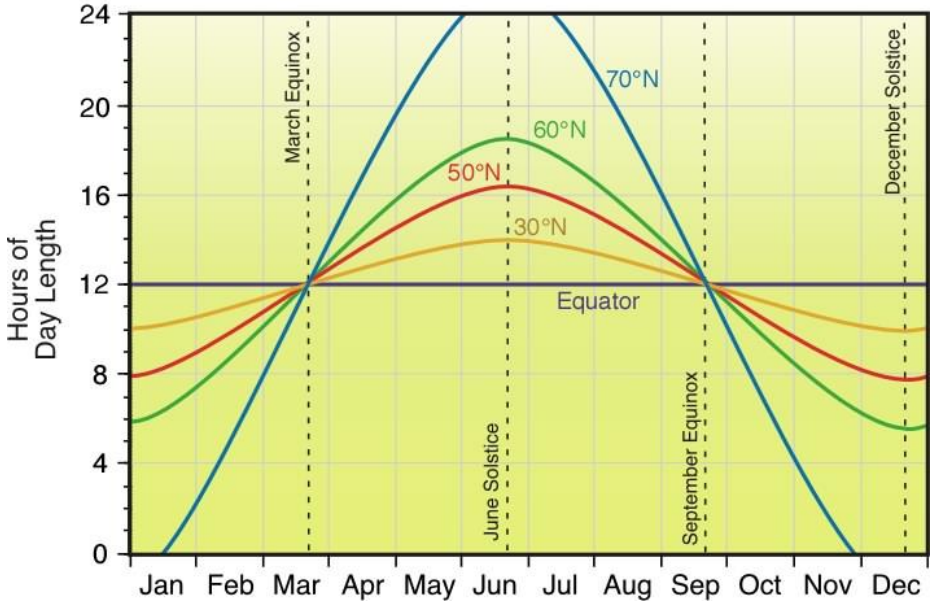
Time series handling

Dates

- time zones (daylight savings ?)
- `solartime` (https://github.com/bgctw/solartime; noon when sun is at zenith)



https://commons.wikimedia.org/wiki/File:World_Time_Zones_Map.png

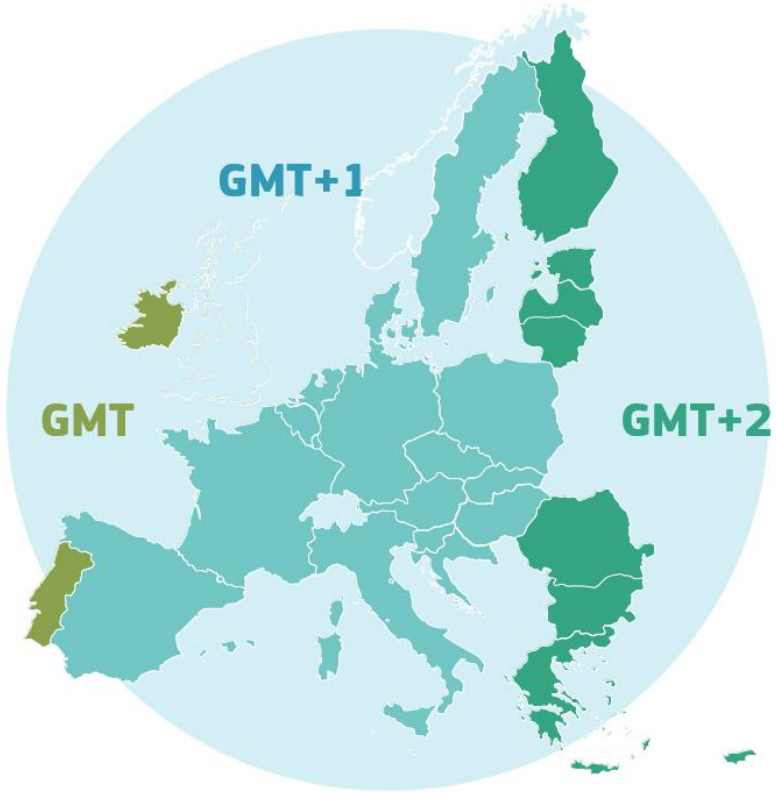


http://www.physicalgeography.net/fundamentals/6i.html

Time series handling

Dates

- time zones (daylight savings ?)
- `solartime` (https://github.com/bgctw/solartime; noon when sun is at zenith)



Source: ec.europa.eu/transport/themes/summertime_en

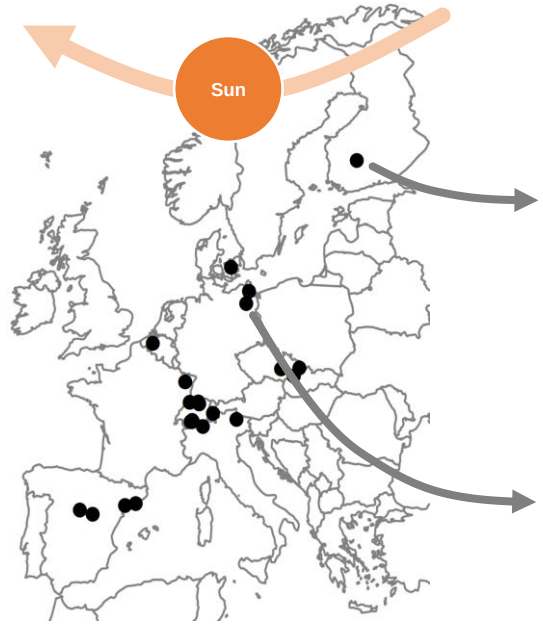
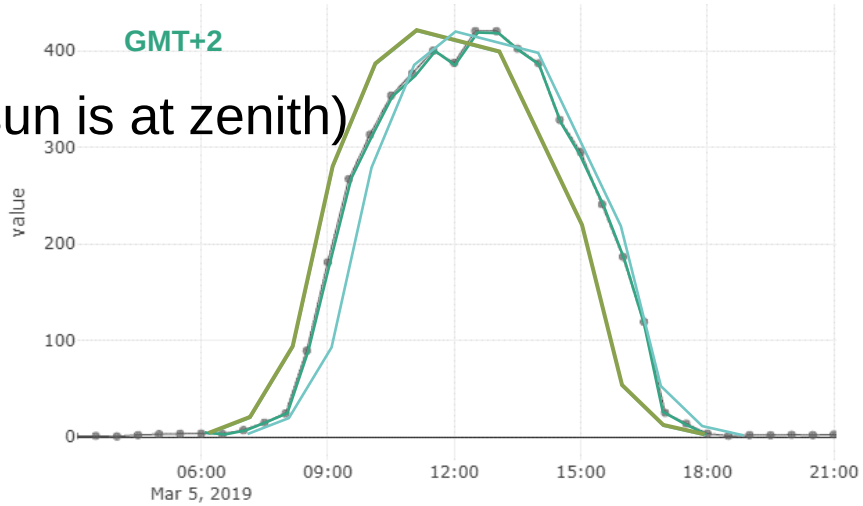
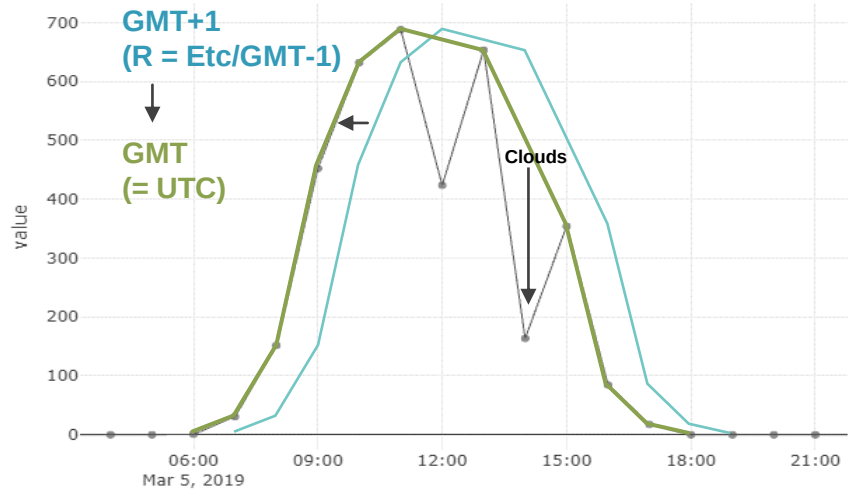


Fig. Sites with global irradiance (W/m^2) data.

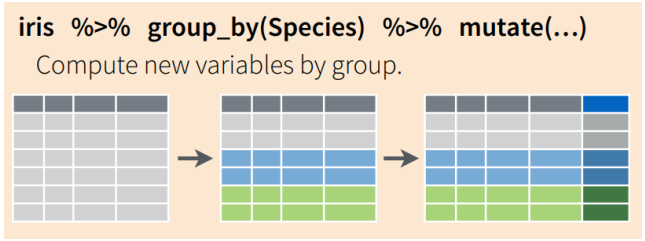




Time series handling

Temporal aggregation

- base R
- `dplyr`



30-min data

site	sensor	tree	depth	timestamp	time	tz	value
STE1	deltaT4_out	4	out	2020-08-24 18:46:00	2020-08-24 18:46:00	EDT	-0.025268594
STE1	deltaT4_out	4	out	2020-08-24 19:16:00	2020-08-24 19:16:00	EDT	-0.027292142
STE1	deltaT4_out	4	out	2020-08-24 19:46:00	2020-08-24 19:46:00	EDT	-0.025367214
STE1	deltaT4_out	4	out	2020-08-24 20:16:00	2020-08-24 20:16:00	EDT	-0.029156584
STE1	deltaT4_out	4	out	2020-08-24 20:46:00	2020-08-24 20:46:00	EDT	-0.029327615
STE1	deltaT4_out	4	out	2020-08-24 21:16:00	2020-08-24 21:16:00	EDT	-0.031191612
STE1	deltaT4_out	4	out	2020-08-24 21:46:00	2020-08-24 21:46:00	EDT	-0.031252544

1-h data

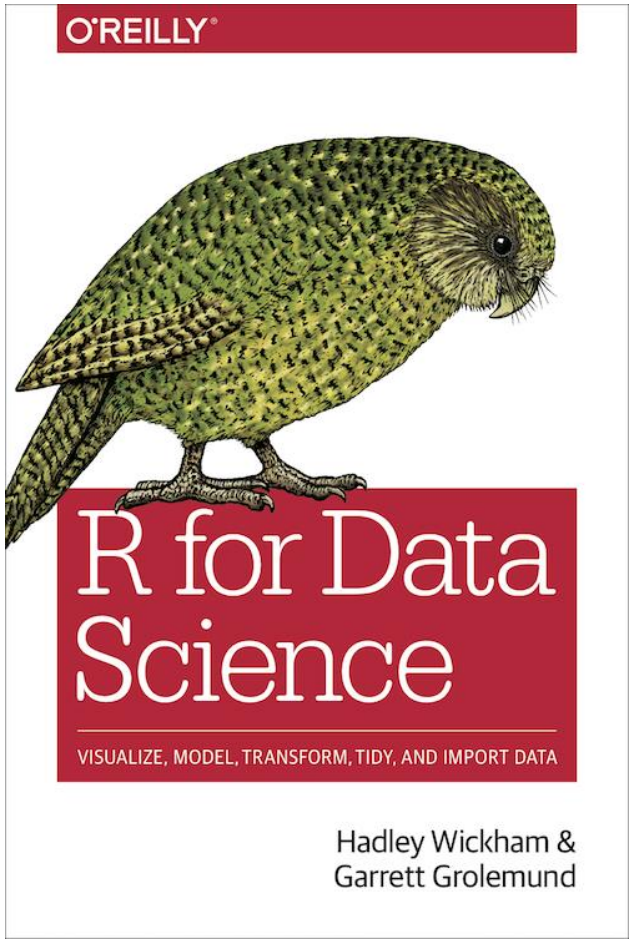
sensor	site	date	doy	hour	tree	depth	tz	value
deltaT4_out	STE1	2020-08-24 17:00:00	237	17	4	out	EDT	-0.0232645516
deltaT4_out	STE1	2020-08-24 18:00:00	237	18	4	out	EDT	-0.0223245229
deltaT4_out	STE1	2020-08-24 19:00:00	237	19	4	out	EDT	-0.0263296781
deltaT4_out	STE1	2020-08-24 20:00:00	237	20	4	out	EDT	-0.0292420997

```r
# aggregate to hourly data
data_h = data %>%
  group_by(sensor, site,
           date=ymd_h(substr(data$timestamp, 1, 13)),
           doy=yday(data$timestamp),
           hour=hour(data$timestamp)) %>%
  summarise(tree = unique(tree),
            depth=unique(depth),
            tz=unique(tz),
            value=mean(value, na.rm=T))
```

More examples

- aggregate(·) https://deep-tools.netlify.app/talk/uhelsinki-2021-rpeters-ahurley/
- dplyr | group_by(·) https://www.rstudio.com/wp-content/uploads/2015/02/data-wrangling-cheatsheet.pdf

Time series handling | additional resources



https://r4ds.had.co.nz/index.html

TUTORIAL

Time Series 04: Subset and Manipulate Time Series Data with dplyr

Authors: Megan A. Jones, Marisa Guarinello, Courtney Soderberg, Leah A. Wasser **Last Updated:** May 13, 2021

https://www.neonscience.org/resources/learning-hub/tutorials/dc-time-series-subset-dplyr-r

Home/Courses /Earth analytics /**Intro to R & Work with Time Series Data**

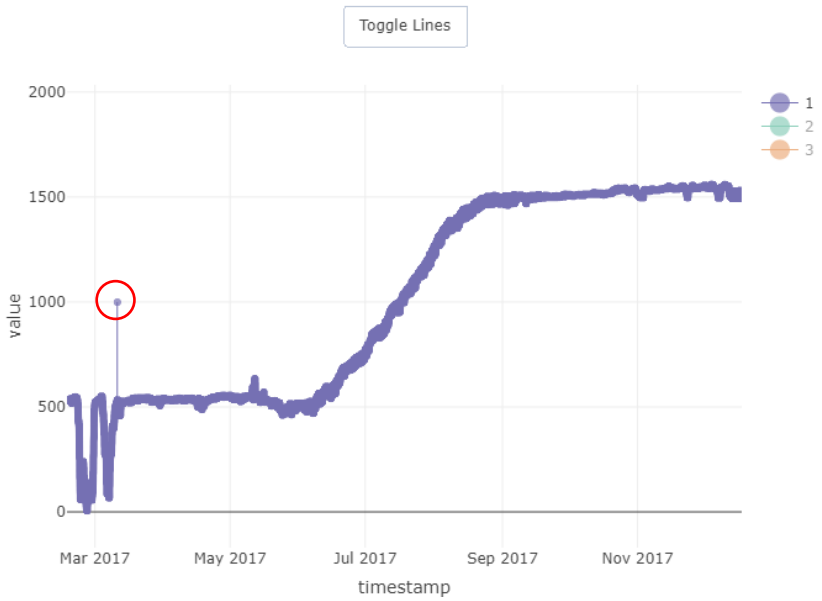
https://www.earthdatascience.org/courses/earth-analytics/time-series-data/

Data ‘cleaning’ with datacleanr

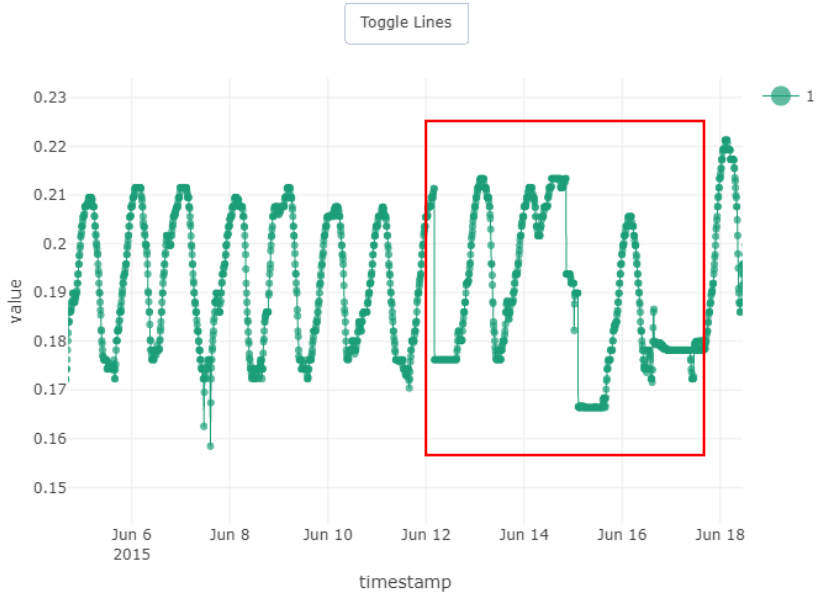
Typical data issues

Outlier and sensor failure issues *Removing data should always be done with care!*

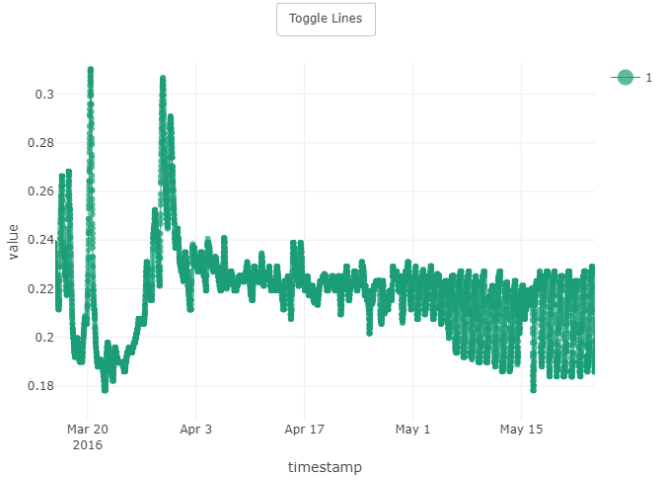
Outliers (dendrometer data)

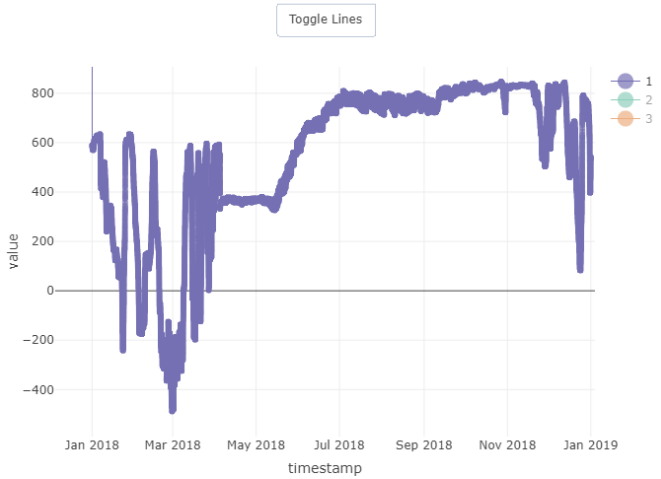


Sensor failure (sap flow data)



What about spring data?





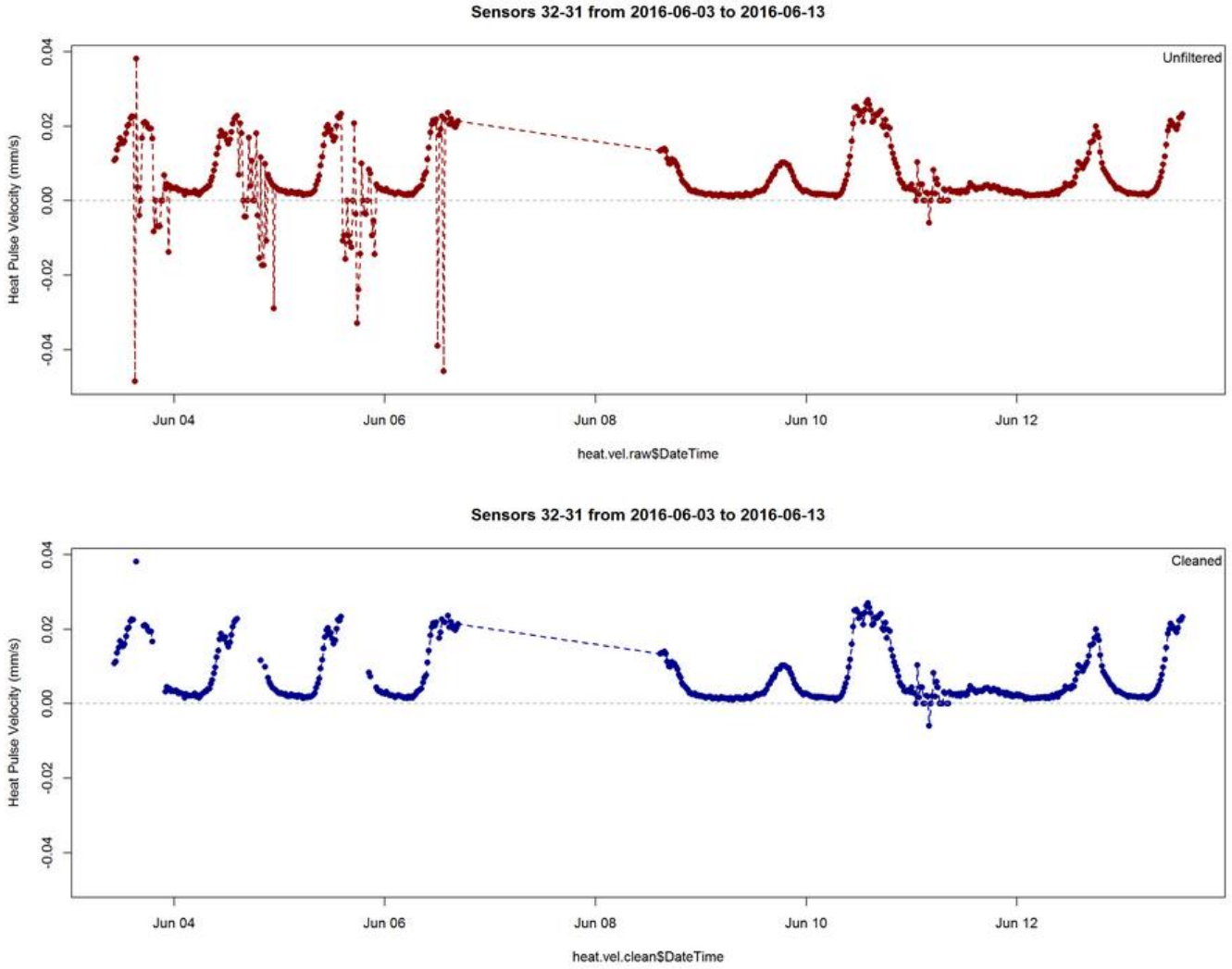
Data ‘cleaning’ – ways forward?

Manual processing:

- *Quality Control with diagnostic plots*
  - *Time Series*
  - *X/Y (e.g., Sapflow vs. Environment)*

- *Quality Assurance with code:*
  - *Filters*
    - *Moving average*
    - *Threshold*
    - *Outlier detection*
  - *Adjustments (see TREX)*

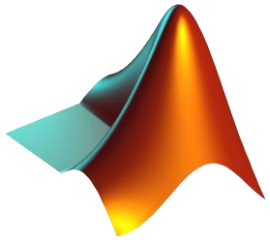
→ *Long series & many sites = much time!*
→ *No “one-size-fits-all” solutions*
→ ***Must be done reproducibly***



Data ‘cleaning’ – ways forward?

(Reproducible) processing and cleaning:

- *Several excellent **programmatic** tools*
  - → *Spreadsheet software (!)*
  - → *Software & libraries*
  - → *Bespoke code*



Focus on R and packages!

- *Extensively used in Environmental Sciences*
  - → *interoperable*

Long series, many sites.. ?

datacleanr – our way forward

A new R-based package
A flexible and efficient tool for interactive data cleaning


```
# grab all data from ZHANG
zhang <- cosore::csr_table("data", c("d20190424_ZHANG_maple",
                                     "d20190424_ZHANG_oak")) %>%
  # adjust for grouping
  mutate(CSR_PORT = as.factor(CSR_PORT))

# group by CSR_DATASET and CSR_PORT
datacleanr::dcr_app(zhang)
```

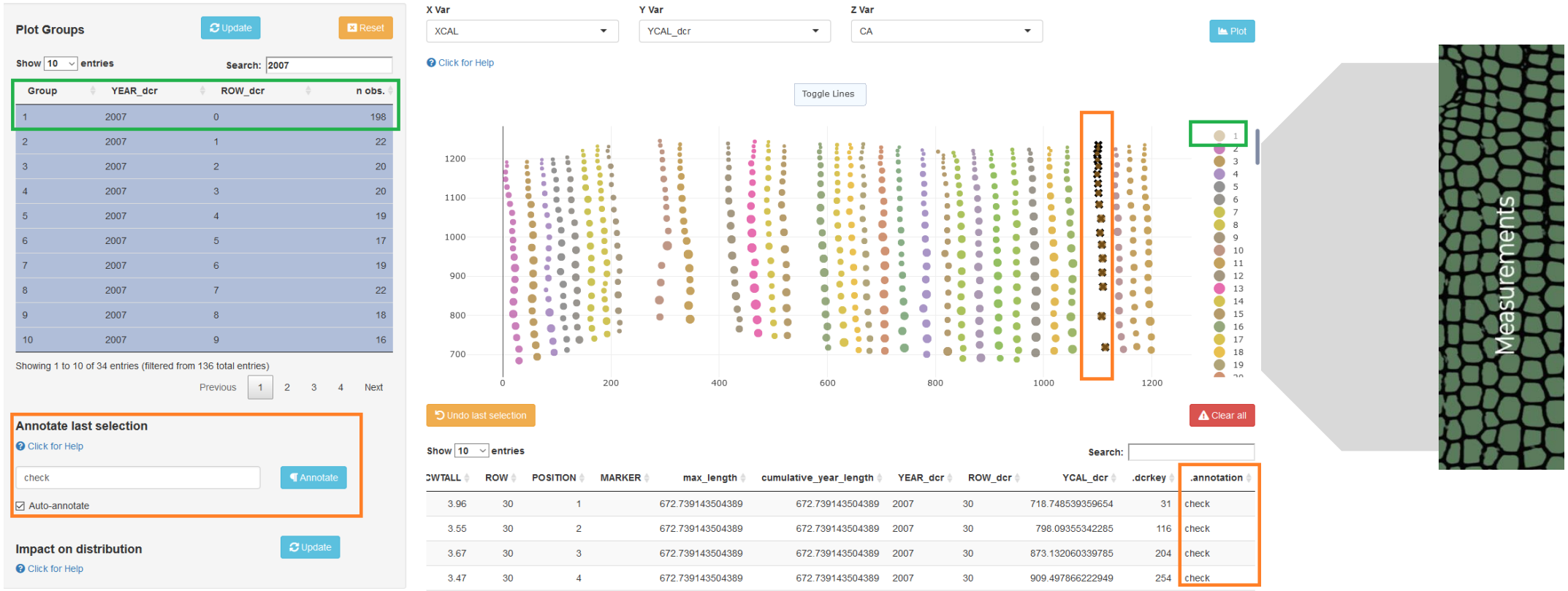
Properties:
- Uses R (links with other packages);
- Freely available (avoid license costs);
- Uses R shiny (interactive approach).
- **Reproducible**

Structure of the tool:
- Set-up & overview;
- Filtering;
- Visual cleaning and annotating;
- Extract.

datacleanr – our way forward

Versatile

Tested on multiple temporal-and spatial-specific data sets

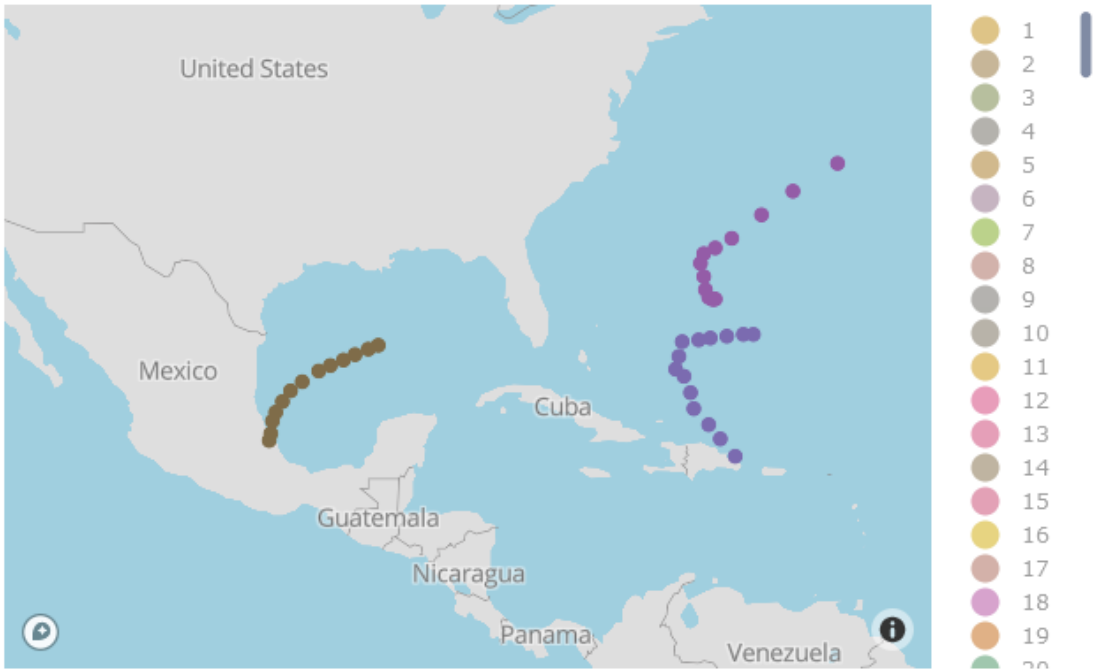


datacleanr – our way forward

Versatile

Tested on multiple temporal-and spatial-specific data sets

Group	name	n obs.
155	Mindy	14
165	Odette	14
13	AL042000	13
15	AL061988	13
53	Bess	13
74	Don	13
162	Nine	13
185	Sean	13
6	AL022000	12
34	AL121999	12

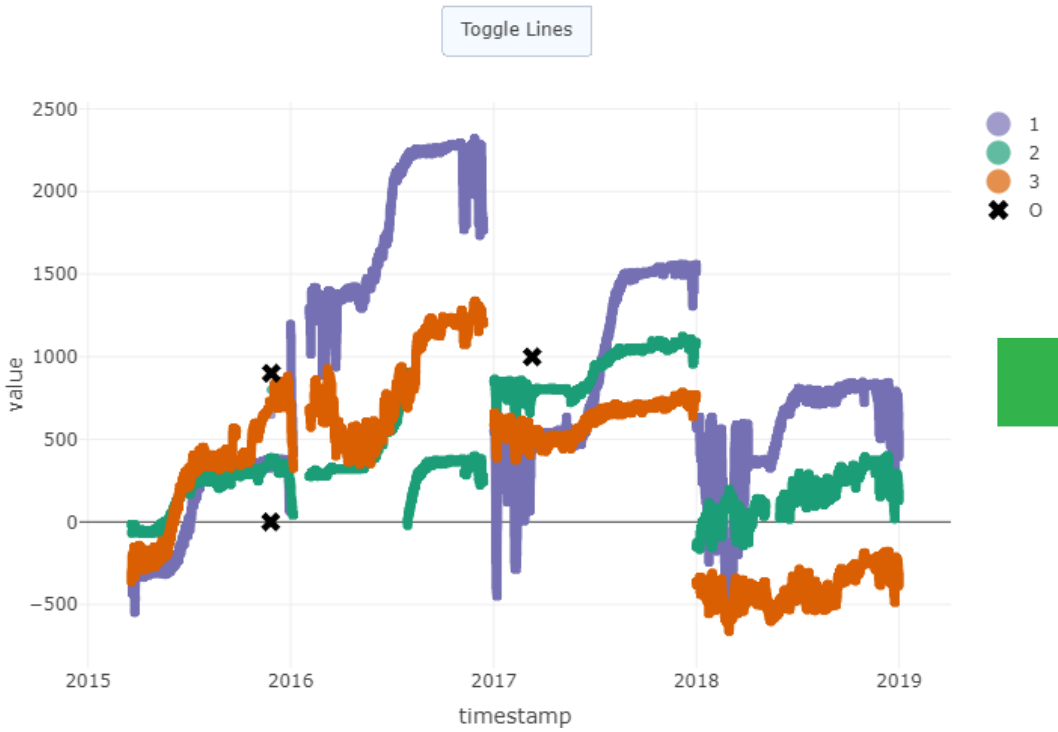


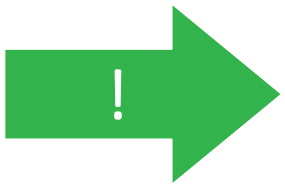
datacleanr – our way forward

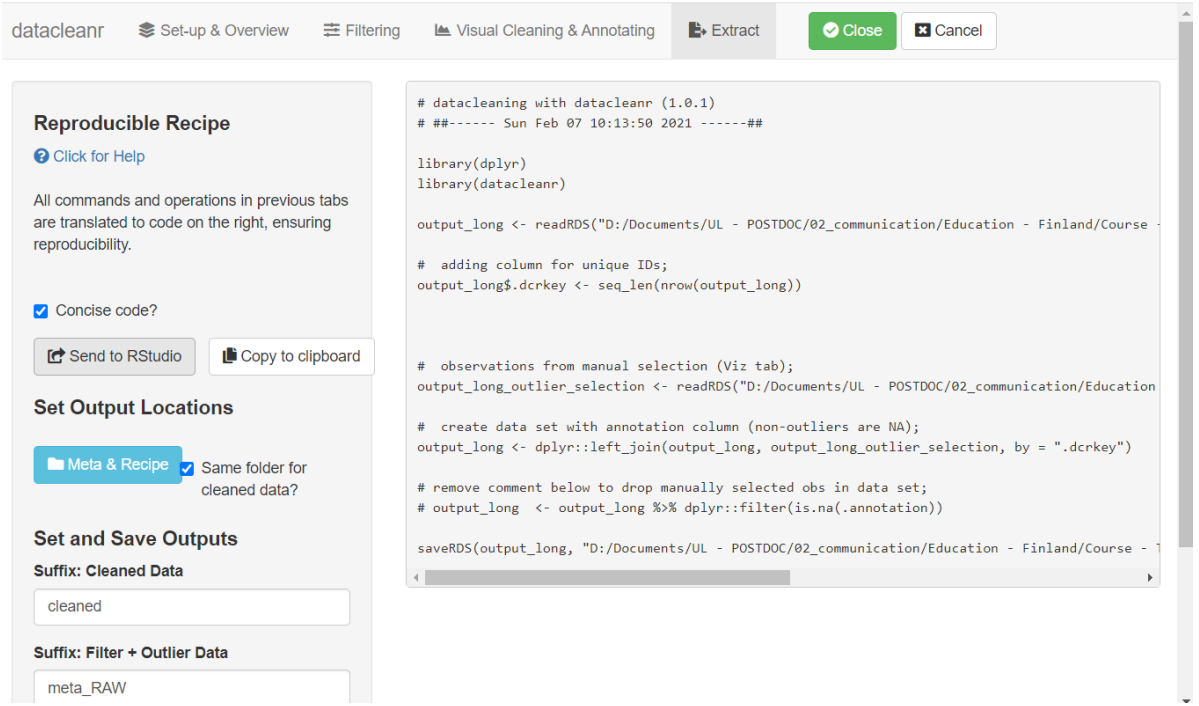
North American Dendroecological Fieldweek

Extract

Reproducible recipe to cook up some fresh data







Additional Resources

Hurley AG, Peters RL, Pappas C, Steger DN, Heinrich I (2022)
Addressing the need for interactive, efficient, and reproducible data processing in ecology with the datacleanr R package. PLoS ONE 17(5): e0268426. https://doi.org/10.1371/journal.pone.0268426

https://github.com/the-hull/datacleanr

https://deep-tools.netlify.app/#workshops

Live Demo

Data processing

Goal? *Make standardized time series processing workflows for widely used monitoring techniques more accessible.*

Data processing

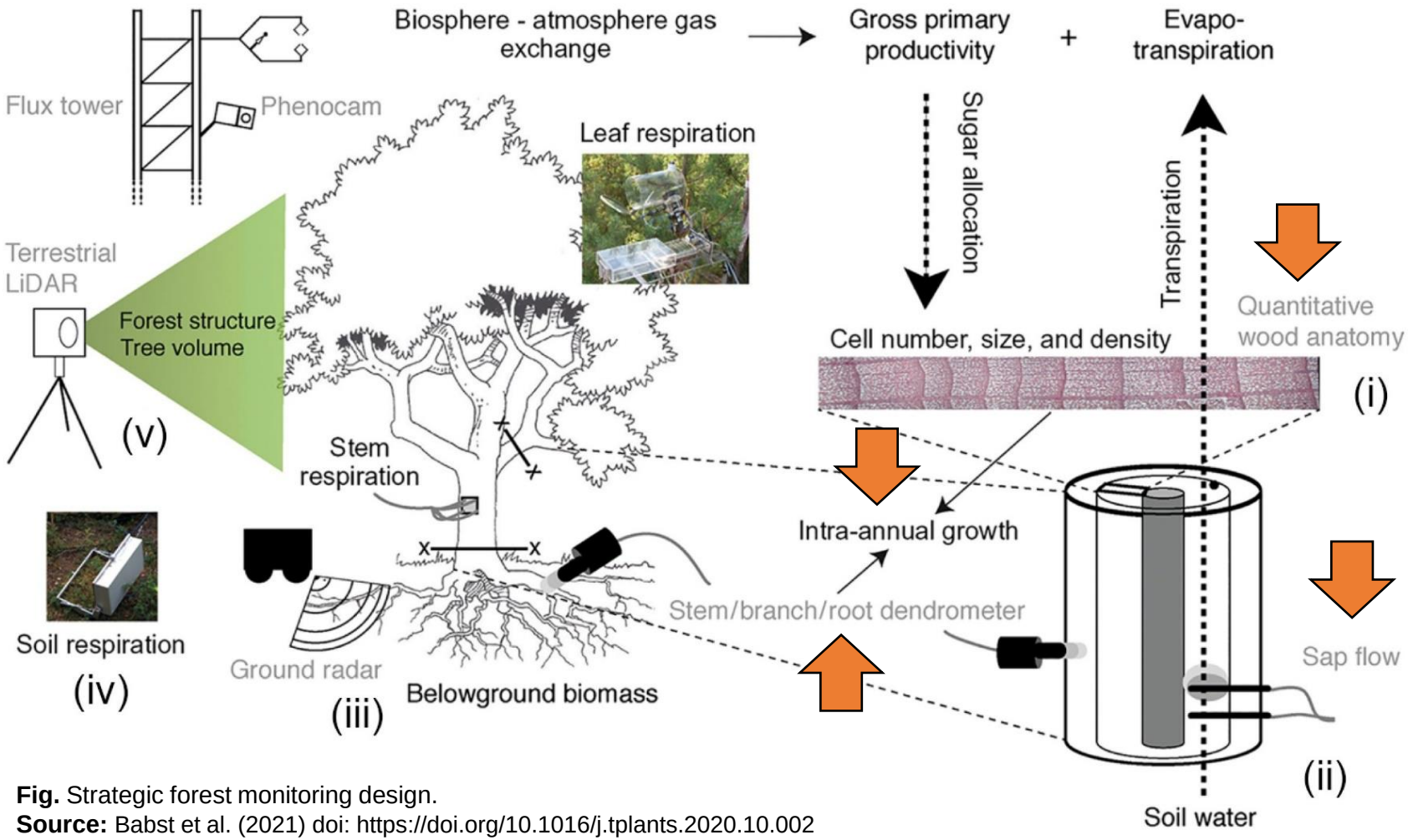


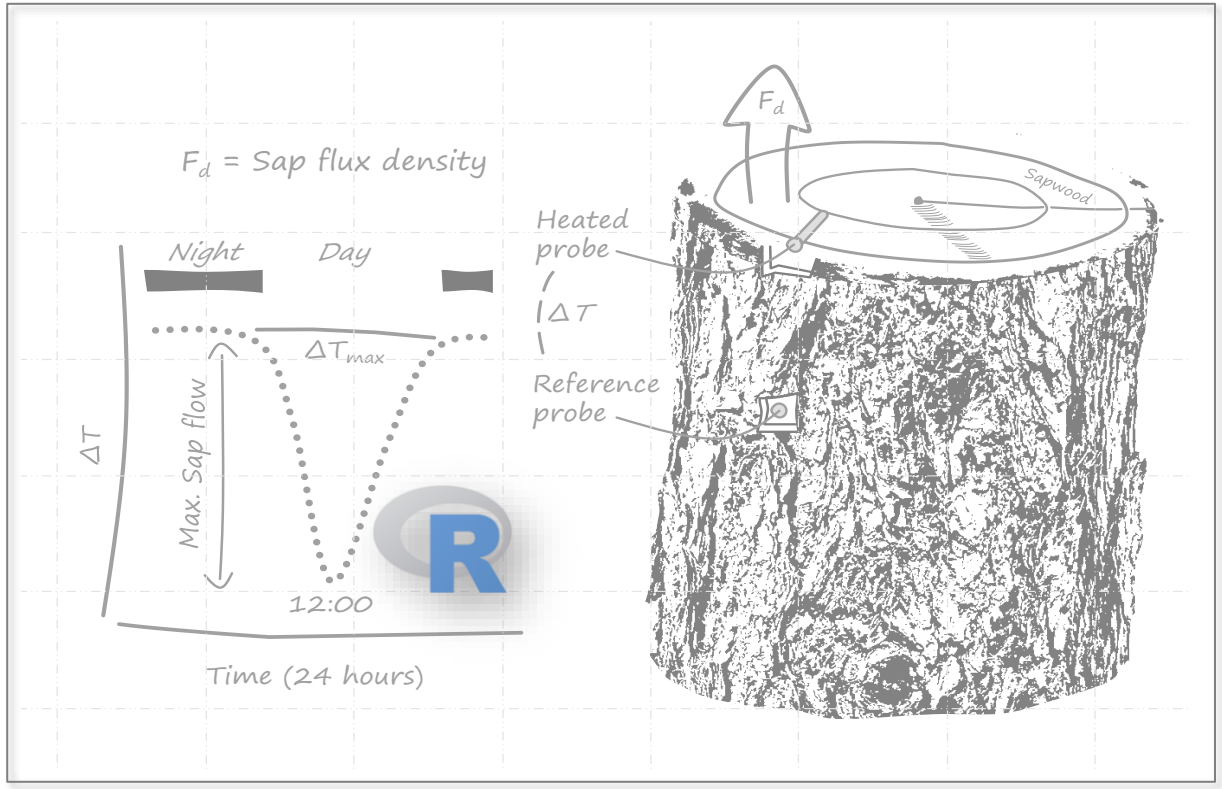
Fig. Strategic forest monitoring design.
Source: Babst et al. (2021) doi: https://doi.org/10.1016/j.tplants.2020.10.002

Forest monitoring
Experimental Framework to Strategically Pair Monitoring of Carbon (C) Allocation Processes in Forests

So what?
The different measurements need to be processed properly

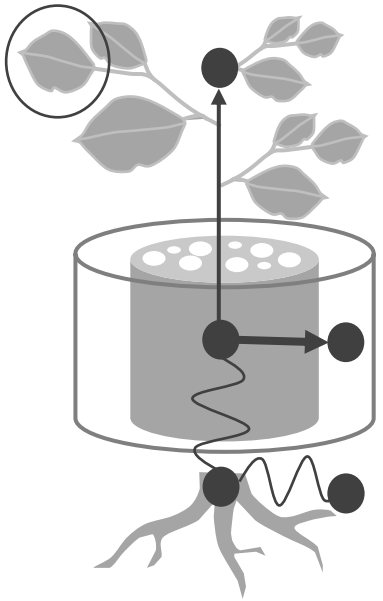
Data processing

Goal? *Make standardized time series processing workflows for widely used monitoring techniques more accessible.*



NADEF 2022

R tools for time series analysis



Structure

Canopy: Sap flow
Bark: Dendrometers
Wood: Structure
Stem: Growth

Packages

01_TREX
02_treenetproc
03_RAPTOR
04_Other

Sap flow measurements

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

TREX 1.0.0 | Reference

Médiane | Gisèle Trudel @UQAM

Peters *et al.* (2020)

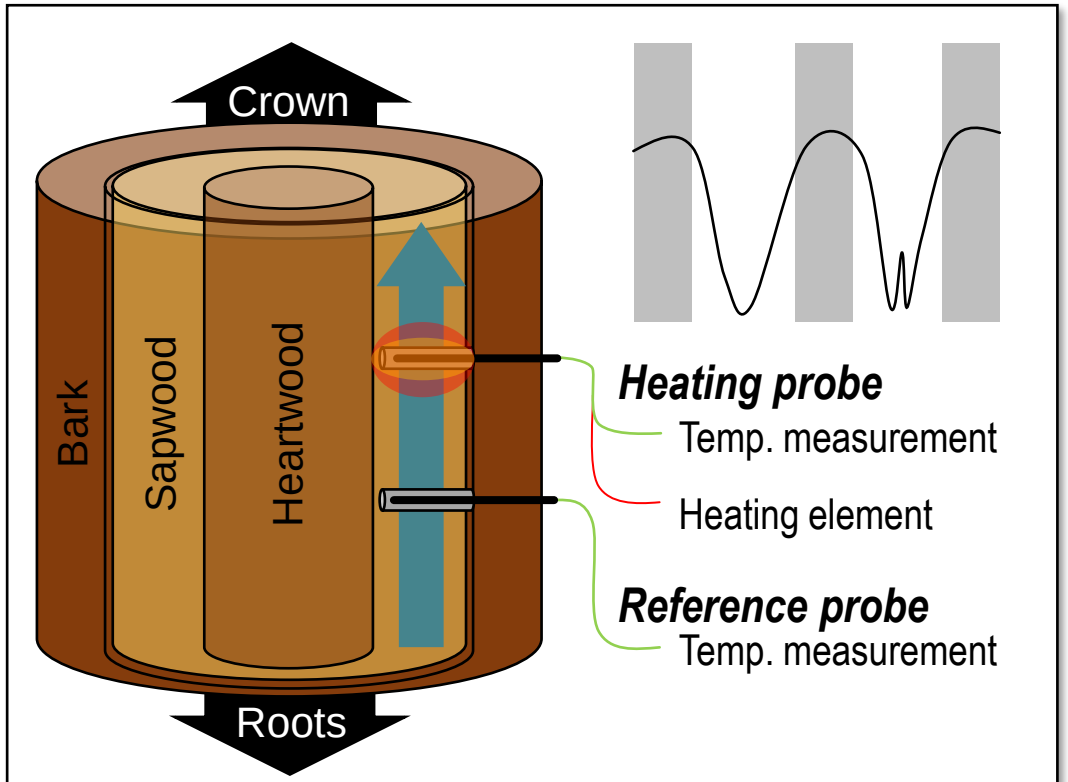
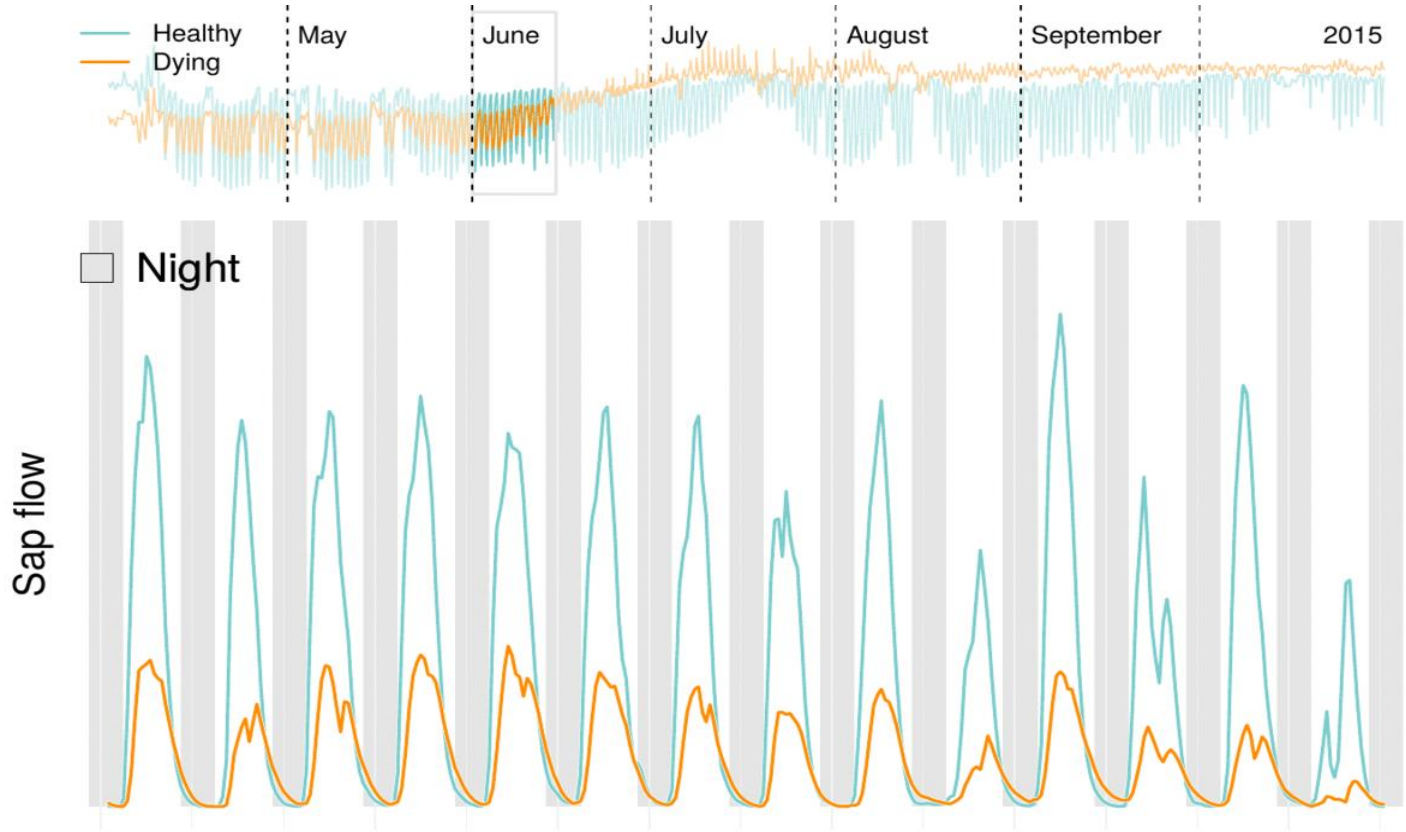
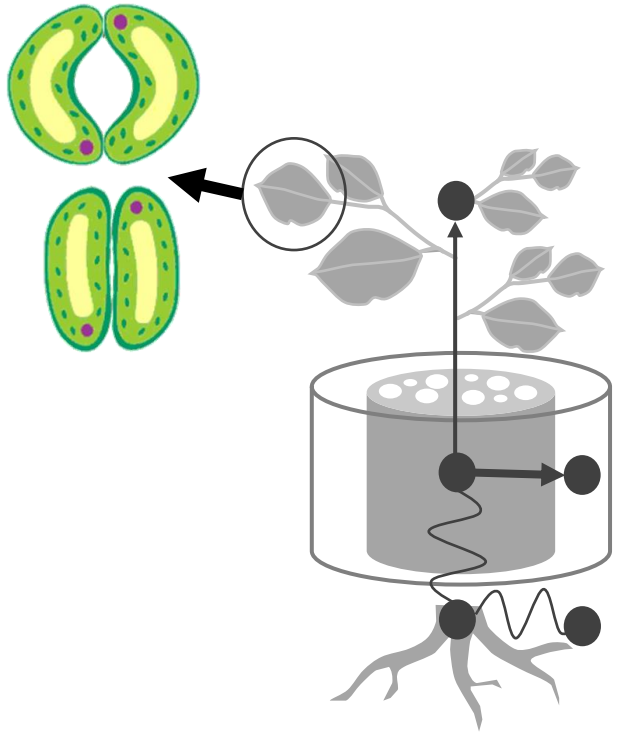


Fig. Schematics of thermal dissipation method.

Sap flow measurements

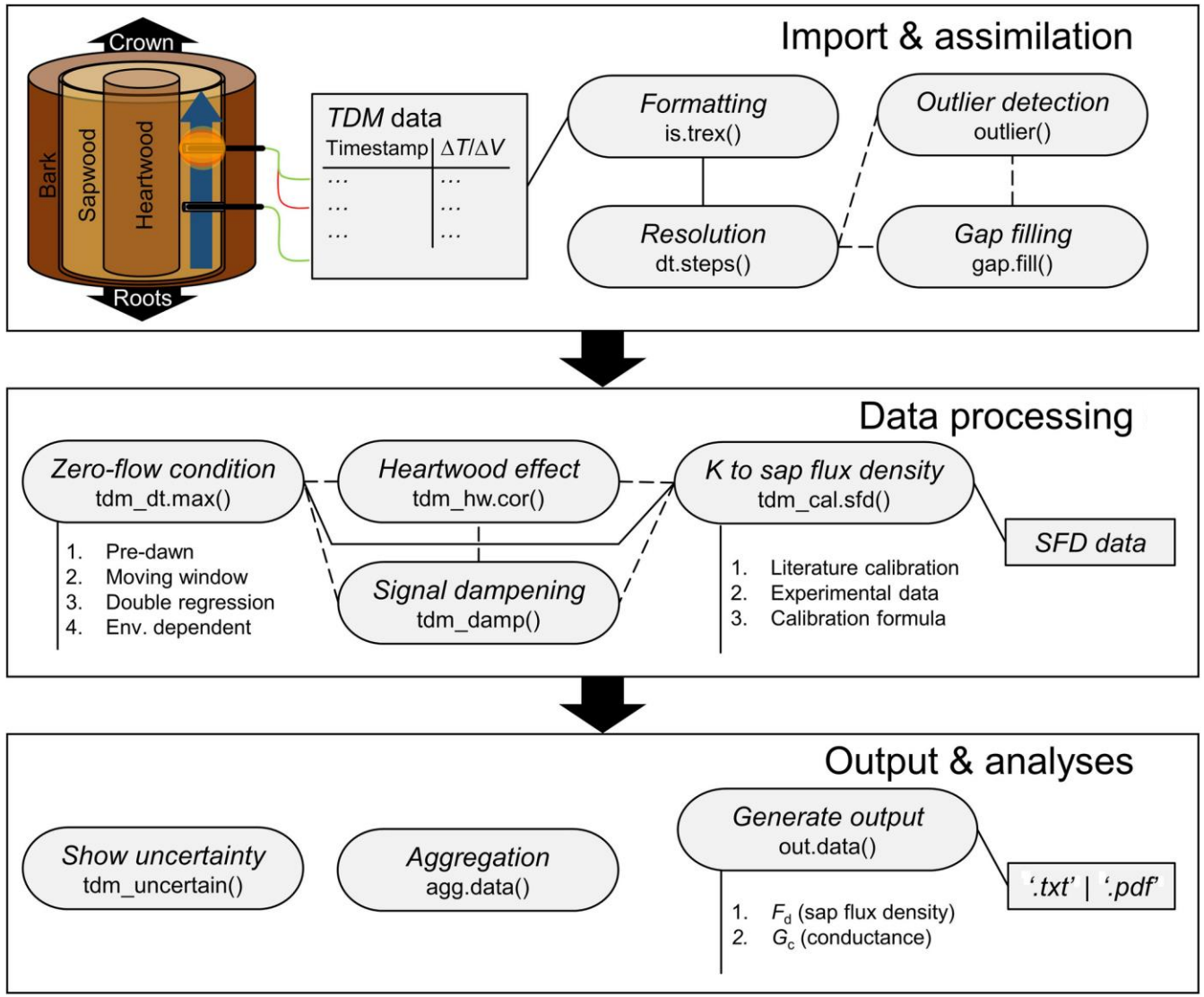
Input – Thermal dissipation probe measurements
tdm.data()

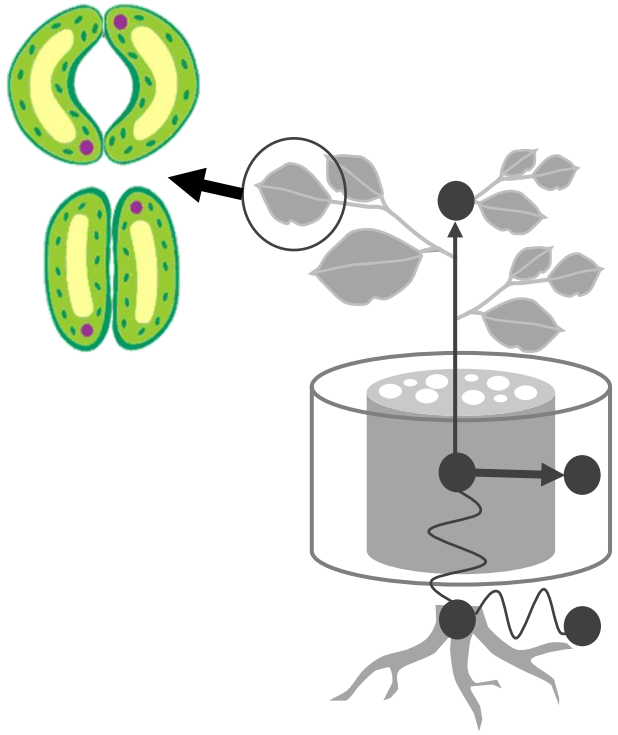




Sap flow measurements

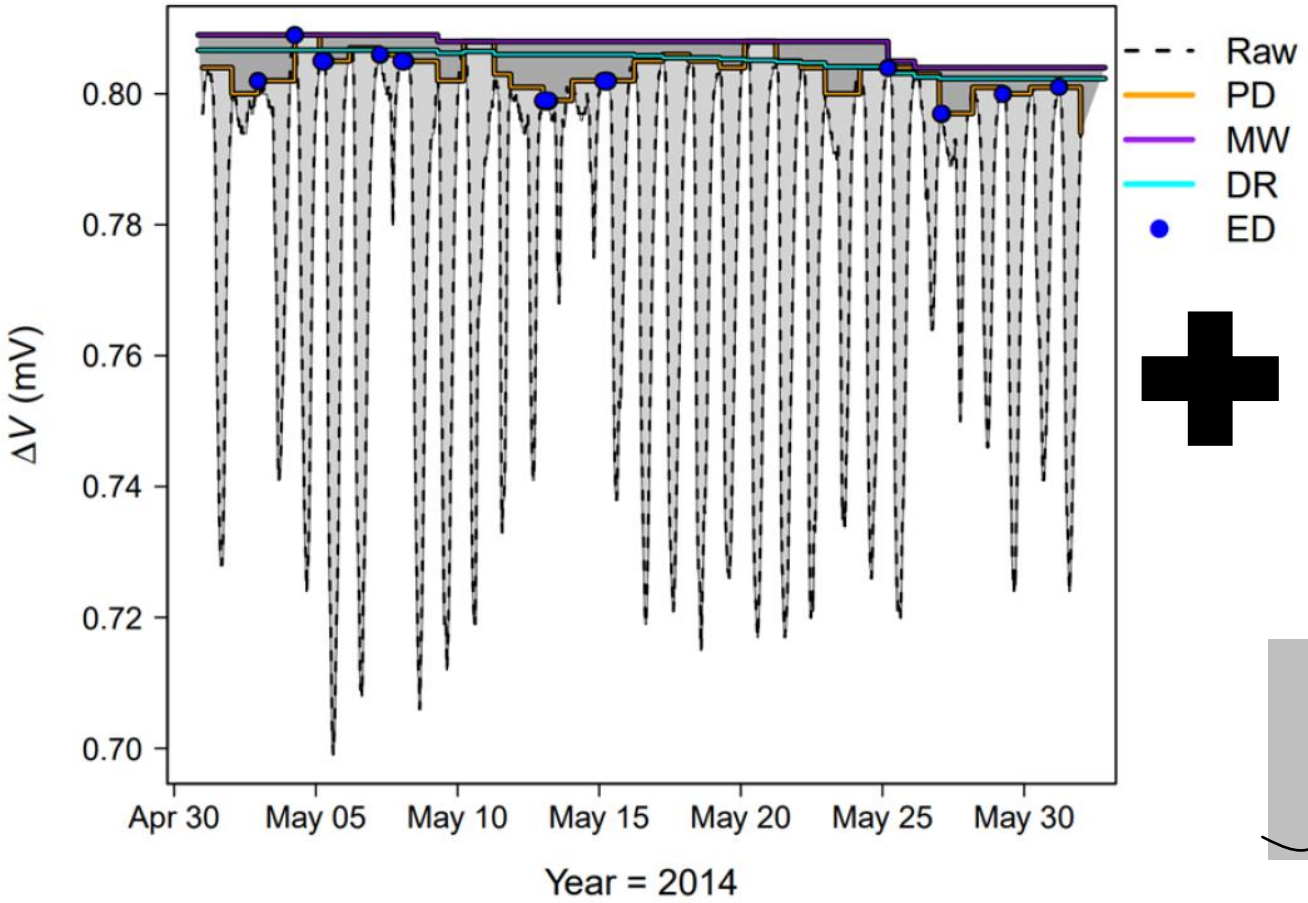
Workflow



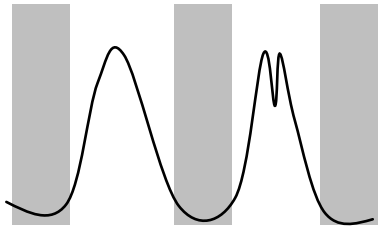


Sap flow measurements

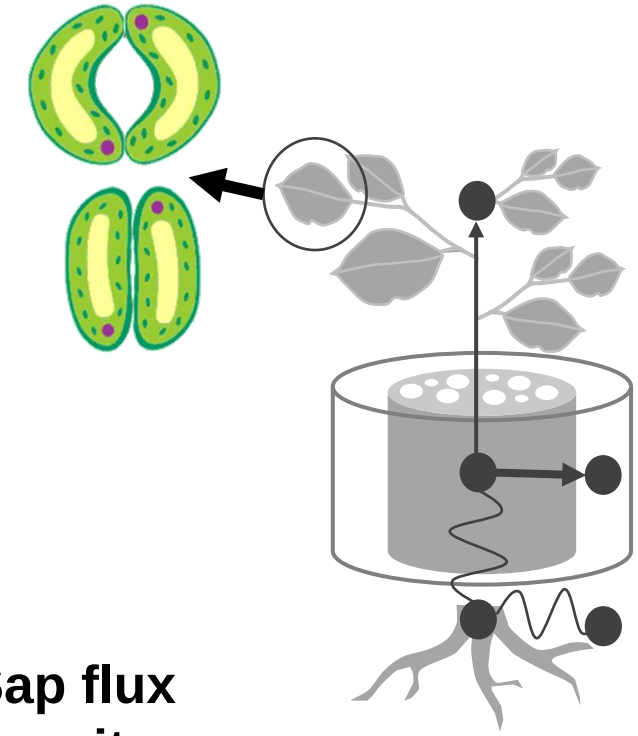
Functionalities – Determining zero flow
tdm_dt.max()



Calibration values
tdm_cal.sfd()

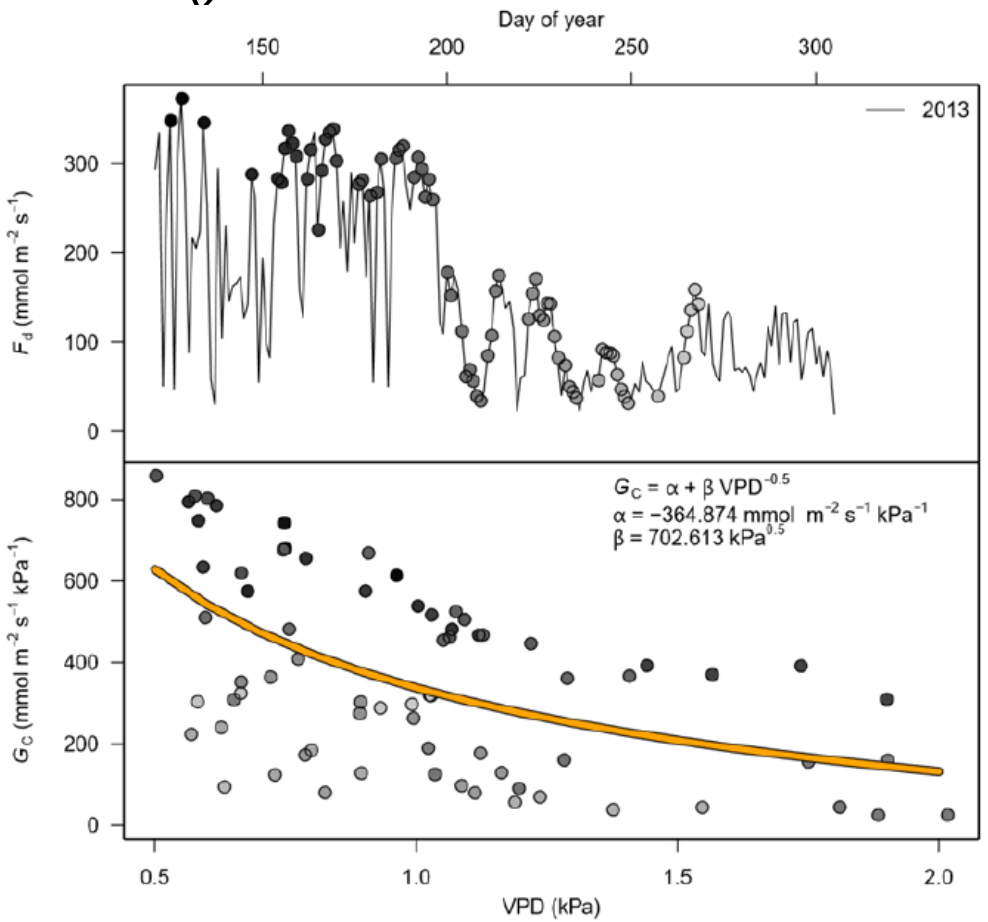


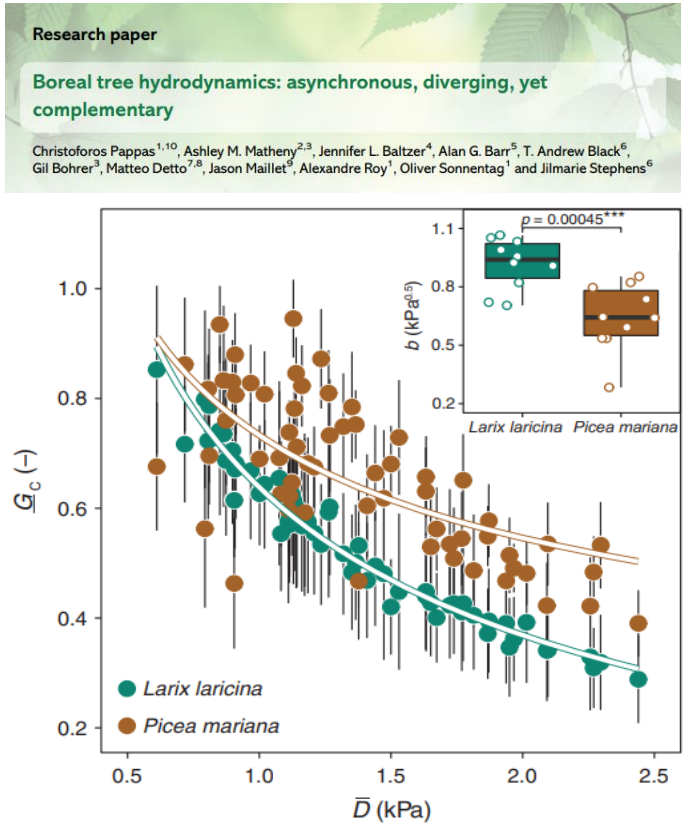
Sap flux density

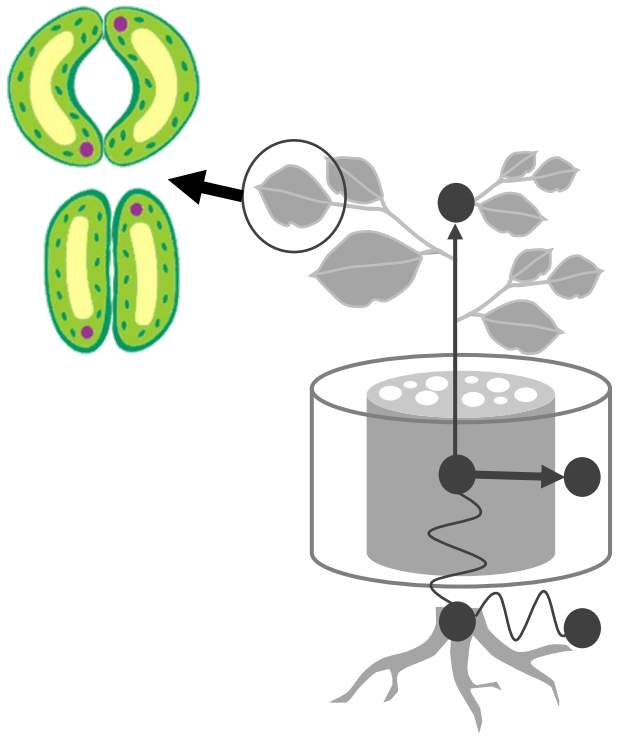


Sap flow measurements

Output – Canopy conductance behavior
out.data()







Dendrometer measurements

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

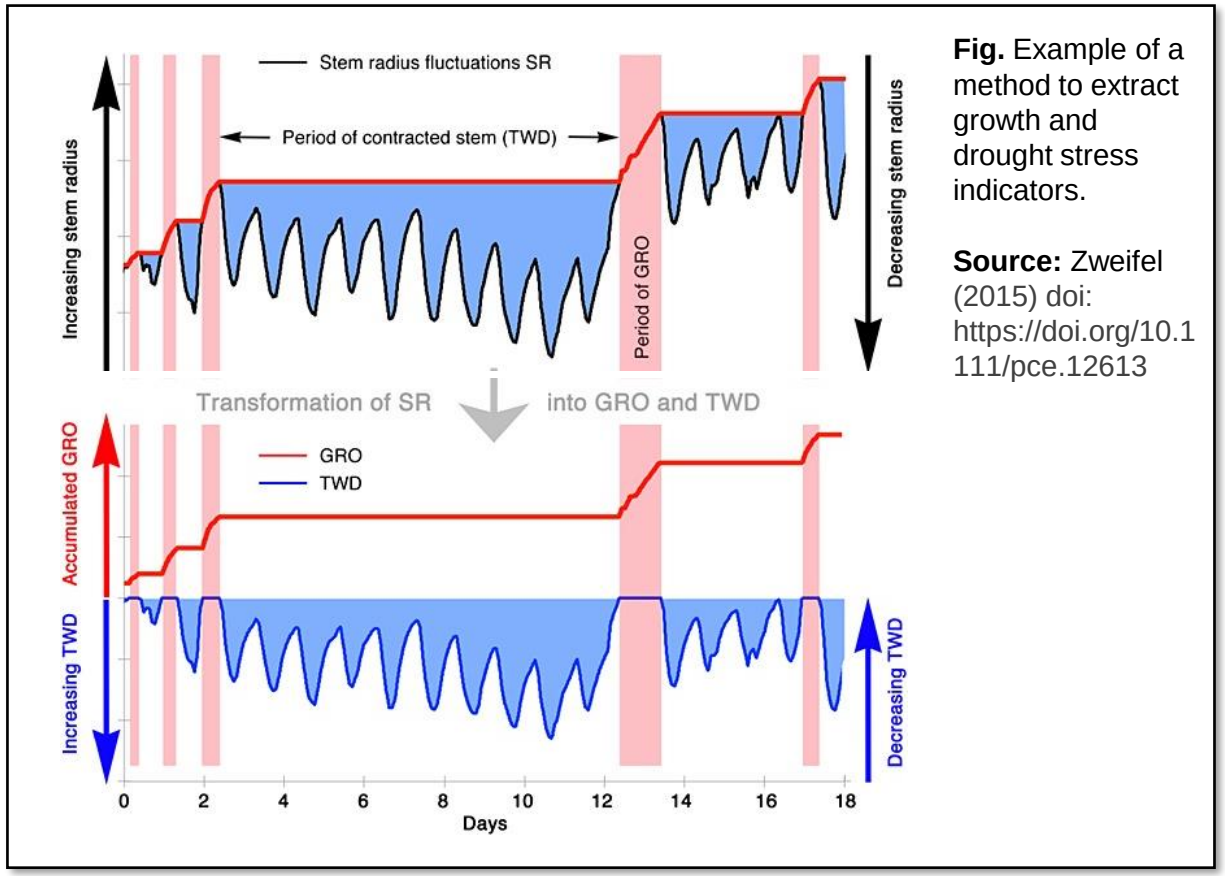
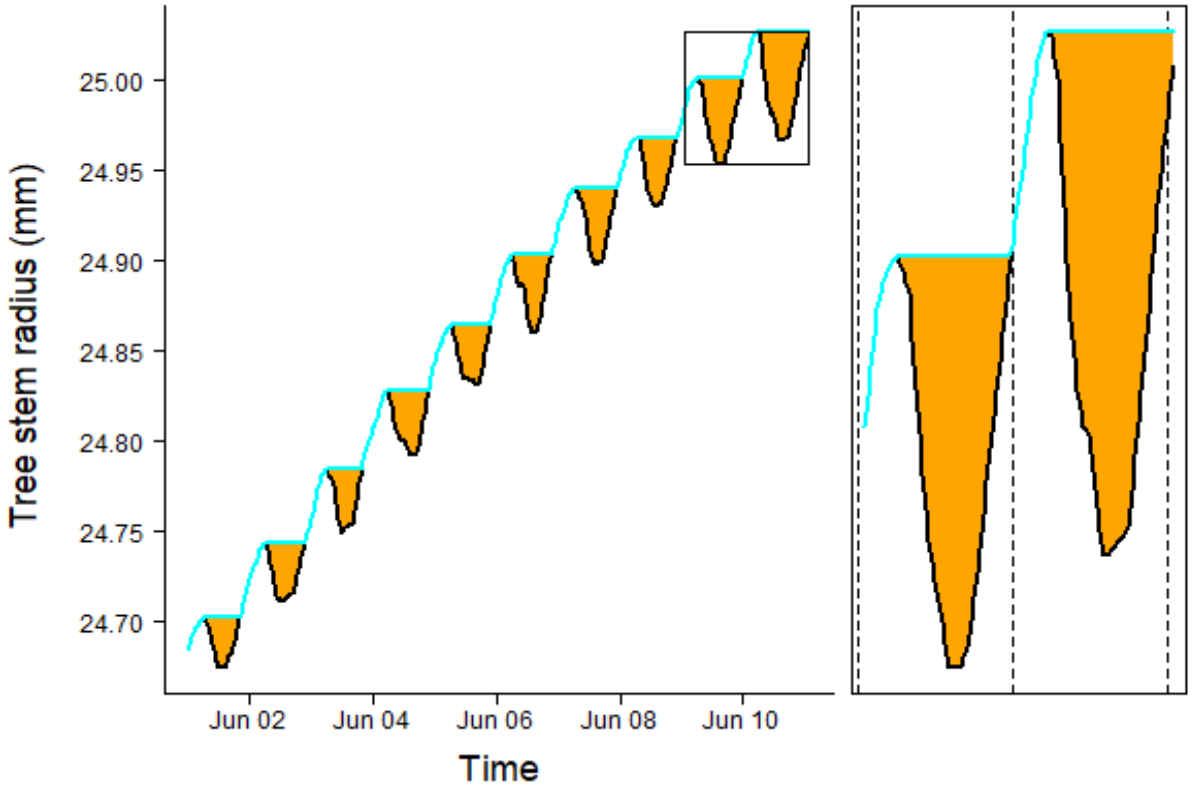


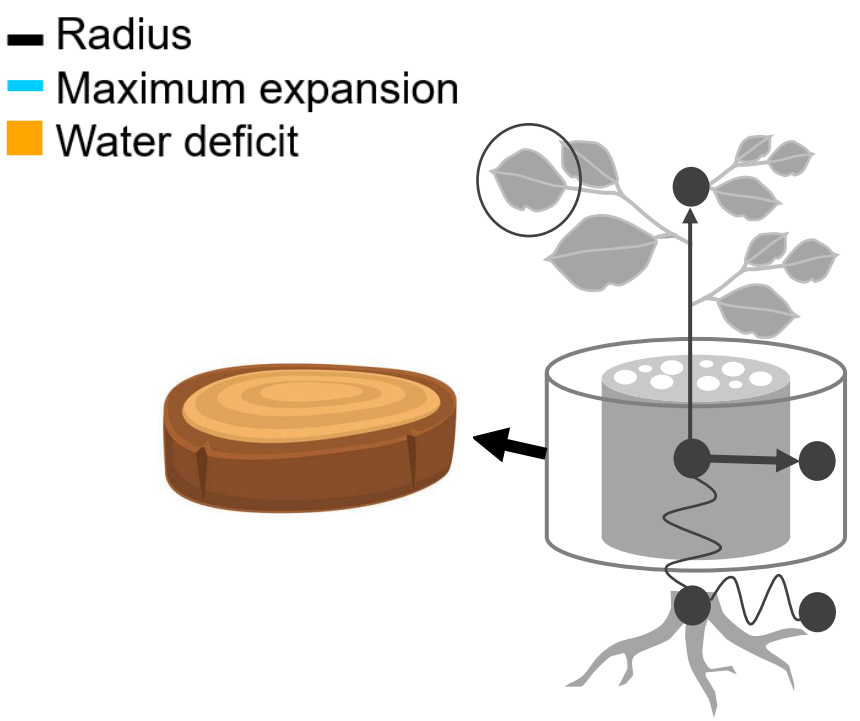
Fig. Example of a method to extract growth and drought stress indicators.

Source: Zweifel (2015) doi: https://doi.org/10.1111/pce.12613

Dendrometer measurements

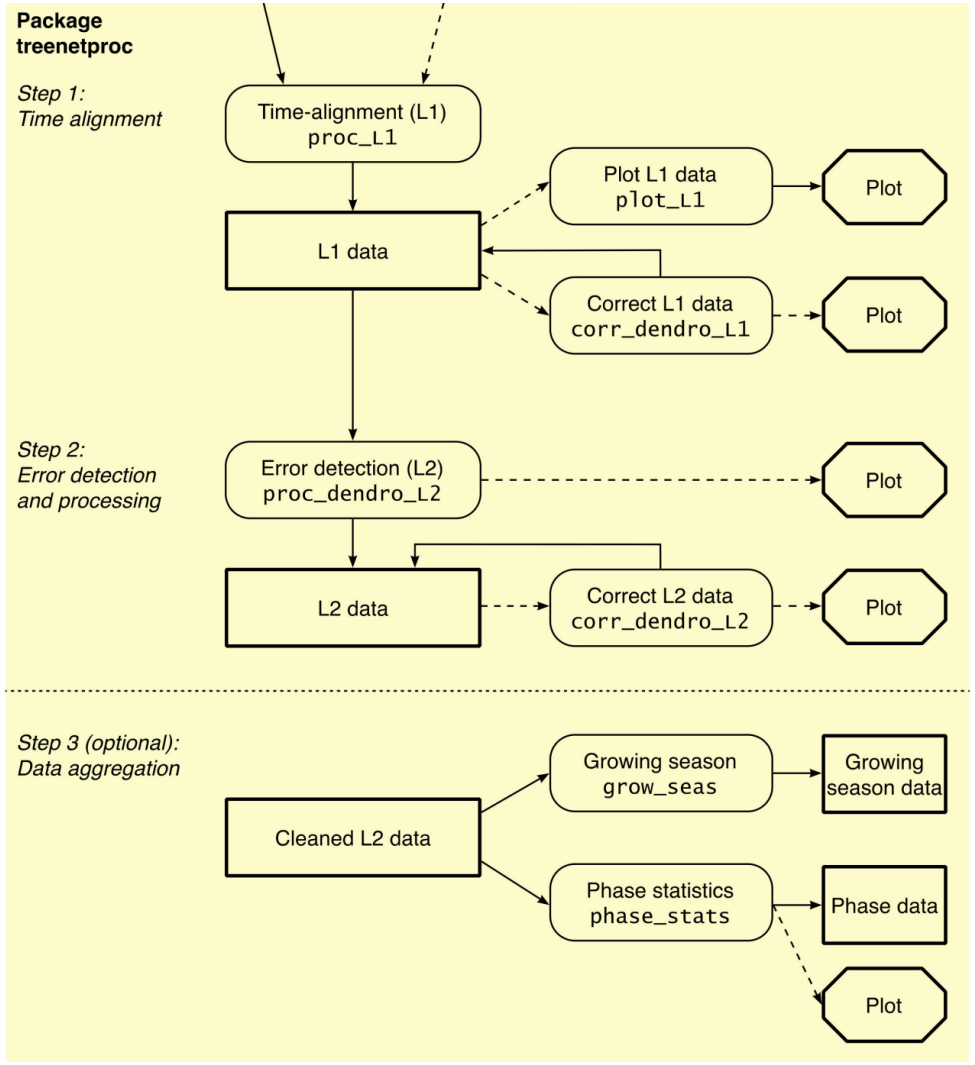
Input – Point dendrometer measurements
dendro_data_L0()

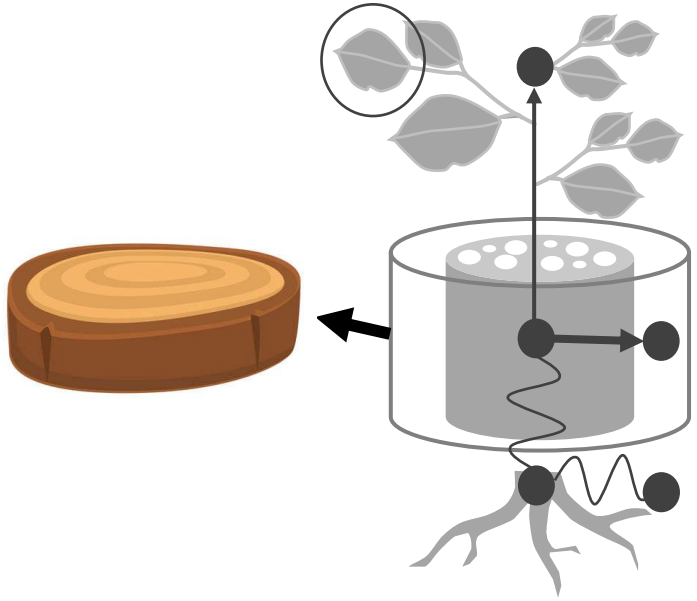




Dendrometer measurements

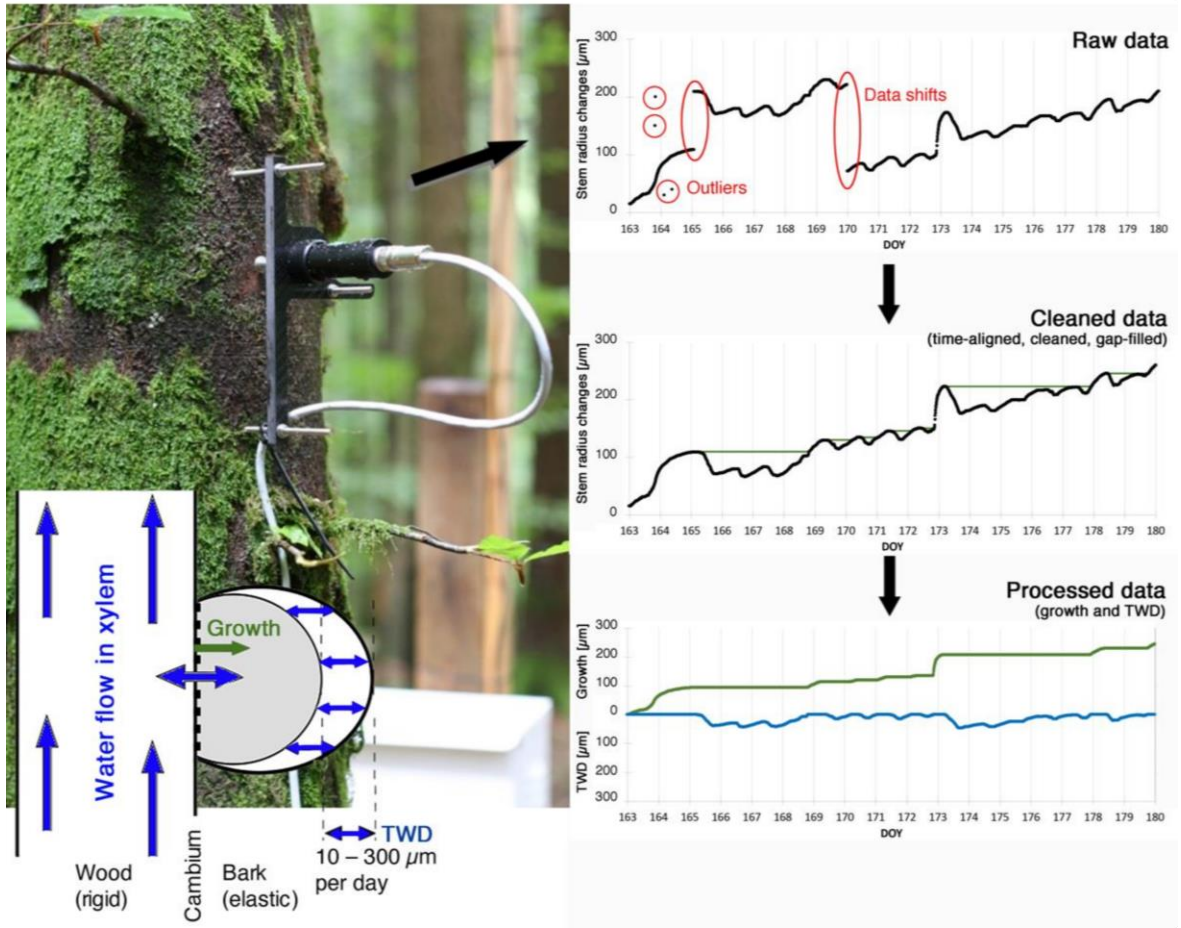
Workflow





Dendrometer measurements

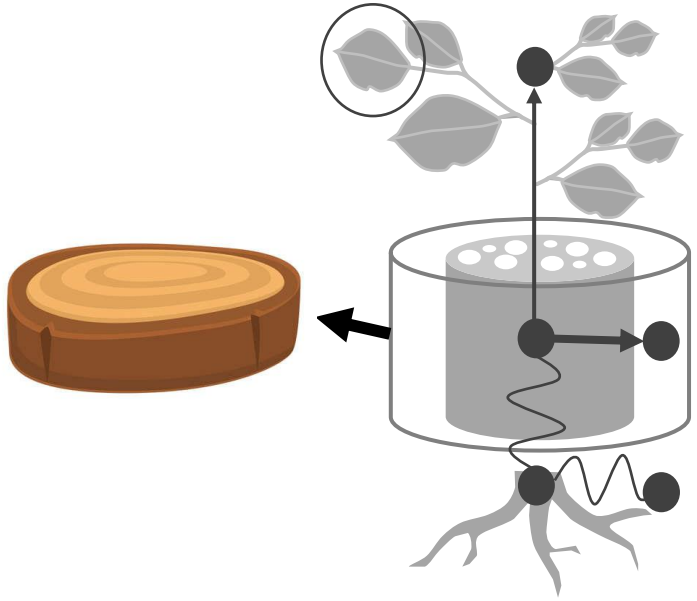
Functionalities – Extracting growth and TWD
proc_dendro_L1()



dendro_data_L0()

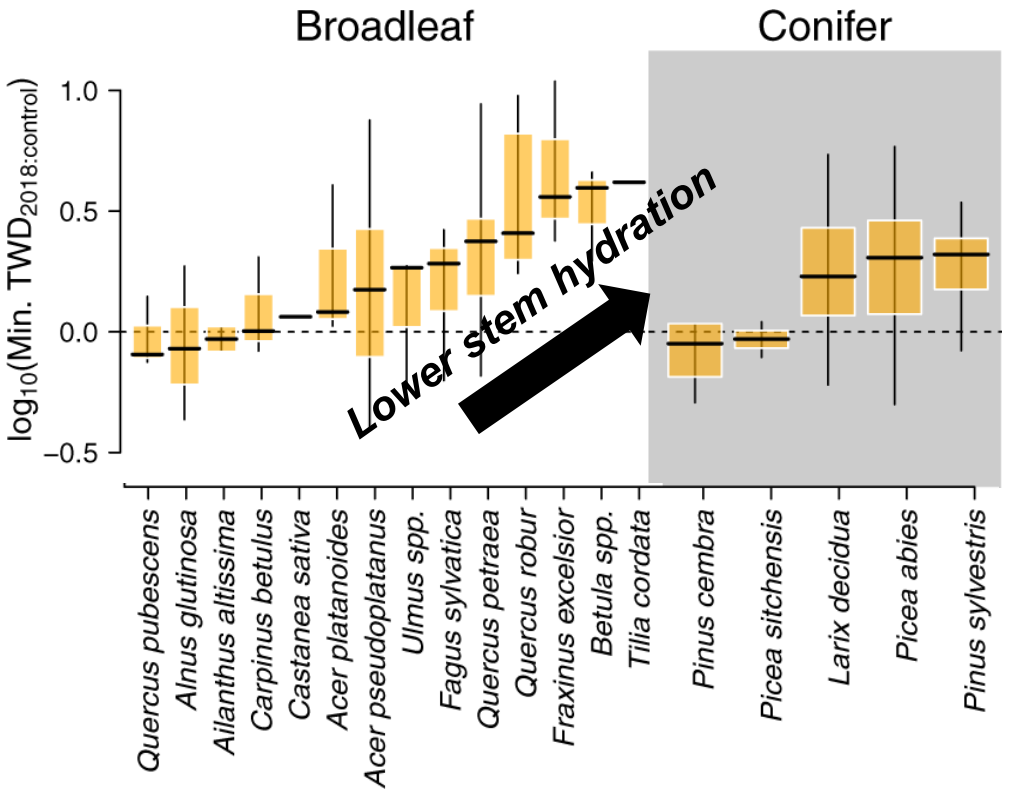
proc_dendro_L1()

proc_dendro_L2()



Dendrometer measurements

Output – Night-time stem shrinkage
proc_dendro_L2()

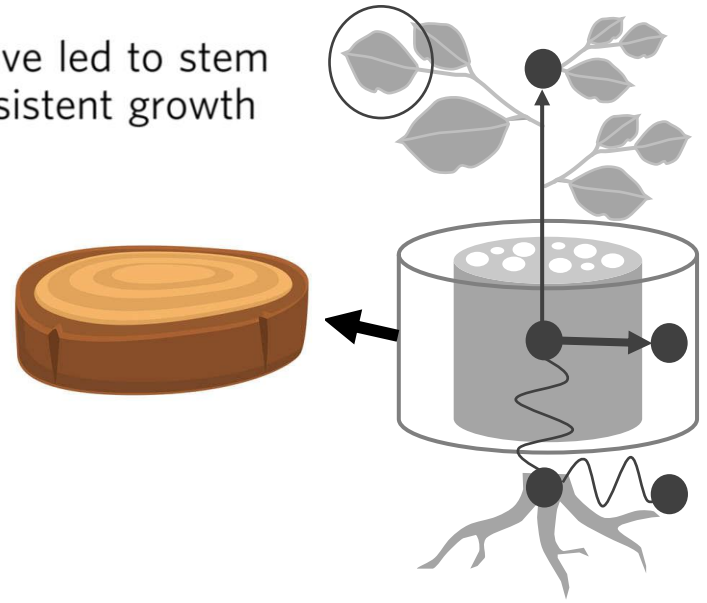


nature COMMUNICATIONS

ARTICLE

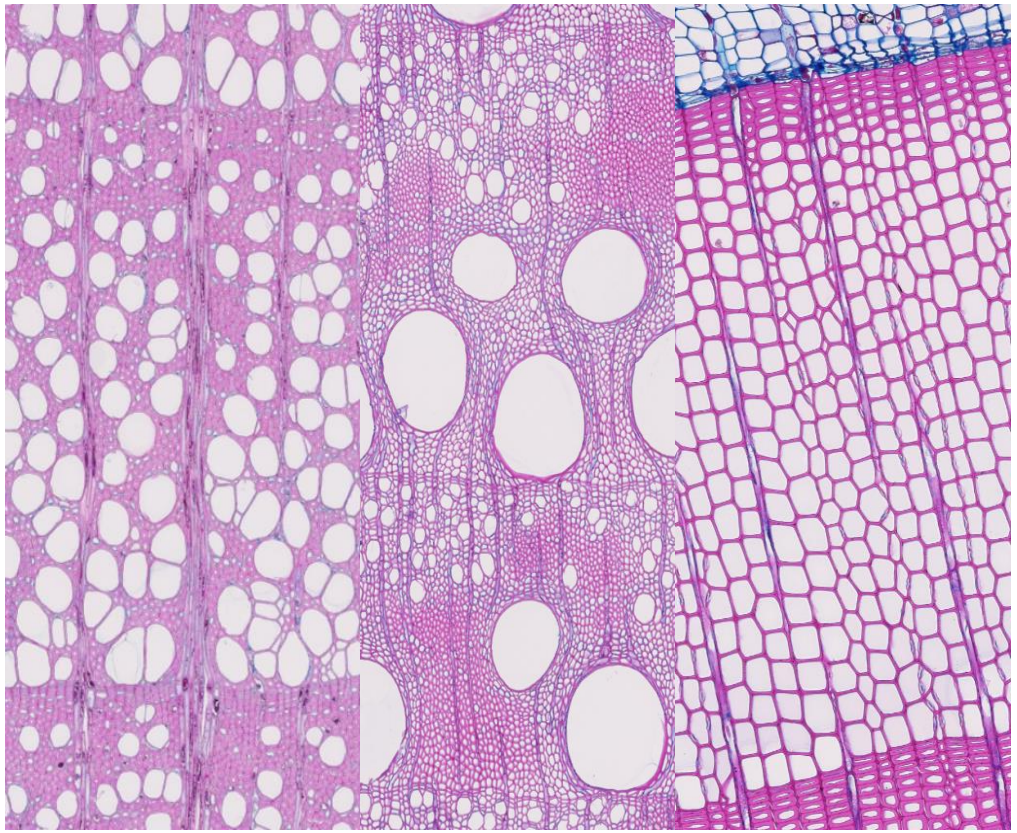
https://doi.org/10.1038/s41467-021-27579-9 OPEN

The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests



Quantitative wood anatomy

Wood anatomy - Utilizing the RAPTOR R package (https://github.com/the-Hull/raptor)



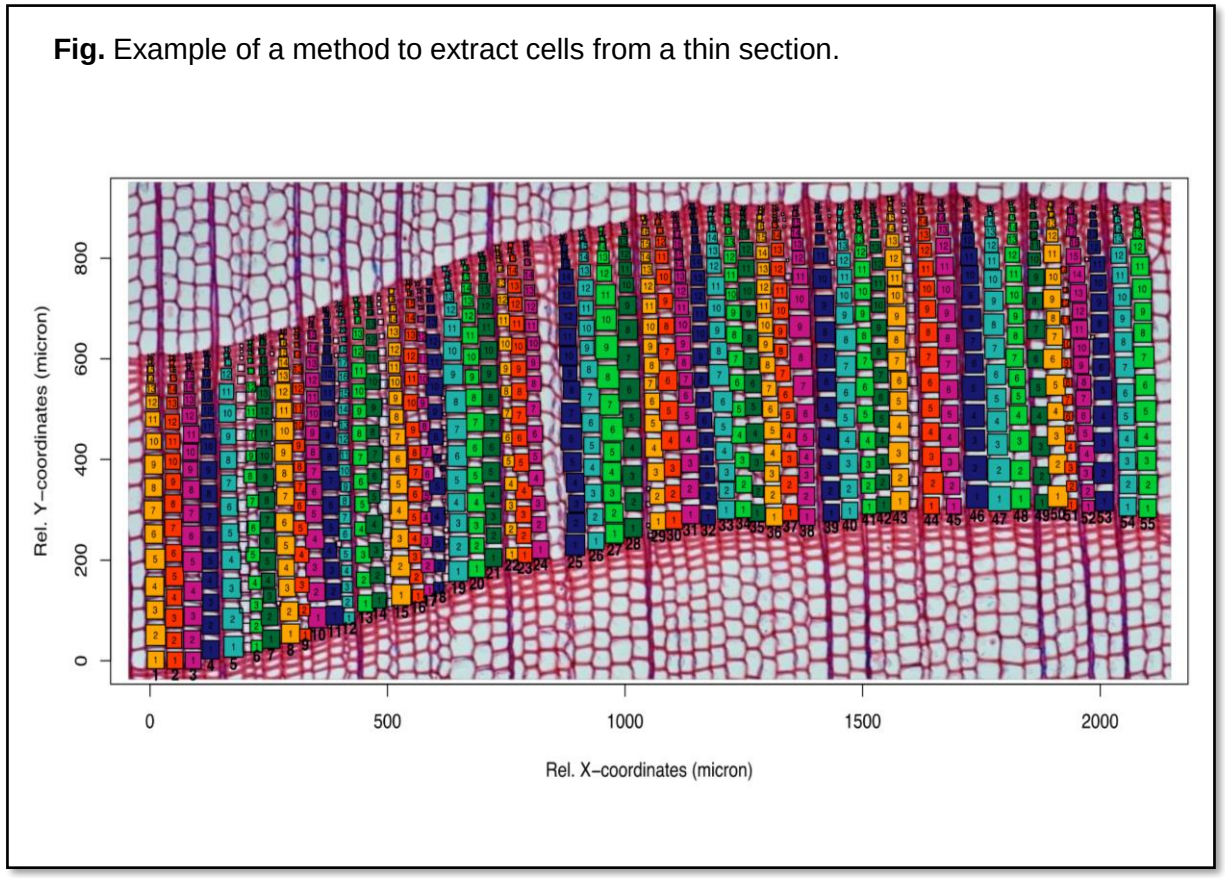
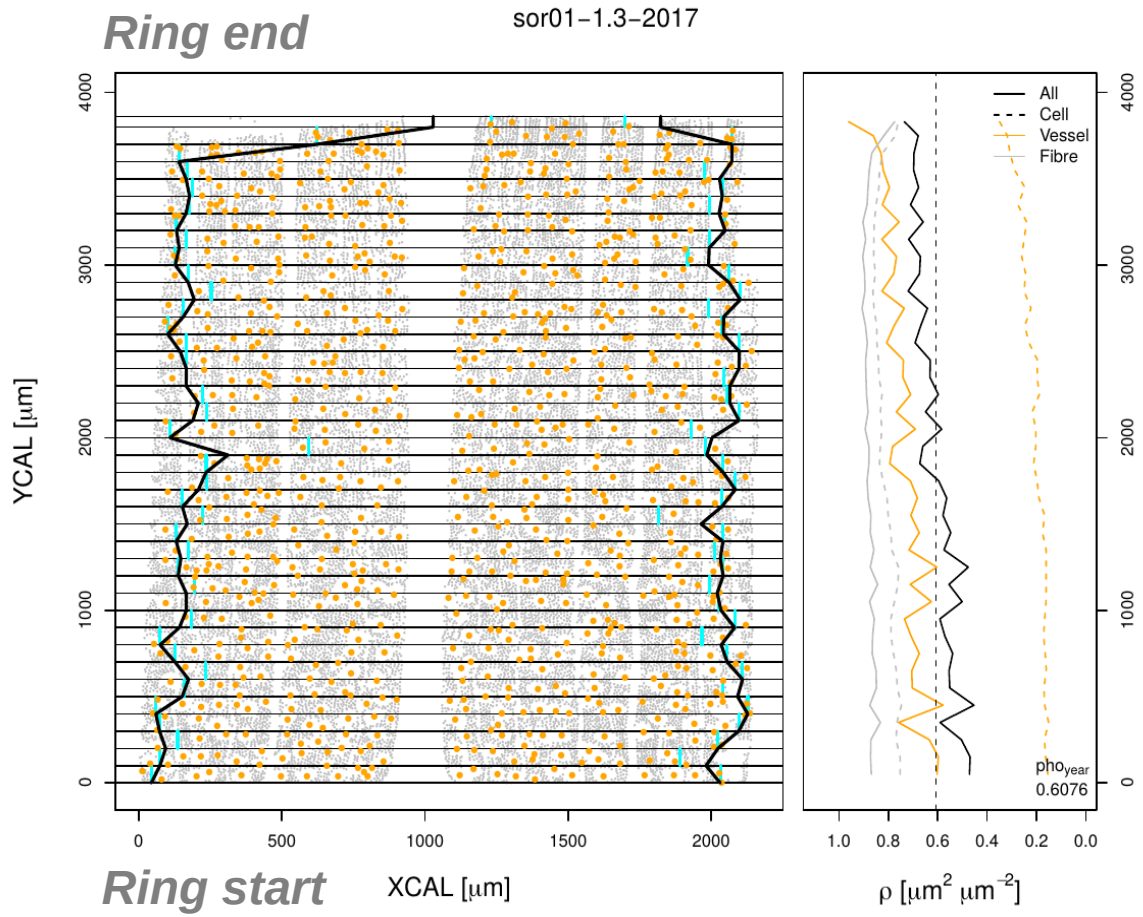
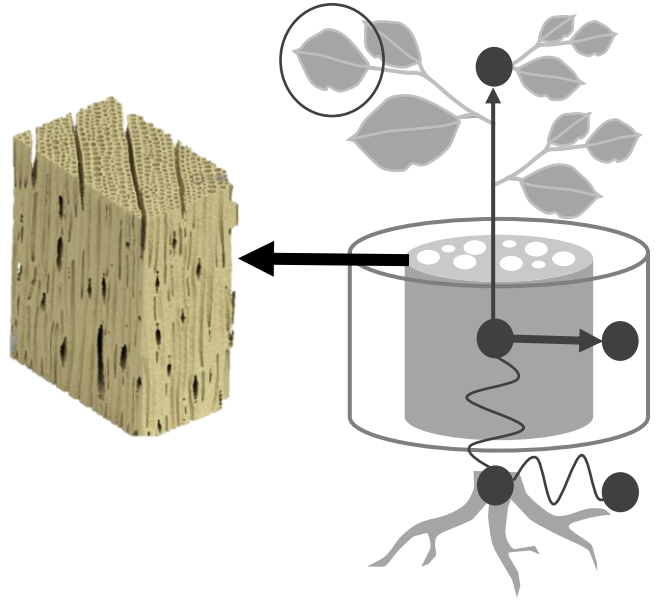


Fig. Example of a method to extract cells from a thin section.

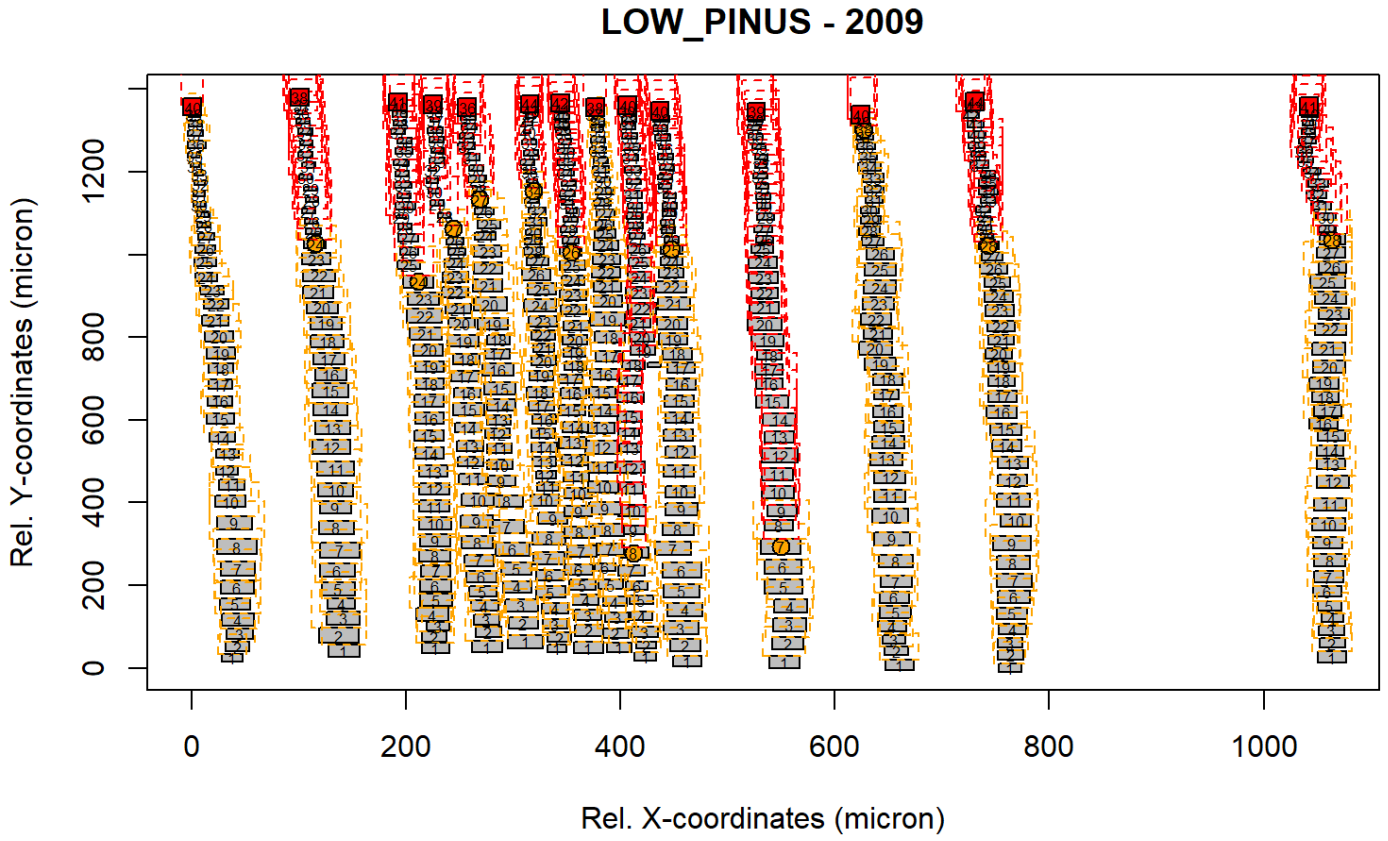
Quantitative wood anatomy

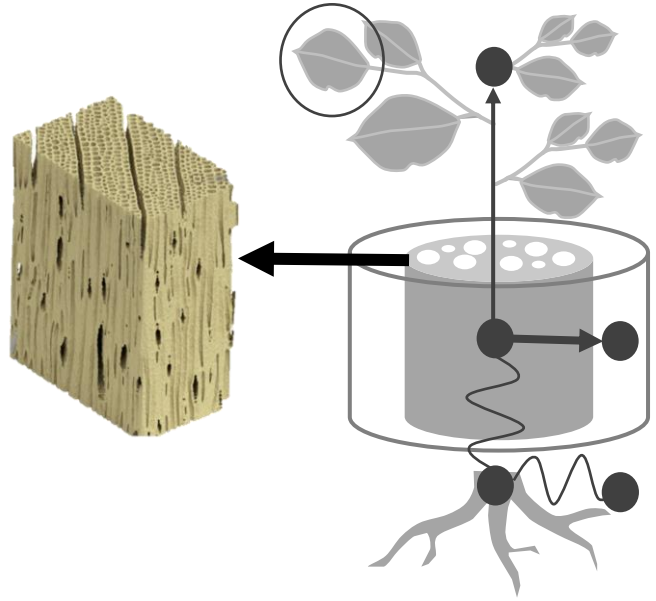
Input – Cell position and properties
example.data()





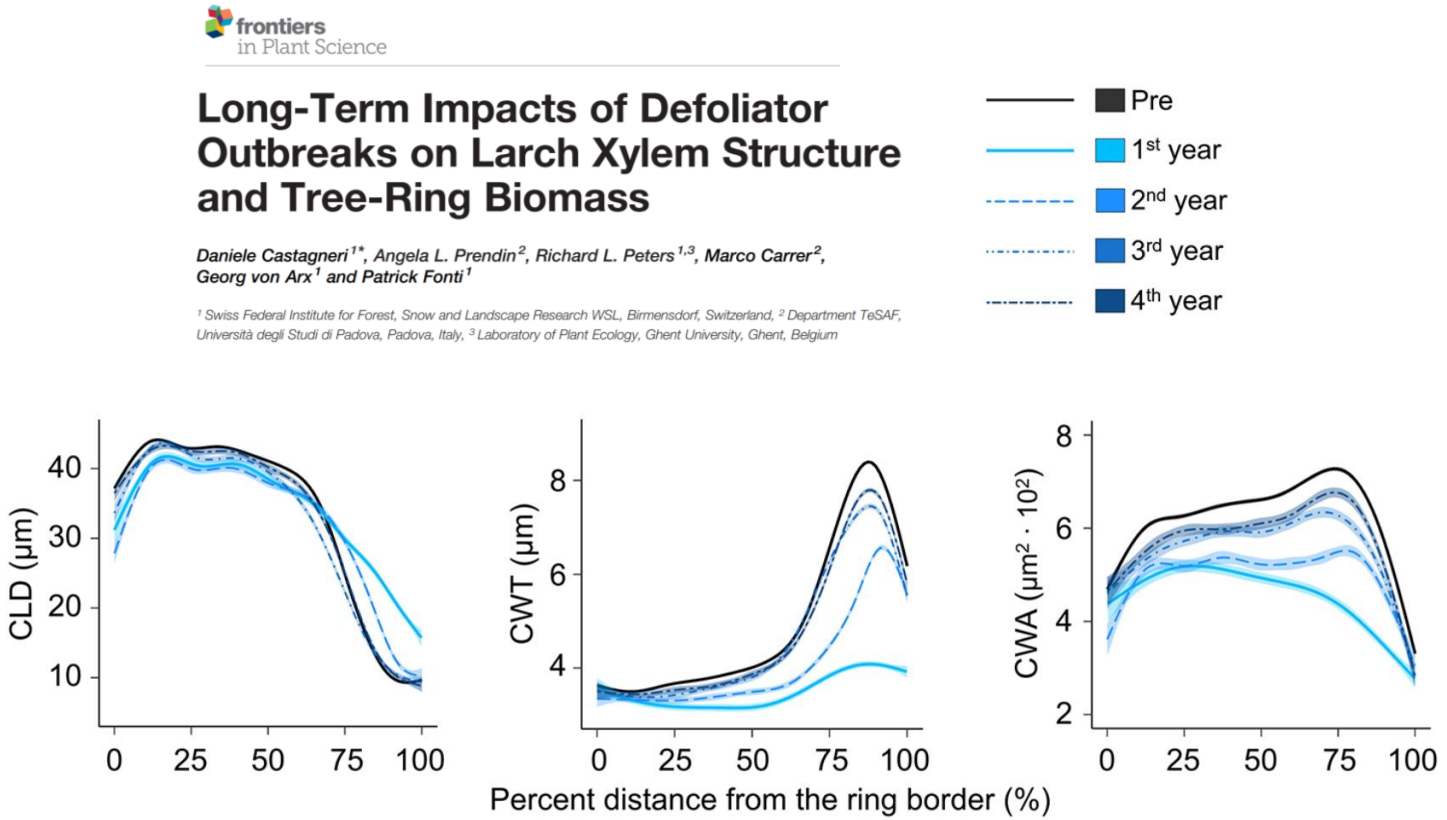
Functionalities – Detection of cell ordering
pos.det()

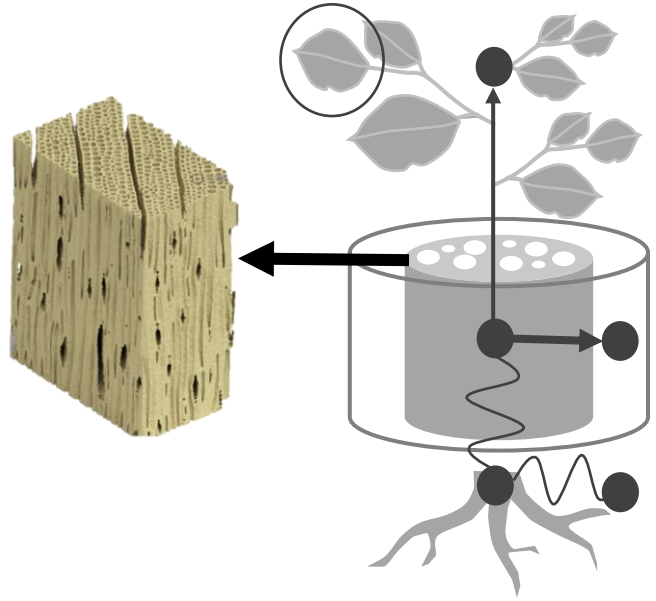




Quantitative wood anatomy

Output – Impact of insect outbreaks on radial profiles
batch.mode()





Data processing | additional resources

dplR -> dendrochrology program library in R
treeclim -> climate correlation functions
dendroTools -> daily resolution analysis of climate-growth relationships
caviar -> tool for processing wood formation data

plantecophys -> basic ecophysiological functions (photosynthesis)
FluxnetLSM -> tool for processing flux tower data
BAAD -> Biomass and allometry database for woody plants
phenor -> phenological modelling

raster -> package for extracting climate data from raster climate products
SPEI -> calculate standardised precipitation-evapotranspiration index
simpleRCRU -> a wrapper function to extract climate data from CRU

Data interpretation

Data interpretation

Hysteresis curves (sub-daily)

Interpretation:
Explore sub-daily lag-effects between forcing (VPD, PAR, etc) and response (e.g., sap flow) associated with tree internal water storage and stomata regulation.

Data:
- Sap flow (TDM)
- VPD and PAR

Analyses:
- `dplyr`
- `ggplot2`

-> see also `hysteresis` package
https://cran.r-project.org/web/packages/hysteresis/vignettes/index.html

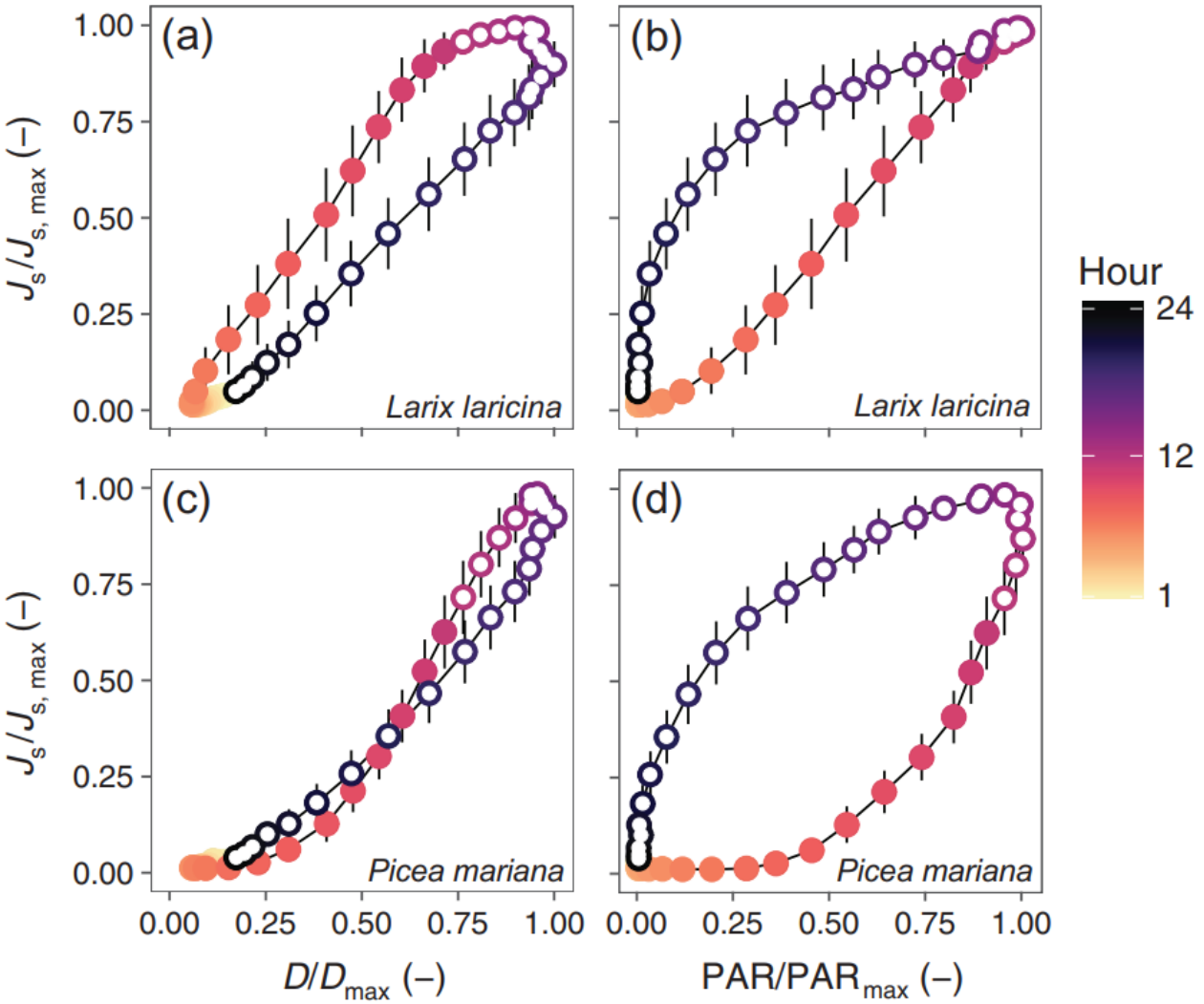


Fig. Hysteresis curves of sap flow vs. environmental drivers (VPD, PAR)
Source: Pappas et al. (2018) doi: https://doi.org/10.1093/treephys/tpy043

Data interpretation

Growth and climate (daily)

Interpretation:
Early wood growth (first 75%, panels A,C,E) decreases considerably with high VPD in early spring and summer for *Picea glauca* in the Boreal Plains (Alberta).

Data:
- Wood anatomy
- Daily climate (daymet; https://daymet.ornl.gov/)

Analyses:
- `RAPTOR`
- `dendroTools`
- `daymetr`

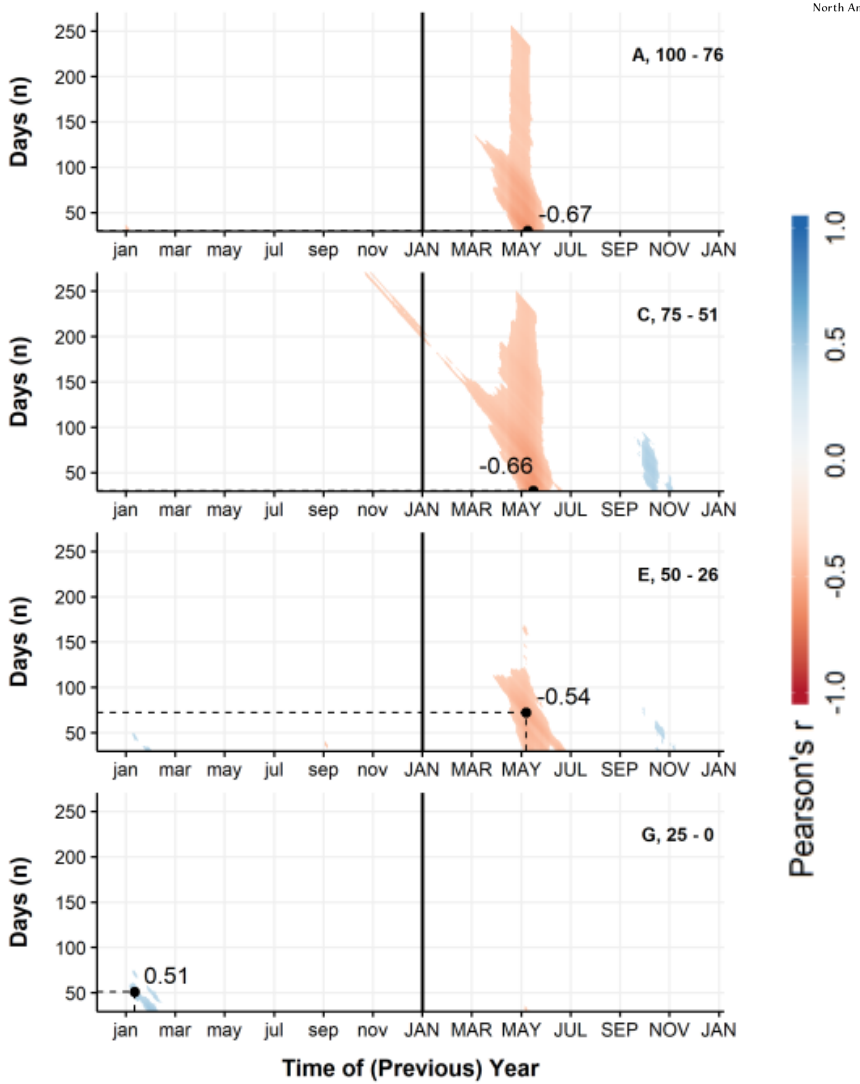


Fig. Moving-window cross-correlation between lumen diameter of the early wood and VPD
Source: Hurley (2020) https://etheses.bham.ac.uk//id/eprint/10413/

Data interpretation

Growth trends (annual)

Interpretation:
Annual growth increments are on average greater for recently planted urban trees, especially during early life stages.

Data:
- Tree growth (BAI) from Berlin averaged across age classes

Analyses:
- `dplR`
- `mgcv` (GAM with autocorrelation structure)

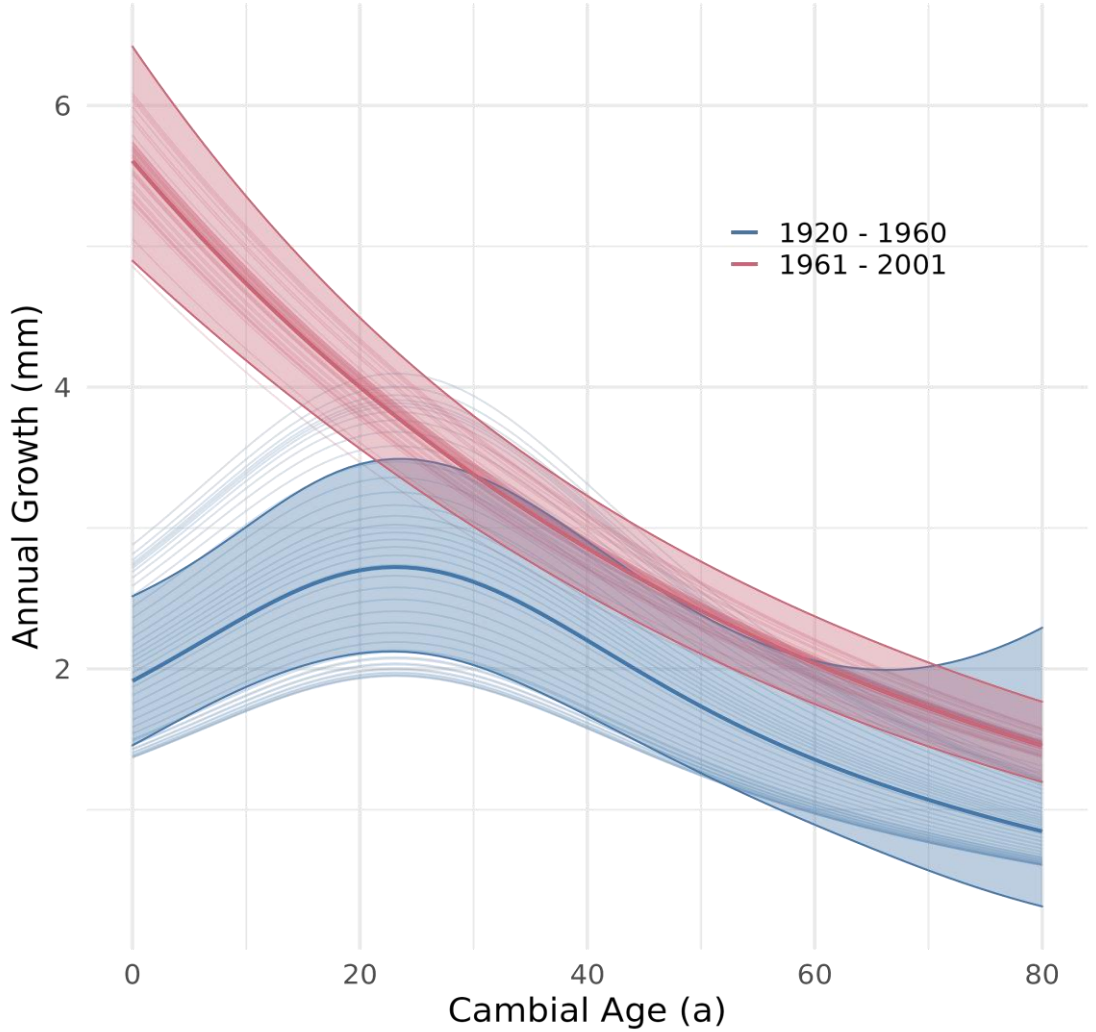


Fig. Trends in annual tree growth in relation to tree age
Source: Hurley (in prep.)

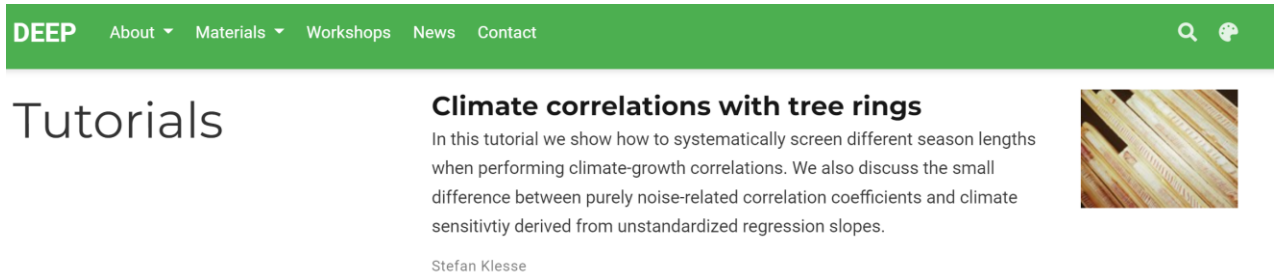
Data interpretation

Climate-growth correlations (annual)

Interpretation:
Pinpoint time-windows that a given climatic variable (P, T, SPEI, WI, etc.) affects most tree growth (TRW).

Data:
- climate data, e.g., daily; E-OBS
  https://www.ecad.eu/download/ensembles/download.php
- tree ring widths (annual)

Analyses:
- step-by-step workflow by S. Klesse @deep
  https://deep-tools.netlify.app/2020/11/26/climcor-intro/



https://deep-tools.netlify.app/2020/11/26/climcor-intro/

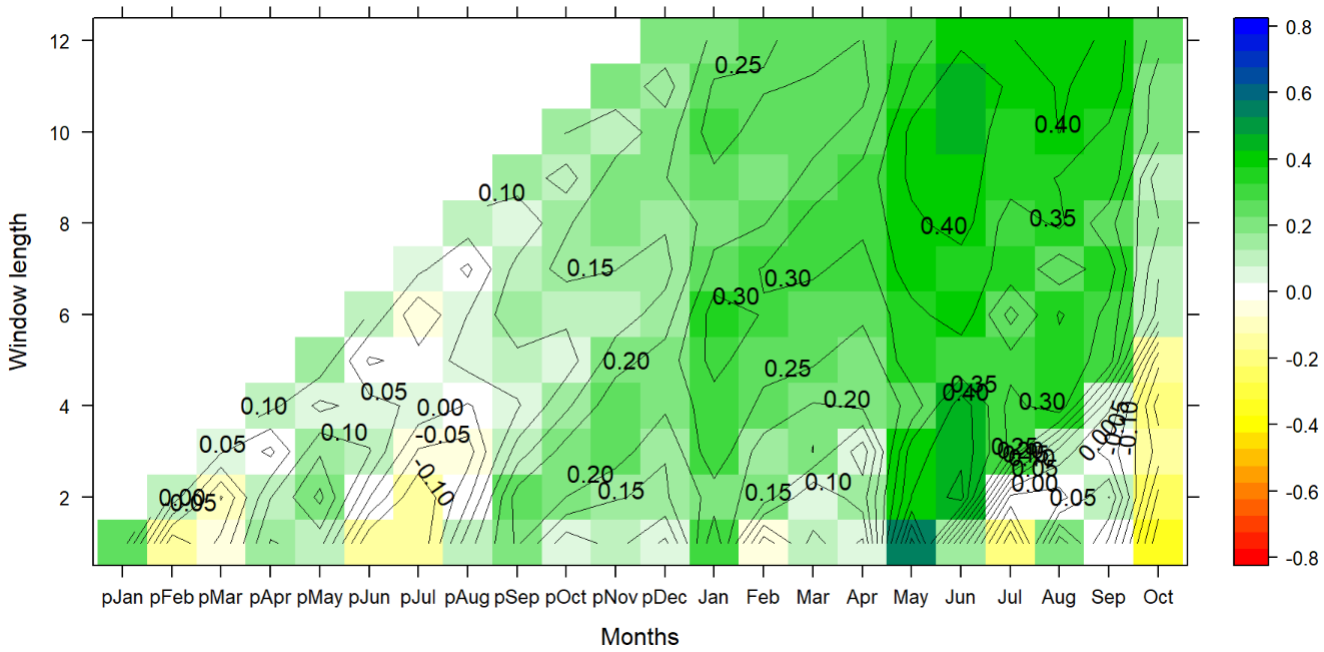


Fig. Monthly precipitation vs Annual tree growth cross-correlations for different time-windows
Source: S. Klesse | https://deep-tools.netlify.app/2020/11/26/climcor-intro/

Data interpretation

Carbon source/sink (seasonal + annual)

Interpretation:
Identify coupling (or decoupling) strength between seasonal C source (GPP) and annual C sink (ring widths)

Data:
- tree rings (annual)
- eddy-covariance-derived GPP (monthly)

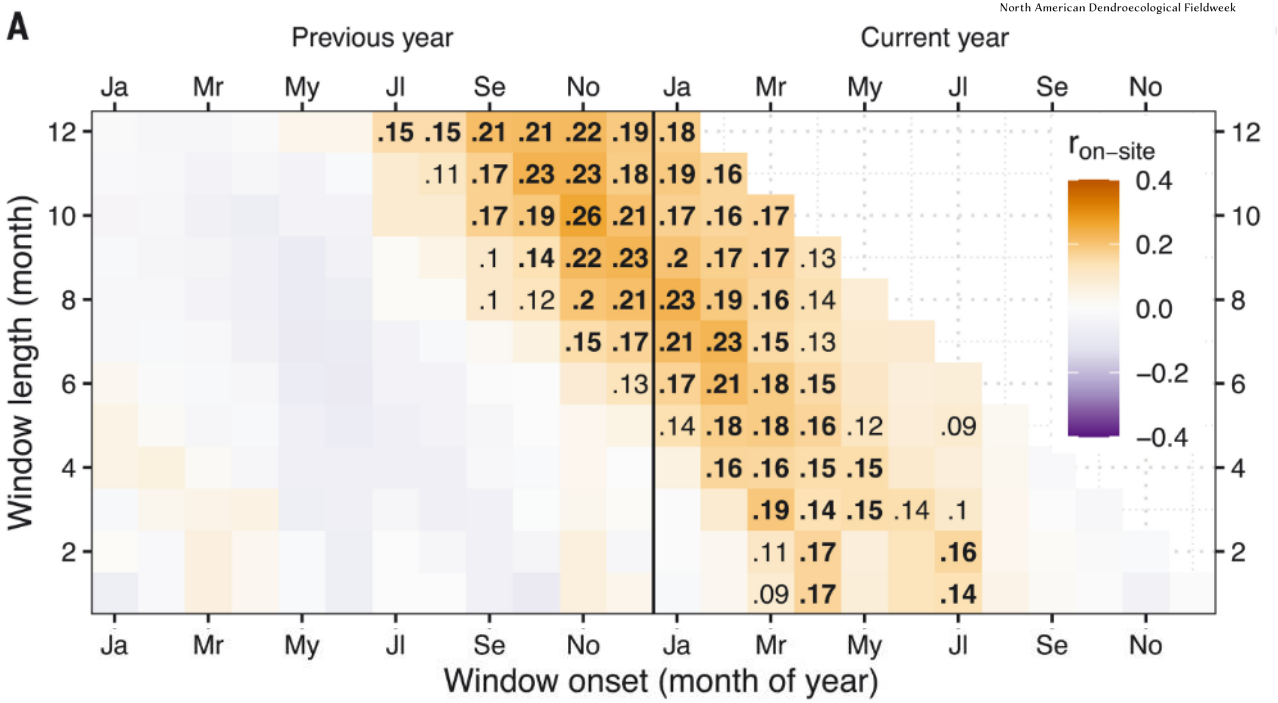


Fig. Moving-window correlation between GPP and TRW
Source: Cabon et al. (2022) doi: 10.1126/science.abm4875

Data interpretation

Climatology (annual)

Interpretation:
Climate space (long-term climatology), co-variation between MAP and MAT, and association with specific spatial extents.

Data:
- WorldClim (https://www.worldclim.org/)
- Shapefiles/AOI

Analyses:
- `raster`
- `ggplot2`

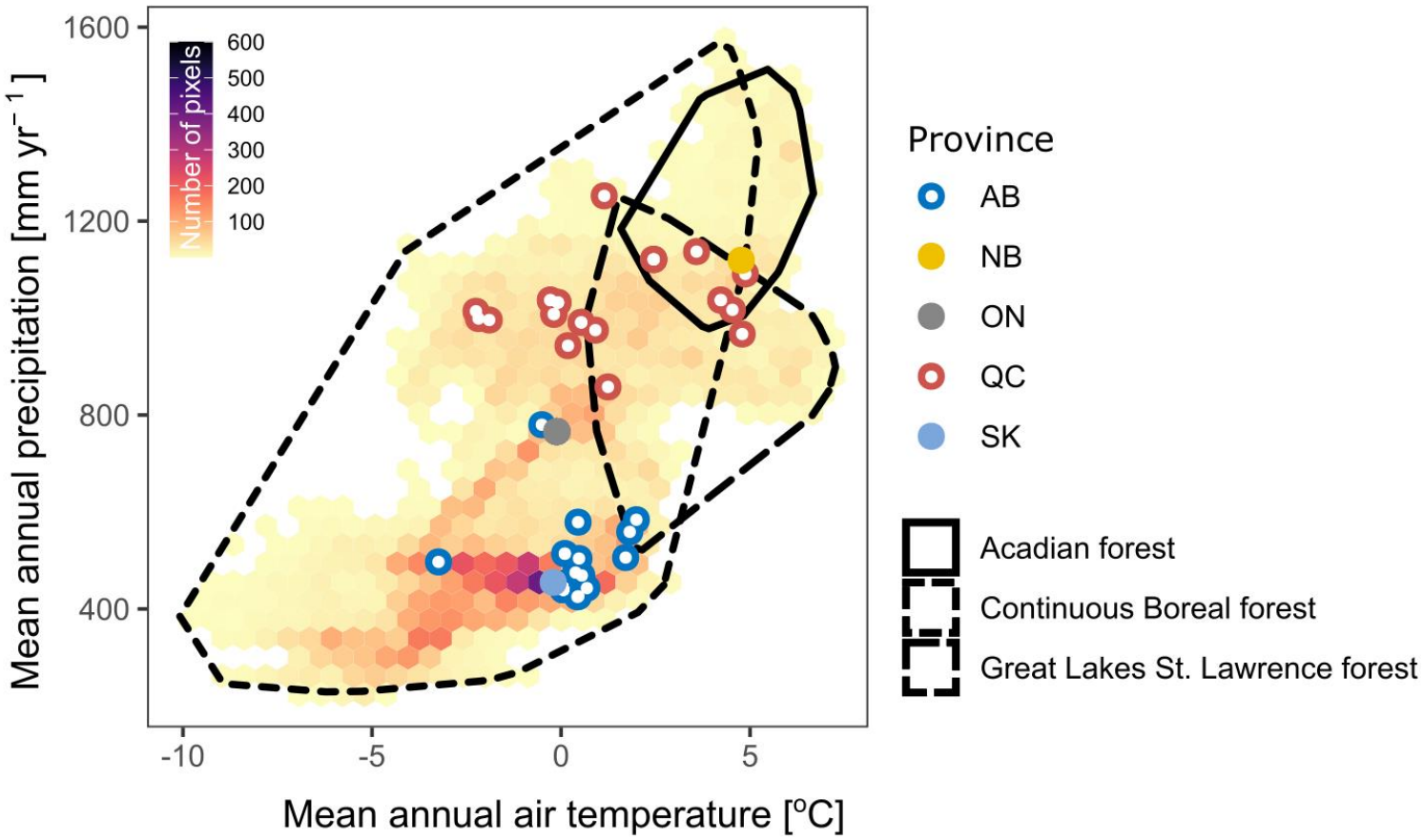


Fig. Climate space and specific site/areas of interest
Source: Pappas et al. (2021) https://link.springer.com/chapter/10.1007/978-3-030-80767-2_16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