Supplementary Materials

Mathematical description of the data preparation algorithms.

Temperature.

Input temperature data:

Raw temperature data T are considered as a set:

$$\mathrm{T} = \left\{ t_{year,doy} \middle| year \in \{1929 \dots 2016\}, doy \in \{1 \dots 365\} \right\},$$

where doy is the name of the Day Of the Year (DOY) variable.

Internal data:

The intra-annual smoothed temperature T_{intra} with the sliding window w (in days) is a set:

$$T_{intra}(w) = \left\{ t^{w}_{year,doy} \middle| year \in \{1929 \dots 2016\}, doy \in \{1 \dots 365\} \right\}$$
$$= \left\{ \frac{\sum_{d \in \left[doy - \left\lfloor \frac{w}{2} \right\rfloor \dots\, doy + \left\lfloor \frac{w}{2} \right\rfloor \right]} t_{year,d}}{w} \middle| \begin{matrix} year \in \{1929 \dots 2016\}, \\ doy \in \{1 \dots 365\} \end{matrix} \right\}$$

- If $i \leq 0$: $t_{year,i} = t_{year-1,365+\,i}$;
- If $i > 365$: $t_{year,i} = t_{year+1,i-365}$
- If $year \notin \{1929 \dots 2016\}$, $t_{year,i}$ is not considered

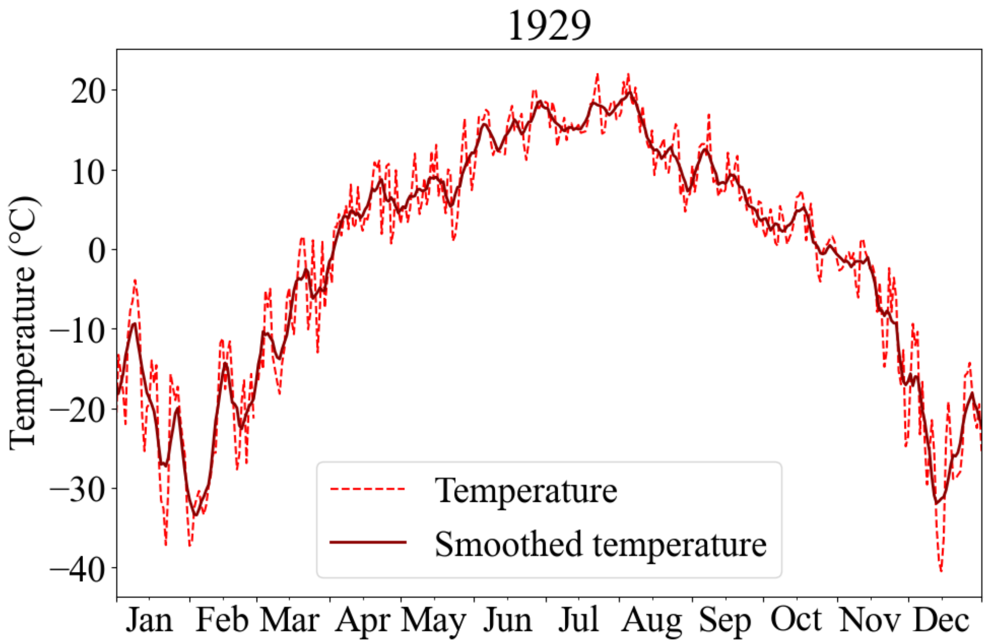

Figure S1. Example of daily (or intra-annual) smoothing. The raw (red dashed) and smoothed (w=7, 1 day step) daily Tashtyp temperature.

Dependent variable:

The inter-annual smoothed temperature T_{inter} with the sliding window W for DOY doy:

$$T_{inter}(w, W, doy) = \left\{t^{w,W}_{year,doy} \middle| year \in \{1929 \dots 2016\}\right\} = \left\{\frac{\sum_{y \in \left[year - \left\lfloor \frac{W}{2} \right\rfloor \dots year + \left\lfloor \frac{W}{2} \right\rfloor\right]} t^{w}_{y,doy}}{W} \middle| year \in \{1929 \dots 2016\}\right\},$$

where $doy \in DOY_{sig}(w, W)$;

$DOY_{sig}(w, W) \subseteq \{152, \dots, 243\}$ (the subset of tree-ring growing days (growing season)) is the set of DOYs for which the Pearson correlation between the inter-annual and the intra-annual smoothed temperatures ($\left\{t^{w,W}_{year,doy} \middle| year \in \{1929 \dots 2016\}\right\}$ and $\left\{t^{w}_{year,doy} \middle| year \in \{1929 \dots 2016\}\right\}$) was significant (p<0.001) (see Figure S3 and an example in Table S3)

In other terms, for each set of w, W, $|DOY_{sig}(w, W)|$ time series were obtained.

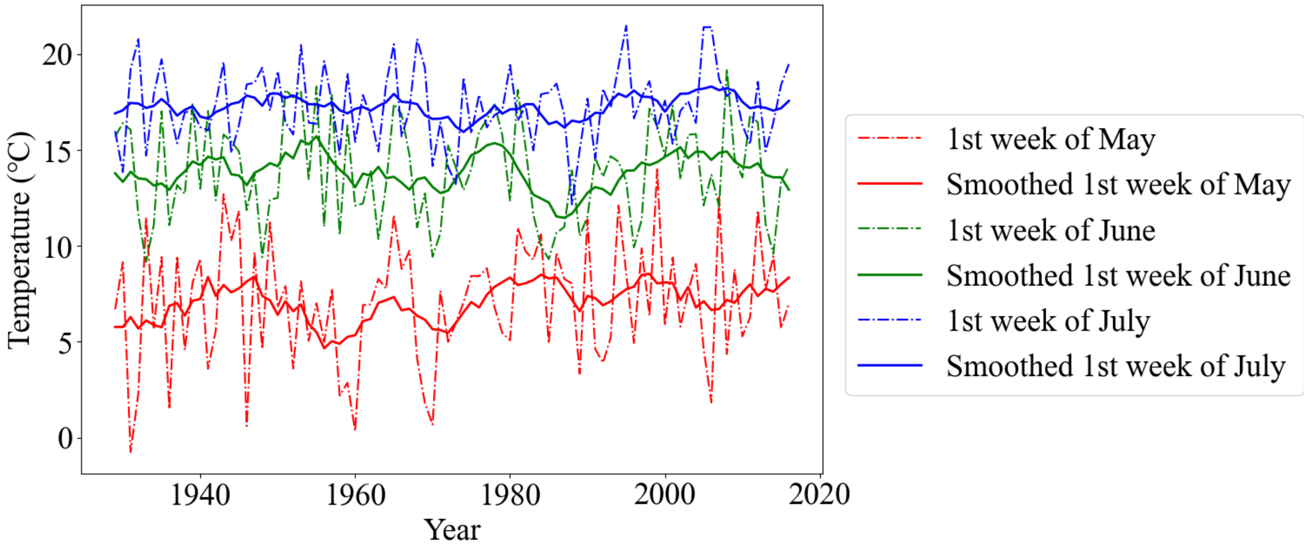

Figure S2. Example of unsmoothed and 9-year (or inter-annual) smoothing of temperature characteristics: mean values of the 1st week of May (red dotted curve), June (green dotted curve) and July (blue dotted curve) and their smoothed analogs (solid thick lines), respectively.

Table S1. Examples of the temperature time series $T_{inter}(w, W, doy)$ for $w = 7, W = 9, |DOY_{sig}(7, 9)| = 63$

Year	$\boldsymbol{T_{inter}(7, 9, 152)}$	**…**	$\boldsymbol{T_{inter}(7, 9, 243)}$
1929	12.328571	…	10.622857
…	…	…	…
2016	11.374286	…	10.622857

Tracheids data.

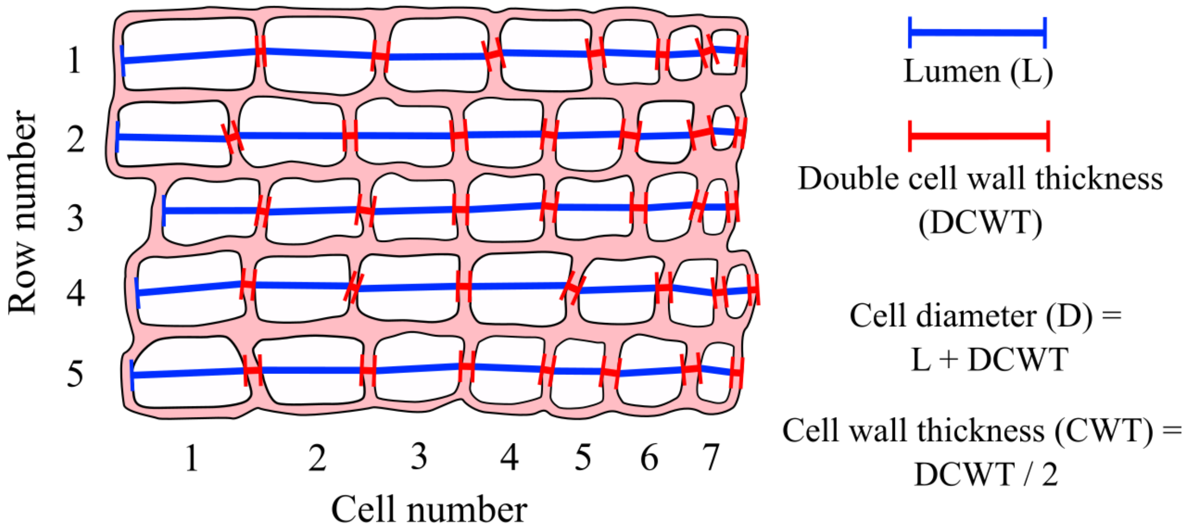

Figure S3. Example of cell measurements for the year 1653 of Tree №2.

Input data.

1. $T = \{t_1, \ldots, t_7\}$ is the set of trees.
2. $Y(t) = \{y_{t1}, \ldots, y_{tn_t}\}$ is the set of years for which the cell measurements for the tree t are available, $t \in T$
3. $Y = \bigcup_{t \in T} Y(t) = \{1653, \ldots, 2018\}$ is the set of the years for which the measurements are available.
4. $T(y) = \{t_{y1}, \ldots, t_{ym_y}\}$ is the set of trees for which the measurements for the year y are availvable, $y \in Y$

$$\left(T \equiv \bigcup_{y \in Y} T(y)\right)$$

5. $e^{raw} = e^{raw}(t, y) = \{e_1^{raw}, \ldots, e_\varepsilon^{raw}\}$ are the raw tracheid data where:

$$e_k^{raw} = e_k^{raw}(t, y) \in \{d_k^{raw}, c_k^{raw}\}$$

$d_k^{raw} = d_k^{raw}(t, y)$ is the diameter of the k^{th} cell in a raw tracheid

$c_k^{raw} = c_k^{raw}(t, y)$ is the cell wall thickness of the k^{th} cell in a raw tracheid

$\varepsilon = \varepsilon(t, y)$ is the number of cells in $e^{raw}(t, y)$

$$k = \overline{1, \varepsilon}, t \in T, y \in Y(t)$$

6. $n = 15$ is the number of cells for the tracheid standardization procedure.

Description of the standardization procedure.

For each e^{raw} an intermediate sequence e^* is constructed as a set:

$$e^* = \{\underbrace{e_1^{raw}, \ldots, e_1^{raw}}_{n}, \underbrace{e_2^{raw}, \ldots, e_2^{raw}}_{n}, \ldots, \underbrace{e_\varepsilon^{raw}, \ldots, e_\varepsilon^{raw}}_{n}\}$$

The tracheid data $e = \{e_1, \ldots, e_n\}$ standardized to n cells are obtained by:

$$e_i = \frac{1}{\varepsilon} \sum_{j=\varepsilon\cdot(i-1)+1}^{\varepsilon\cdot i} e_j^*, i = \overline{1, n}$$

Using this procedure, the following sets were obtained:

$d = \{d_1, \ldots, d_n\}$ are the tracheid cell diameters standardized to n cells;

$c = \{c_1, \ldots, c_n\}$ are the tracheid cell wall thicknesses standardized to n cells.

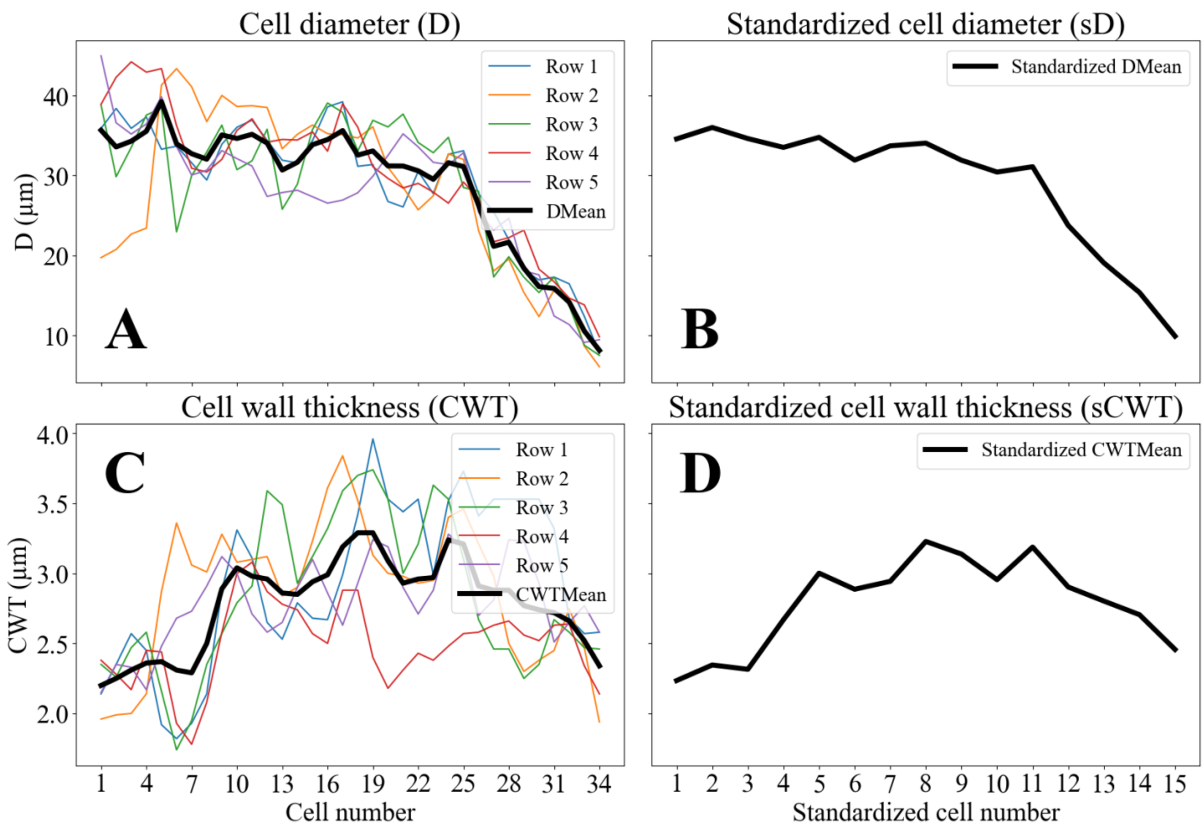

Figure S4. Dmean (A) and CWTmean (C) tracheidograms for the year 1653 of Tree №1, and their standardization to 15 cells (B,D).

Description of the standardized tracheidogram.

A tracheidogram standardized to N cells is considered as a set:

$$R(t, y) = d \cup c = \{d_1, \ldots, d_n, c_1, \ldots, c_n\},$$

where:

$d_i = d_i(t, y)$ is the diameter of the i^{th} cell in the standardized tracheidogram;

$c_i = c_i(t, y)$ is the cell wall thickness of the i^{th} cell in the standardized tracheidogram;

$i = \overline{1,n}, t \in T, y \in Y(t)$.

Developing annual (year-to-year) mean standardized tracheidograms.

A mean standardized tracheidogram $R_{mean}(y)$ is obtained as a simple average of individual $R(t,y)$ for each tree:

$$R_{mean}(y) = \frac{1}{|T(y)|} \sum_{t \in T(y)} R(t,y)\,, y \in Y.$$

$R_{mean}(y)$ can be considered as a set:

$$R_{mean}(y) = \{d_1^{mean}(y), \ldots, d_n^{mean}(y), c_1^{mean}(y), \ldots, c_n^{mean}(y)\},$$

where $y \in \{1653, \ldots, 2018\}$ is the year over 1653-2018 (see Table S4).

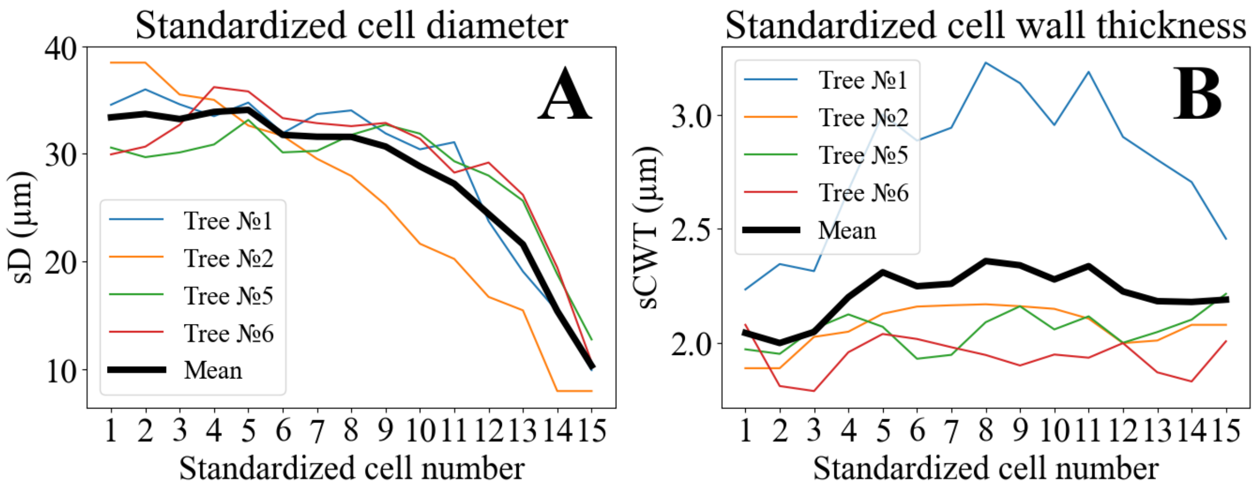

Figure S5. Example of the mean standardized tracheidograms (thick black curves) for the 1653 year: radial cell diameter (A) and cell wall thickness (B).

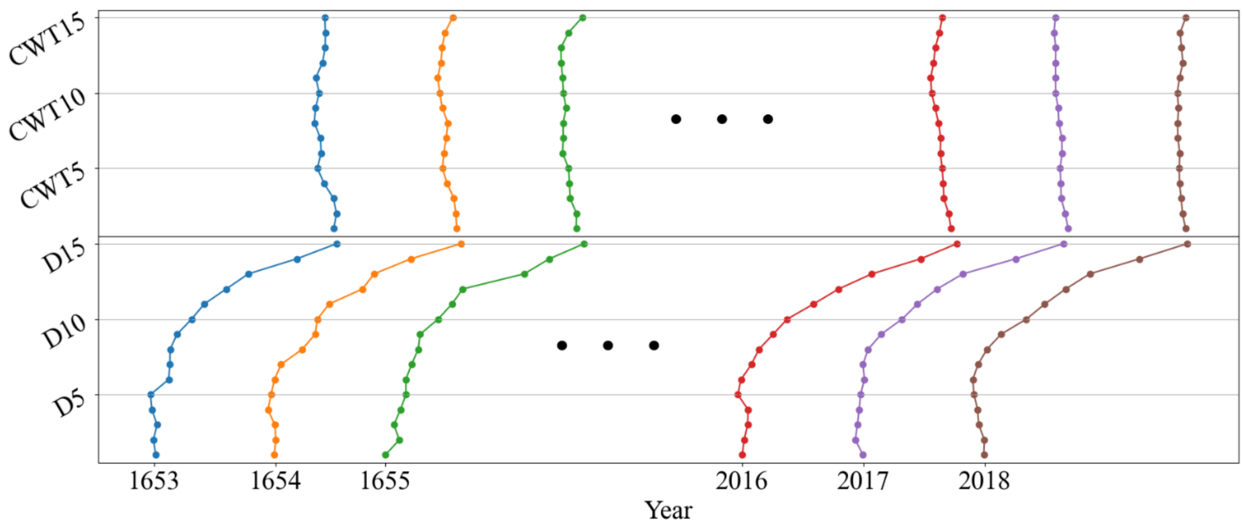

Figure S6. Obtained tracheidogram objects

Table S2. Examples of thirty ($2 \cdot n = 30$) mean tracheidogram chronologies

Year	$\boldsymbol{d_1^{mean}}$	**…**	$\boldsymbol{d_n^{mean}}$	$\boldsymbol{c_1^{mean}}$	**…**	$\boldsymbol{c_n^{mean}}$
1653	33.396263	…	10.315296	2.044464	…	2.190193
…	…	…	…	…	…	…
2018	36.341875	…	10.376250	2.311458	…	2.308333

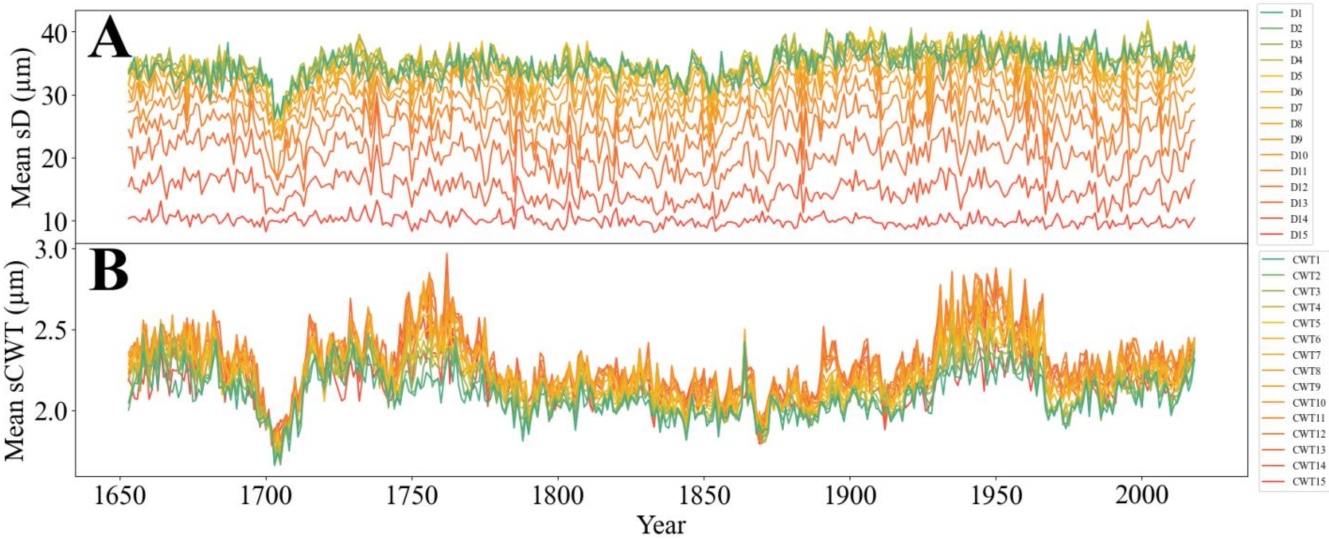

Figure S7. The obtained 30 cell chronologies: 15 mean standardized cell diameters (A) and corresponding 15 cell wall thicknesses (B).

Then, inter-annual smoothed tracheid chronologies (d_i^W, c_i^W) with the sliding window W were obtained by:

$$d_i^W = \left\{ \frac{\sum_{y \in \left[year - \left\lfloor \frac{W}{2} \right\rfloor \dots\, year + \left\lfloor \frac{W}{2} \right\rfloor\right]} d_i^{mean}(y)}{W} \middle| year \in \{1929 \dots 2016\} \right\},$$

$$c_i^W = \left\{ \frac{\sum_{y \in \left[year - \left\lfloor \frac{W}{2} \right\rfloor \dots\, year + \left\lfloor \frac{W}{2} \right\rfloor\right]} c_i^{mean}(y)}{W} \middle| year \in \{1929 \dots 2016\} \right\},,$$

where $i = \overline{1, n}$.

Table S3. Example of inter-annual smoothed tracheid chronologies for $W = 9$

Year	$\boldsymbol{d_1^9}$	**…**	$\boldsymbol{d_n^9}$	$\boldsymbol{c_1^9}$	**…**	$\boldsymbol{c_n^9}$
1653	33.951284	…	10.281403	2.142082	…	2.140274
…	…	…	…	…	…	…
2018	36.376124	…	9.802172	2.199169	…	2.258423

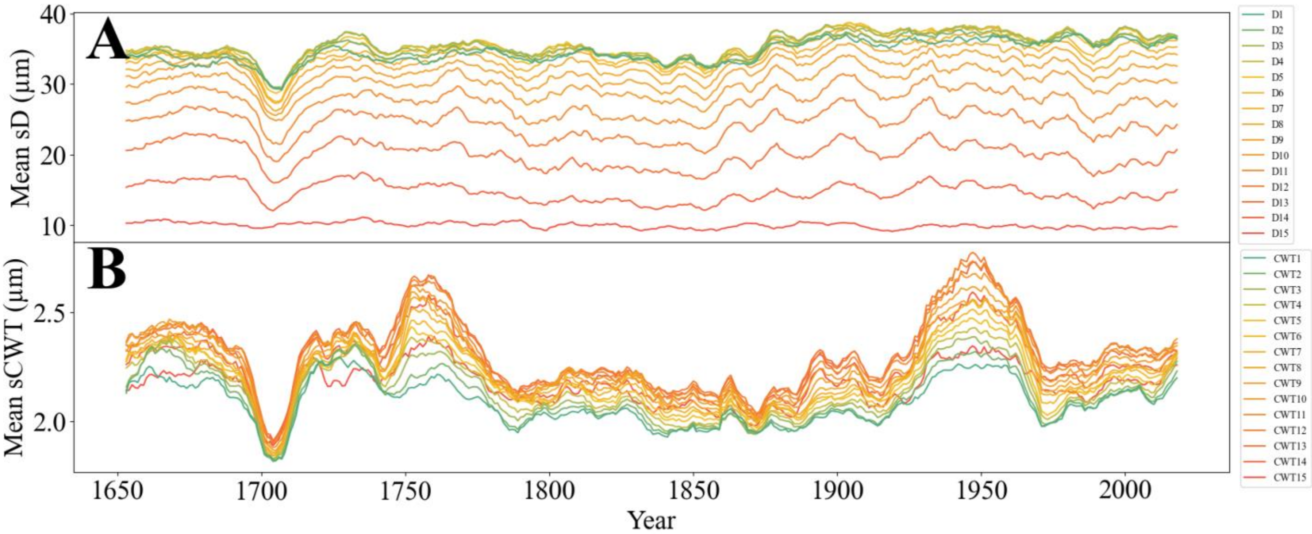

Figure S8. Example of 9-year smoothed cell chronologies: mean standardized cell diameters (A) and corresponding cell wall thicknesses.

For the obtained inter-annual smoothed tracheid chronologies (Table S5) we used the principal component analysis and obtained $2 \cdot n = 30$ PC chronologies (see Table S6).

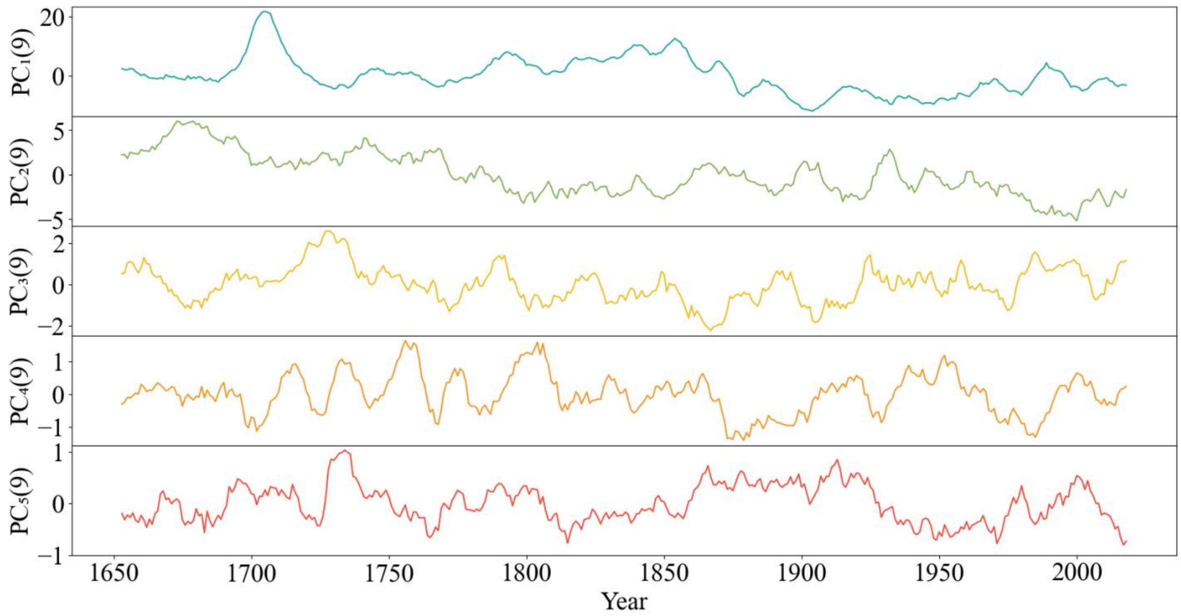

Figure S9. First five principal components (PC) of the smoothed (9-year sliding window) tracheid chronologies.

Table S4. Example of PC chronologies for $W = 9$

Year	$\boldsymbol{PC_1(9)}$	**…**	$\boldsymbol{PC_{2\cdot n}(9)}$
1653	4.280042	…	0.001796
…	…	…	…
2018	-7.254340	…	-0.009413

In other terms:

$$PC_i(W) = \left\{ pc_i^W(y) \middle| y \in \{1653 \dots 2016\} \right\},$$

where $i = \overline{1, n}$.

Independent variables:

The inter-annual smoothed PC chronologies with the sliding window W:

$$PC_i(W) = \left\{ pc_i^W(y) \middle| y \in \{1653 \dots 2016\} \right\},$$

where $i = \overline{1, P}$;

P is the number of fist principal components for regression model development, which was varied from 4 (90% of the explained variance) to 9 (99% of the explained variance).

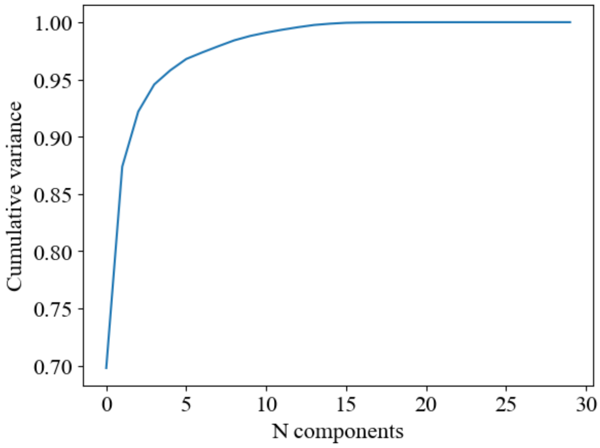

Figure S10. Cumulative explained variance of the tracheidogram objects

Table S5. PCA transformation matrix for first five principal components

Tracheid feature	PC1	PC2	PC3	PC4	PC5
D1	-0.217	-0.319	0.248	-0.430	-0.476
D2	-0.245	-0.239	0.331	-0.245	-0.146
D3	-0.268	-0.210	0.330	-0.046	0.294
D4	-0.275	-0.202	0.190	0.109	0.354
D5	-0.292	-0.217	0.087	0.232	0.225
D6	-0.309	-0.184	-0.110	0.370	0.069
D7	-0.293	-0.112	-0.298	0.306	-0.201
D8	-0.299	-0.029	-0.326	0.099	-0.126
D9	-0.298	0.064	-0.300	-0.106	-0.077
D10	-0.281	0.143	-0.221	-0.286	-0.116
D11	-0.293	0.289	-0.210	-0.170	0.145
D12	-0.270	0.378	0.068	-0.249	0.154
D13	-0.206	0.480	0.231	0.009	-0.100
D14	-0.129	0.403	0.418	0.313	-0.032
D15	-0.008	0.109	0.124	0.016	0.070

CWT1	-0.010	0.015	0.052	0.069	-0.084
CWT2	-0.011	0.021	0.058	0.082	-0.098
CWT3	-0.012	0.022	0.058	0.094	-0.115
CWT4	-0.012	0.022	0.053	0.103	-0.125
CWT5	-0.013	0.021	0.053	0.106	-0.134
CWT6	-0.014	0.020	0.052	0.109	-0.147
CWT7	-0.014	0.019	0.050	0.116	-0.163
CWT8	-0.014	0.020	0.050	0.119	-0.174
CWT9	-0.015	0.021	0.049	0.119	-0.190
CWT10	-0.016	0.020	0.053	0.122	-0.191
CWT11	-0.016	0.020	0.053	0.121	-0.191
CWT12	-0.017	0.019	0.048	0.117	-0.182
CWT13	-0.016	0.020	0.048	0.111	-0.175
CWT14	-0.014	0.018	0.045	0.092	-0.151
CWT15	-0.009	0.011	0.029	0.065	-0.105

Modeling

For the best model fit a triplet of hyperparameters (w, W, P) was varied as follows: $w \in \{1, \dots, 14\}, W \in \{1, \dots, 11\}, P \in \{4, \dots, 9\}$

For each triplet (w, W, P) we obtained the set of independent variables $PC_1(W), \dots, PC_P(W)$ and the set of dependent variables $T_{inter}(w, W, doy), doy \in DOY_{sig}(w, W)$.

For each $doy \in DOY_{sig}(w, W)$ a separate multiple linear regression (MLR) model $MLR_{w,W,P,doy}(year)$ was developed.

The final MLR models were considered as ensembles of the individual MLR models obtained in the rolling leave-one-out cross-validation (RLOO CV) procedure:

$$MLR_{w,W,P,doy}(year) = k_0 + \sum_{l=1}^{P} k_l \cdot pc_i^W(y),$$

where: $k_l = k_l(w, W, P, doy) = \frac{\sum_{\theta=1}^{N(W)} k_l^\theta}{N}, l = \overline{0, P}$;

$k_l^\theta = k_l^\theta(w, W, P, doy)$is the l^{th} coefficient of the θ^{th} individual MLR model, obtained in the RLOO CV procedure.

$N = 2016 - 1929 + 1 = 88$ is the total number of the individual MLR models, obtained in the RLOO CV procedure;

$$MLR_{w,W,P,doy}^\theta(year) = k_0^\theta + \sum_{l=1}^{P} k_l^\theta \cdot pc_i^W(y)\,, \theta = \overline{1929{,}2016}$$

$MLR^{\theta}_{w,W,P,doy}(year)$ is the θ^{th} individual MLR model, obtained in the RLOO CV procedure.

To obtain the θ^{th} individual MLR model, $T_{inter}(w, W, doy)$ was split into calibration ($T^{cal}_{inter}(w, W, doy)$) and verification ($T^{ver}_{inter}(w, W, doy)$) sets by the rules of the **RLOO CV procedure**:

1. The θ^{th} element (year) of $T_{inter}(w, W, doy)$ is considered as a verification set
2. The elements from $\left[\theta - \left\lfloor\frac{W}{2}\right\rfloor, \theta\right) \cup \left(\theta, \theta + \left\lfloor\frac{W}{2}\right\rfloor\right]$ are omitted ($\left\lfloor\frac{W}{2}\right\rfloor$ is the floored division).
   This is done to prevent the data from the θ^{th} element from getting into the calibration set due to smoothing with the W inter-annual sliding window and affecting the elements from $\left[\theta - \left\lfloor\frac{W}{2}\right\rfloor, \theta\right) \cup \left(\theta, \theta + \left\lfloor\frac{W}{2}\right\rfloor\right]$.
   All the indices from $\theta - \left\lfloor\frac{W}{2}\right\rfloor < 1929$ or $\theta + \left\lfloor\frac{W}{2}\right\rfloor > 2016$ are ignored
3. All other elements are considered as a calibration set

Year / Model №	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	…	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
1929	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
1930	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
1931	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
1932	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31	…	14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
1933	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
1934	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
1935	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
…							…						…						…						
2010	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
2011	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
2012	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
2013	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31	…	14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
2014	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
2015	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37
2016	12.33	12.34	12.35	12.27	12.33	12.15	12.25	11.97	12.40	12.54	13.20	13.31		14.61	14.06	14.26	14.16	13.76	13.35	13.56	13.67	13.03	12.50	12.17	11.37

Figure S11. Visualization of the Rolling Leave-One-Out Cross Validation procedure for the data with the sliding windows w=7, W=9, for the doy=152. The red cells are considered as a verification set for the corresponding model, the gray cells are omitted, and the white cells are considered as a calibration set for the corresponding model.

Table S6. Example of the calibration and verification sets for $w = 7, W = 9, doy = 152$, $\theta = 2000$:

Year	$T^{ver}_{inter}(7, 9, 152)$
2000	14.922222

Verification set

Year	$T^{cal}_{inter}(7, 9, 152)$
1929	12.328571
…	…
1995	13.076190
2005	14.922222

…	…
2016	11.374286

Calibration set

After obtaining the calibration and verification sets, the coefficients k_l^{θ} of the θ^{th} individual MLR model are obtained by training the model on the calibration set.

To evaluate the individual models on the calibration sets, the coefficient of determination ($R^2_{cal,\theta}$) and the Root Mean Squared Error ($RMSE_{cal,\theta}$) were calculated between $T^{cal}_{inter}(w, W, doy)$ and $\{MLR^{\theta}_{w,W,P,doy}(year) \big| year \in T^{cal}_{inter}(w, W, doy)\}$.

After training the $N = 88$ models, one for each year, the chronology of the verification values was obtained as:

$$CRN^{ver}_{w,W,P,doy} = \{MLR^{1929}_{w,W,P,doy}(1929), \dots, MLR^{2016}_{w,W,P,doy}(2016)\}$$

and the mean metrics $R^2_{cal} = \frac{\sum_{\theta=1929}^{2016} R^2_{cal,\theta}}{N}$, $RMSE_{cal} = \frac{\sum_{\theta=1929}^{2016} RMSE_{cal,\theta}}{N}$ were calculated to evaluate the total quality of the individual models on the calibration set.

To evaluate the individual models on the verification set, R^2_{ver} and $RMSE_{ver}$ were calculated between $CRN^{ver}_{w,W,P,doy}$ and $T_{inter}(w, W, doy)$.

After the individual evaluating, the final MLR model $MLR_{w,W,P,doy}(year)$ was developed by averaging the coefficients of the individual models.

To evaluate the final model, R^2_{sim} and $RMSE_{sim}$ (*sim* – simulated) were calculated between $T_{inter}(w, W, doy)$ and $\{MLR_{w,W,P,doy}(year) \big| year \in T_{inter}(w, W, doy)\}$.

Table S7. Model coefficients

Period	PC1	PC2	PC3	PC4	PC5	Constant
A	-0.280	-0.524	-1.034	0.128	0.399	11.761
B	0.200	-0.152	-0.233	0.565	0.627	18.621