**Supporting Information:** Drought impacts on tree carbon sequestration and water use – evidence from intra-annual tree-ring characteristics

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Table S1. **Allometric characteristics of the four selected trees.** DBH, diameter at breast height.

| Tree ID | DBH (cm) | Height (m) | Bark width (cm) | Age (years) |
|---------|----------|------------|-----------------|-------------|
| S1      | 74.9     | 34.1       | 2.1             | 94          |
| S2      | 60.2     | 29.2       | 0.9             | 75          |
| S3      | 98.2     | 35.1       | 1.8             | 88          |
| S4      | 51.9     | 21.0       | 0.7             | 33          |
Figure S1. Climate conditions of the selected years. The climate–space diagram shows a 2D kernel density estimate based on growing season (1 April to 30 September) temperature and precipitation for the period 1961–2016. Blue and red points represent the selected growing seasons 2014 and 2015, respectively. Data was retrieved from CHELSA (Karger et al., 2017).
Figure S2. Methodology and abbreviations applied in this study. Observations of cell formation were assessed in terms of the kinetics of cell formation, including the timing of the beginning and the end of the cell enlargement (bE, cE) and wall thickening (bW, cW) phases. Quantitative wood anatomical analyses (QWA) included total cell wall area (CWA), cell lumen area (CLA), total cell area (CTA), and total cell radial diameter (Crad). The rates of cell enlargement and wall thickening were calculated by combining CTA with duration of the cell enlargement (dE) and CWA with wall thickening (dW). Sections of the tree rings (60 µm for earlywood and 40 µm for latewood) were used for stable carbon isotope (δ¹³C) analyses. Crad was used to assess the percentage of the tree ring width occupied by each cell. This made it possible to transform time into space, in order to represent the changes in isotopic composition across the ring width and over time.
Figure S3. Seasonal dynamics of the Normalized Difference Vegetation Index. The black line and grey shaded area represent the mean value and the 95% confidence interval, respectively, obtained from GAMMs for the period 2003–2013. The green and brown lines and dots are values from the years 2014 and 2015, respectively.
Figure S4. Average relative stem radius changes throughout the two growing seasons. The red line indicates when growth occurred and the blue shaded areas represent periods when tree shrinkage lasted more than 24 h (Tree Water Deficit; TWD).
Figure S5. Mean duration of the enlargement and wall thickening phases for individual cells in the years 2014 (A, C) and 2015 (B, D) for the four studied Norway spruce trees. Cell counts (A, B) and percentage of the ring width (C, D) are shown. Each rectangle represents a single tracheid. The grey band indicates the period when the change in stem radius was negative (TWD; darker grey indicates a greater deficit) for more than 24 h during the extreme summer drought in 2015.
Figure S6. Ratio between the duration and rate of cell kinetics. The cell enlargement (A, B) and wall thickening (C, D) phases during the years 2014 (green lines) and 2015 (brown lines) are shown. Each rectangle represents a single tracheid. The grey band indicates the period when the change in stem radius was negative (TWD; darker grey indicates a greater deficit) for more than 24 h during the extreme summer drought in 2015.
Figure S7. Intra-annual δ^{13}C values of tree-ring cellulose from Norway spruce from the years 2014 and 2015.
**Notes S1. Calculation of cell kinetics (timing and duration) and rates.**

Following the approach of Cuny et al. (2013) and Pérez-de-Lis et al. (2021), we calculated the kinetics (timing and duration) of each cell in the enlargement, wall thickening and mature phases. To do so, the cumulative sums of the number of cells in each of the three differentiating phases (EWMZ, WMZ and MZ) were calculated as:

\[
\begin{align*}
\text{EWMZ}_{ij} &= \text{EZ}_{ij} + \text{WZ}_{ij} + \text{MZ}_{ij} \\
\text{WMZ}_{ij} &= \text{WZ}_{ij} + \text{MZ}_{ij} \\
\text{MZ}_{ij} &= \text{MZ}_{ij}
\end{align*}
\]

where \( \text{EZ} \) is the number of cells in the enlargement phase, \( \text{WZ} \) the number of cells in the wall thickening phase and \( \text{MZ} \) the number of mature cells, \( \text{EWMZ} \) the sum of cells in any of the three phases, \( \text{WMZ} \) the sum of cells in wall thickening and maturing phases for each tree \( i \) and date \( j \).

There are sources of noise inherent to cell cambial monitoring, including: (i) variability in the number of cells between dates due to changing of the sampling location within the stem and (ii) differences among sampled trees.

The first source of noise (i) affects the kinetics calculations because it usually generates mismatches when fitting the patterns between EWMZ, WMZ and MZ (Fig. S2). Moving averages with three-day windows were applied to \( \text{EWMZ}_{ij} \), \( \text{WMZ}_{ij} \) and \( \text{MZ}_{ij} \) to reduce the variability among sampling dates. Afterwards, the number of cells in \( \text{WMZ}_i \) and \( \text{MZ}_i \) were fixed at date \( j \), when \( j \) \( \text{EZ}_i=0 \) and \( \text{WZ}_i=0 \), respectively. This is because no new cells entered the respective enlargement and wall thickening phases, and therefore any potential increase in cell sums could be directly associated with discrepancies among tree radial files.

To account for between-tree variability (ii), generalized additive mixed models (GAMMs) were then applied to EWMZ, WMZ and MZ assuming a quasi-Poisson distribution of residuals (Wood, 2006). Day of year (DOY) was the main predictor and tree was included as a random effect to account for non-independent data (i.e., repeated measures over time). GAMMs were then used to predict the number of cells over the growing season for EWMZ, WMZ and MZ. The inverse functions of the resulting models were used to predict the timing of the cell differentiation phases for all the mature cells obtained from the GAMM average (Fig. S4):

\[
\begin{align*}
\text{bE}_i &= \text{GAMM(EWMZ)}^{-1} \\
\text{cE}_i &= \text{GAMM(WMZ)}^{-1} \\
\text{bW}_i &= \text{GAMM(WMZ)}^{-1} \\
\text{cW}_i &= \text{GAMM(MZ)}^{-1} \\
\text{bM}_i &= \text{GAMM(MZ)}^{-1}
\end{align*}
\]

where \( \text{bE} \) is the beginning of the enlargement phase, \( \text{bW} \) is the beginning of the wall thickening phase, \( \text{bM} \) is the beginning of the mature phase, \( \text{cE} \) is the cessation of the enlargement phase, \( \text{cW} \) is the cessation of the wall thickening phase, and \( \text{bM} \) is the beginning of the mature phase.
Consequently, the duration of each cell’s enlargement (dE$_i$) and wall thickening (dW$_i$) phases could be calculated as:

\[
\begin{align*}
\text{dE}_i &= \text{cE}_i - \text{bE}_i \\
\text{dW}_i &= \text{cW}_i - \text{bW}_i
\end{align*}
\]  

(9) (10)

Daily rates of enlargement (rE$_i$) and wall thickening (rW$_i$) of each cell could then be calculated by combining durations with cell anatomical characteristics:

\[
\begin{align*}
\text{rE}_i &= \frac{\text{CTA}_i}{\text{dE}_i} \\
\text{rW}_i &= \frac{\text{CWA}_i}{\text{dW}_i}
\end{align*}
\]  

(11) (12)

where CTA$_i$ and CWA$_i$ are the individual cell area and wall area, respectively.
Notes S2. Calculation of stable-isotope-derived physiological parameters

The discrimination against $^{13}$C during carbon diffusion and fixation by plants ($\Delta^{13}$C), including the sum of discriminations beyond those associated with the production of primary photosynthetic assimilates (Belmecheri & Lavergne, 2020; Lavergne et al., 2020), was calculated as:

$$\Delta^{13}$C (‰) = \frac{\delta^{13}$CO$_2 - (\delta^{13}$C$_S - d)}{1 + (\delta^{13}$C$_S - d)/1000}$$

where $d$ represents the sum of post-photosynthetic isotope fractionations between the leaf organic matter and the tree-ring material, which usually varies around 2.1 ± 1.2‰ (Frank et al., 2015). Calculating $\Delta^{13}$C corrects for the effect of the decrease in $\delta^{13}$C of the atmosphere due to fossil fuel burning since the beginning of industrialization on $\delta^{13}$C$_S$ values (Tans et al., 1979). Furthermore, the isotopic fractionations occurring at the leaf level are described in the biochemical model that includes a photorespiratory effect (Francey & Farquhar, 1982; Keeling et al., 2017):

$$\Delta^{13}$C (‰) = a + (b - a) \frac{C_i}{C_a} - f \frac{\Gamma^{*}}{C_a}$$

where $a$, $b$ and $f$ represent the isotope fractionations occurring as a result of CO$_2$ diffusion in air (4.4‰; Craig 1953) and of effective Rubisco carboxylation (28±2‰) and photorespiration (12±4‰; Ubierna & Farquhar 2014). $\Gamma^{*}$ (Pa) is the CO$_2$ compensation point in the absence of mitochondrial respiration, suggested by Bernacchi et al. (2001) to be:

$$\Gamma^{*} = 42.75 \times 10^{-6} P_{atm} \exp(15.26 \frac{T - 298}{T})$$

$C_i$ is the estimated leaf intercellular CO$_2$ concentration and can be obtained by combining Eq. 13 and Eq. 14, and is needed to calculate the intrinsic water-use efficiency (iWUE), which is the ratio between photosynthetic assimilation rates ($A$) and stomatal conductance during photosynthesis ($g_s$):

$$iWUE (\mu mol CO_2 mol H_2O^{-1}) = \frac{A}{g_s} = C_a(1 - \frac{C_i}{C_a})/1.6$$

Daily $\delta^{13}$CO$_2$ and atmospheric CO$_2$ concentration ($c_a$) values required for these calculations were obtained from the high-elevation research station Jungfraujoch (7°59' E, 46°33’ N, 3580 m a.s.l.), which is located a horizontal distance of approximately 20 km from our study site (Sturm et al., 2013). Average $\delta^{13}$CO$_2$ and $c_a$ values during the exact time period of each cell’s wall thickening phase were used.
Notes S3. Calculation of daily woody biomass (carbon sequestration)

The daily woody biomass production of our study trees was calculated based on the sum of rates of wall deposition occurring in all cells differentiating on a given day \( r_{W,WZ} \), following Cuny et al. (2015):

\[
r_{W,WZ} = \sum_{i=1}^{WZ} r_{Wi}
\]

where \( WZ \) is the daily number of cells in the wall thickening phase and \( r_{wi} \) is the wall deposition rate (\( \mu m^2 \text{ day}^{-1} \)) of cell \( i \) in the thickening phase. We then upscaled \( r_{W,WZ} \) to a total daily rate of wall deposition at the ring level \( r_{W,TR} \) by accounting for the number of radial cell files composing the ring transversal section at breast height, which was obtained by dividing the mean circumference at breast height of the studied trees by the mean tangential width of a radial file derived from wood anatomical cell characteristics:

\[
r_{W,TR} = r_{W,WZ} \times n_{RF}
\]

where \( n_{RF} \) is the number of radial cell files forming the tree ring at the periphery of the stem. Next, we upscaled \( r_{W,S} \) to a total daily rate of wall deposition at the stem level \( r_{W,S} \) by assuming a cone shaped stem of average tree height \( H \).

\[
r_{W,S} = \frac{1}{3} \times H \times r_{W,TR}
\]

Finally, we converted the total daily rate of wall deposition at the stem level to \( C \) in woody biomass production \( (\text{WBP}, \text{ g C day}^{-1} \text{ tree}^{-1}) \), assuming a wall density of 1.5 g cm\(^{-3}\) and a carbon percentage in wood of 50% of dry weight (Lamlom & Savidge, 2003):

\[
\text{WBP} = 1.5 \times r_{W,S} \times 0.5
\]
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