



Spatial decoupling of drought exposure and growth loss in German forests during the 2018–2022 drought sequence

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Abstract. The 2018–2022 drought sequence coincided with widespread forest stress in Central Europe, but tree-growth responses differed markedly among species and hydroclimatic settings. Here, we analyzed radial-growth responses along a west–east transect across Germany using a multi-site tree-ring network spanning five common forest species: European beech (*Fagus sylvatica*), pedunculate oak (*Quercus robur*), sessile oak (*Quercus petraea*), Scots pine (*Pinus sylvestris*), and Douglas fir (*Pseudotsuga menziesii*). We assessed drought severity and duration using the Standardized Precipitation–Evapotranspiration Index (SPEI, 1951–2024) and estimated growth anomalies relative to the baseline of expected growth under neutral moisture conditions derived from hierarchical generalized additive mixed models.

The 2018–2022 period was the most severe multi-year drought event across the sampled regions at longer accumulation scales (SPEI-24 and SPEI-48), exhibiting exceptional persistence in severity and temporal extent. Growth losses peaked in 2019 for four of the five species, with annual anomalies in that year ranging from –21 to –42 %. Douglas fir responded already in 2018 and reached its strongest single-year deficit of the recent sequence in 2022 ($\approx -66\%$). When integrated over five years, the recent sequence produced some of the strongest sustained growth deficits in the study period for most species within the sampled stands. Analysis across individual drought events suggests additional growth suppression at a given severity in beech and Douglas fir and less suppression in sessile oak during recent events.

Despite the strong regional synchrony of the climatic driver, growth responses remained highly heterogeneous along the transect. Across all species, growth anomalies were less spatially coherent than the climatic driver, and this decoupling emerged even between neighboring stands under near-identical forcing. These results show that a climatically unprecedented, coherent drought produced growth impacts that were neither uniform nor predictable from regional water-balance severity, so that



translating regional severity into stand-level growth losses requires additional information on local water availability and site
20 context.

1 Introduction

Central Europe has recently experienced an exceptional sequence of compound hot-dry summers (Gazol et al., 2025). Between
2018 and 2022, repeated episodes of drought and heat occurred in rapid succession and produced hydroclimatic conditions
that rank among the most severe in the observational record (Rakovec et al., 2022; Schumacher et al., 2024; Knutzen et al.,
25 2025). Across large parts of Germany, soil-moisture deficits accumulated over successive growing seasons and persisted in
deeper soil layers, even where near-surface moisture recovered temporarily (Boeing et al., 2022; Pohle et al., 2025). Under on-
going anthropogenic warming, higher temperatures likely intensified vegetation stress in these hot-dry summers by increasing
atmospheric evaporative demand (Ionita et al., 2021; Gebrechorkos et al., 2025).

For forests, multi-year hot-dry periods are particularly damaging because they impose acute physiological stress while re-
30 covery from earlier episodes is still incomplete, extending impacts beyond the extreme events themselves (Anderegg et al.,
2020). During such events, high atmospheric evaporative demand can intensify canopy water loss and lower plant water po-
tential (Williams et al., 2013; Grossiord et al., 2020; Novick et al., 2016). When soil water supply and hydraulic transport are
insufficient to replace transpirational losses, stomata close to limit dehydration, which reduces photosynthesis and increases
the risk of hydraulic failure (Grossiord et al., 2020; McDowell et al., 2008). Because radial growth depends on sufficient cell
35 turgor and cambial activity, declining tree water status can directly constrain wood formation during drought (Peters et al.,
2021; Cabon et al., 2020; Zweifel et al., 2021). Stress can therefore carry over between episodes, through both hydrologic and
biological legacies. Incomplete replenishment of soil and groundwater stores prolongs water limitation, while canopy and fine-
root loss, xylem damage, and altered carbon balance can depress growth in subsequent years (Kannenberget al., 2019, 2020;
Bose et al., 2024).

40 Consistent with these mechanisms, the 2018–2022 drought sequence coincided with widespread declines in forest vitality
and drought-related tree mortality in Central Europe (Gharun et al., 2024; Knutzen et al., 2025; Obladen et al., 2021). Such im-
pacts are typically assessed using surveys of crown condition, which provide repeated assessments across extensive monitoring
networks, as well as using remote sensing indicators of crown activity, which extend such evaluations across broader spatial
scales (Bussotti et al., 2024; Drechsel and Forkel, 2025). Both approaches, however, primarily characterize canopy condition
45 or activity, which can become decoupled from stem growth (Ferretti et al., 2021; Mašek et al., 2024; Engelmayer et al., 2026).
They therefore do not directly resolve the underlying physiological processes and may fail to reveal sustained growth losses
(van der Maaten et al., 2024).

Tree rings offer a complementary perspective, because radial growth integrates these processes into an annually resolved,
retrospective record at the level of the individual tree (Dobbertin, 2005). This makes it possible to quantify drought-related
50 growth anomalies directly and to place recent extremes in a longer historical context. Previous dendroecological studies have
documented marked growth declines during the early phase of the recent drought sequence, together with pronounced inter-



specific and site-dependent variability (Thom et al., 2023; Schmied et al., 2023). Such site dependence is expected, because local water availability is governed by soil depth, water-holding capacity, and access to groundwater (Walthert et al., 2021; Weigel et al., 2023; Skiadaresis et al., 2019), and therefore varies over distances far shorter than those resolved by gridded climatic drought indices. Complementary high-frequency stem-radius observations revealed substantial stem dehydration and stress during recent hot droughts (Salomón et al., 2022) and provided evidence that responses to consecutive drought years can accumulate (Schnabel et al., 2022). Mortality studies have documented severe post-drought damage and elevated mortality risk (Obladen et al., 2021; Nixon et al., 2025). Yet a historical, growth-centered assessment of the full 2018–2022 drought sequence is still lacking. This period provides a rare opportunity to quantify tree growth responses to an exceptional multi-year drought and to evaluate whether its impacts exceeded those of the most severe droughts of the instrumental record analysed here (1951–2024).

Here, we use a multi-site tree-ring network of 467 trees from five broadleaved and coniferous species, sampled at 16 sites along a pronounced west–east hydroclimatic gradient across Germany, to quantify radial growth responses to the 2018–2022 drought sequence. Growth anomalies are expressed as deviations from expected growth under neutral moisture conditions, predicted by hierarchical generalized additive mixed models calibrated on the pre-2018 period. Specifically, we (i) rank the severity, duration and intensity of the recent sequence against all drought events of the instrumental record (1951–2024) at accumulation scales from 3 to 48 months, (ii) estimate annual and five-year cumulative growth anomalies and place them within each species’ own historical distribution, (iii) test, at the level of individual drought events, whether recent events reduced growth beyond what the historical severity–impact relationship predicts, and (iv) compare the spatial coherence of growth anomalies with that of the climatic driver, thereby assessing how strongly local site context decouples growth from the regional drought signal. Given the exceptional persistence of the recent sequence, we expected growth losses to be correspondingly exceptional, unless local water availability buffered trees against the regional climatic signal. We therefore ask whether the persistence of the recent drought translated into equally exceptional growth impacts, and how far those impacts were modulated by species identity and local site context.

2 Methods and data

2.1 Sampling regions, sites, and design

The study was conducted within the MW³-project and follows a west–east transect across Germany along the Central German Uplands (Fig. 1). The transect was designed to capture a broad hydroclimatic gradient, from more oceanic conditions in the west to more subcontinental conditions in the east. Within each of three regions (West, Central and East), sampling was stratified by elevation, with higher and lower sites selected to distinguish broad-scale hydroclimatic variation from local topographic influences. This altitudinal stratification is most evident in the West and Central regions. In the East, topographic relief is weaker, and suitable sites were farther apart. As a result, the two elevation strata are less closely located and cover a smaller altitudinal range.



The study design comprises six sampling regions, defined by the combination of broad geographic region and elevation class: Eifel (West–High), Niederrhein (West–Low), Kellerwald (Central–High), Caldern (Central–Low), Hohes Holz (East–High), and Mecklenburg Lake District (East–Low) (Table 1, Fig. 1). These sampling regions span approximately 6.3–13.2°E and 50.5–53.3°N, and range in elevation from 70 to 615 m a.s.l. (Table 1).

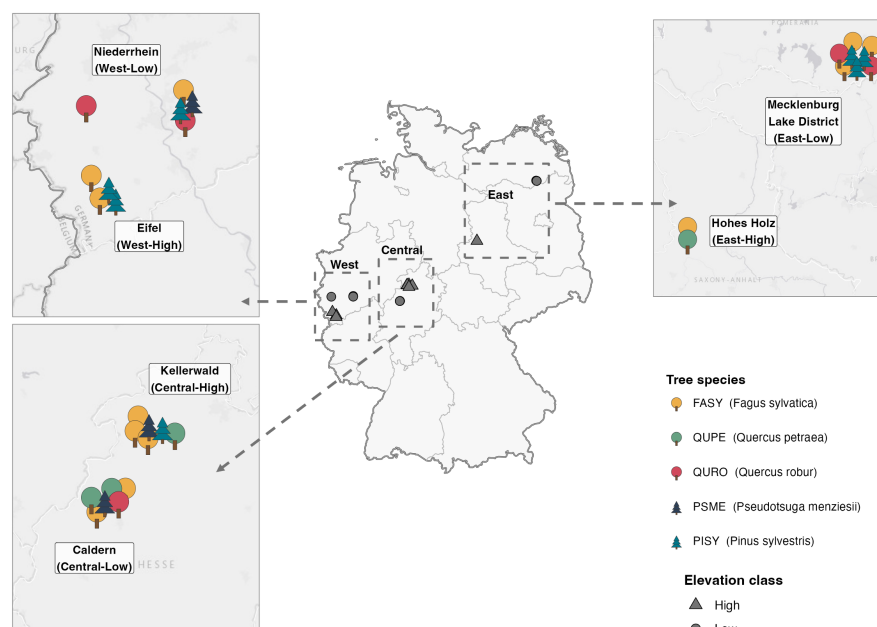


Figure 1. Sampling regions and plot locations across Germany. The three geographic regions (West, Central and East), each comprising a high- and a low-elevation sampling region, are shown on the central map. The surrounding panels provide an enlarged view of each region. Each plot-species unit is represented by a tree symbol, with the color denoting the species and the form showing the tree type (rounded = broadleaf, conical = conifer). Tree symbols that are co-located are offset slightly to ensure they are all visible.

The sampling design is hierarchical. A *sampling region* denotes one of the six region–elevation units listed in Table 1. Within each sampling region, one or more *sites* were sampled (Table 1). Within the sites, one or more *plots* were established as local sampling locations, typically separated by no more than a few hundred meters. A *plot–species unit* denotes the species-specific tree-ring record developed from several trees of a given species sampled within a given plot. Across the six sampling regions, replication ranged from 2 to 8 plot–species combinations and from 45 to 109 sampled trees, with typically around 15 trees per plot–species unit (Table 1).

2.2 Tree-ring dataset and chronology characteristics

Two increment cores were extracted per tree from opposite directions at breast height (1.3 m) using a 5 mm Haglöf increment borer (Haglöf, Långsele, Sweden). Samples were prepared following standard dendrochronological procedures (Stokes and Smiley, 1996; Speer, 2010). Ring widths were measured at the dendrochronological laboratory DeLaWi Tree Ring Analyses

Table 1. Sampling design, replication, and climate context for the sampling regions shown in Fig. 1. Plot-sp denotes plot–species units (i.e., unique combinations of plots and species). Precipitation (mm yr⁻¹) and temperature (°C) are mean annual values for 1991–2020 (DWD).

Label	Region name	Replication				Plot structure		Environment	
		<i>n_{sites}</i>	<i>n_{plots}</i>	<i>n_{plot-sp}</i>	<i>n_{trees}</i>	Species	Elev (m a.s.l.)	<i>P</i> _{1991–2020}	<i>T</i> _{1991–2020}
West–High	Eifel	3	3	4	60	FASY, PISY	460–530	824	8.7
West–Low	Niederrhein	4	4	5	90	FASY, PISY, PSME, QURO	85–132	873	10.7
Central–High	Kellerwald	5	5	6	90	FASY, PISY, PSME, QUPE	340–615	748	8.4
Central–Low	Caldern	1	6	6	95	FASY, PSME, QUPE, QURO	270–350	732	9.2
East–High	Hohes Holz	1	1	2	45	FASY, QUPE	218	643	9.3
East–Low	Meckl. Lake District	2	7	8	109	FASY, PISY, QURO	70–105	618	9.2

(Windeck, Germany) using a Lintab 5 movable-stage measurement system (Rinntech, Heidelberg, Germany) coupled to a stereo microscope (Carl Zeiss, Jena, Germany), with a precision of 0.01 mm. Series were crossdated using TSAP-WIN (Rinn, 2003) and statistically verified with COFECHA (Holmes, 1983).

The dataset includes five tree species: *Fagus sylvatica* (FASY), *Pinus sylvestris* (PISY), *Pseudotsuga menziesii* (PSME), *Quercus petraea* (QUPE), and *Quercus robur* (QURO) (Table 2). FASY is the only species represented in all six sampling regions (12 plots across 10 sites). PISY was sampled in four sampling regions, while PSME, QUPE and QURO occur each in three sampling regions (Table 2). Therefore, inferences based on fewer sampled species primarily reflect the response of the sampled stands.

Table 2. Species-wise sampling replication and chronology characteristics. Values are medians across plot–species units. Length denotes the median ring-series length (years), DBH is diameter at breast height (cm), and Height is tree height (m). Start and End indicate the minimum and maximum first/last ring years observed for each species across all sites.

Species	Replication				Tree attributes (median)			Chronology (max)	
	<i>n_{region}</i>	<i>n_{sites}</i>	<i>n_{plots}</i>	<i>n_{trees}</i>	Length	Height	Dbh	Start	End
FASY	6	10	12	215	172	30.5	47.7	1735	2024
PISY	4	6	7	104	165	29.0	50.9	1715	2024
PSME	3	3	3	45	61	36.0	55.1	1919	2022
QUPE	3	3	4	64	135	32.0	40.7	1798	2024
QURO	3	4	5	61	210	31.5	71.9	1704	2023

Additional dendrochronological metadata are provided in Appendix A. This includes the temporal support of the tree-ring network (Fig. A1), the species-specific distribution of the sampled tree attributes (Fig. A2), plot-level chronology metadata and descriptive statistics (Table A1), and diagnostics of the temporal coverage and signal strength of the measured ring-



width series. Because interseries correlation ($\bar{r}$) and the expressed population signal (EPS) require trend-free series, these
110 diagnostics were computed from spline-standardized ring-width indices using the `dplR` package (Bunn, 2008). Median EPS
exceeds 0.85 for all chronologies except the pedunculate-oak plot PF13 (EPS = 0.665, $\bar{r}$ = 0.293), which rests on five
trees only (Table A1). Because the growth models are fitted to individual tree-level BAI series with tree and plot random
effects (Sect. 2.5) rather than to mean chronologies, limited replication propagates into wider uncertainty rather than into a
biased response estimate, and PF13 was therefore not excluded from the analyses.

115 2.3 Tree-ring processing: basal area increment

Annual ring widths were converted to basal area increment (BAI, $\text{cm}^2 \text{yr}^{-1}$) to express stem growth in an area-based metric.
BAI was calculated using the proportional diameter-reconstruction approach of Bakker (2005), implemented in the `dplR`
package (Bunn, 2008).

For each tree, inside-bark radius at breast height was derived from field measurements of DBH and bark thickness. Ring
120 widths from the two dated cores collected per tree were first combined into a single annual tree-level series by averaging
aligned annual values across cores. The summed ring widths of this tree-level series were used to estimate the measured radial
length represented by the core record. For trees in which the pith was not intercepted, pith offset was calculated as the positive
difference between inside-bark radius and measured radial length. The inside-bark radius and estimated pith offset were then
used to position the ring-width series relative to the stem centre and reconstruct annual stem radius through time. Annual BAI
125 was calculated as the year-to-year increment in reconstructed stem cross-sectional area at breast height:

$$\text{BAI}_{i,t} = \pi (r_{i,t}^2 - r_{i,t-1}^2), \quad (1)$$

where $r_{i,t}$ is the reconstructed inside-bark stem radius of tree i in year t .

As a quality-control step, we compared the radial length represented by each tree-level ring-width series with the geometric
inside-bark radius derived from field measurements of DBH and bark thickness. Trees with extreme mismatch were excluded
130 using a robust outlier criterion based on the percentage deviation between core-based and geometric radius, retaining only trees
within ± 5 median absolute deviations (MAD) of the median. This resulted in 22 out of 489 trees being excluded (4.5 %; cf.
Fig. A6), leaving 467 trees for the growth analyses.

2.4 Climate data and drought metrics

Drought conditions were quantified using the Standardized Precipitation–Evapotranspiration Index (SPEI) (Vicente-Serrano
135 et al., 2010; Beguería et al., 2014), a multiscalar index based on the climatic water balance, defined as precipitation minus
potential evapotranspiration:

$$\text{CWB}_p(m) = P_p(m) - \text{PET}_p(m), \quad (2)$$

where $\text{CWB}_p(m)$ is the monthly climatic water balance (mm) at plot p in month m , $P_p(m)$ is the monthly precipitation total
(mm), and $\text{PET}_p(m)$ is the monthly total potential evapotranspiration (mm).



140 For each plot location, monthly total precipitation and monthly mean, minimum and maximum daily air temperature were taken from the $1 \text{ km} \times 1 \text{ km}$ monthly grids of the DWD Climate Data Center (CDC), interpolated from the DWD station network (Kaspar et al., 2013). Monthly potential evapotranspiration was estimated from these fields with the Hargreaves equation (Hargreaves and Samani, 1982), with extraterrestrial radiation computed from plot latitude and day of year. Climate data were used for the period 1951–2024 as this is the period where station data are most reliable, even though individual ring-width series extend back to 1704 (Table 2).

For each plot, the climatic water balance was accumulated over k consecutive months,

$$\text{CWB}_p^{(k)}(t) = \sum_{j=0}^{k-1} \text{CWB}_p(t-j), \quad (3)$$

where $\text{CWB}_p^{(k)}(t)$ is the accumulated climatic water balance (mm) at plot p for the k -month window ending in month t , and k is the accumulation time scale, i.e. the number of months over which the water balance is accumulated prior to standardization.

150 We used $k = 3, 12, 24$, and 48 months (hereafter SPEI-3, SPEI-12, SPEI-24, and SPEI-48). For each accumulation scale, $\text{CWB}_p^{(k)}$ was transformed separately for each calendar month into dimensionless values $\text{SPEI}_{k,p}(t)$ with an approximately standard-normal distribution, using a non-parametric kernel density estimator (Pohl et al., 2023). Because plots within a site had near identical series, they were then averaged to a site level for each month and accumulation scale.

A month was classified as a drought month when

$$155 \text{ SPEI}_{k,s}(t) \leq -1, \quad (4)$$

where $\text{SPEI}_{k,s}(t)$ is the SPEI value at site s and accumulation scale k in month t . This threshold corresponds to the driest 15.9 % of months in the 1951–2024 reference period ($\Phi(-1) = 0.159$, where Φ is the standard-normal cumulative distribution function), i.e. an expected recurrence of roughly once every six years for any given calendar month, and to the drought classes of McKee et al. (1993).

160 Consecutive drought months were grouped into drought events. For each event e , we recorded its start and end month and its duration D_e (number of months). Event severity S_e was defined as the accumulated deficit over the event,

$$S_e = - \sum_{t \in e} \text{SPEI}_{k,s}(t), \quad (5)$$

and mean intensity I_e as the average monthly deficit,

$$I_e = \frac{S_e}{D_e}, \quad (6)$$

165 where S_e is the (dimensionless) event severity, D_e the event duration in months, I_e the mean event intensity, and the sum in Eq. (5) runs over all months t belonging to event e . Larger values of S_e and I_e therefore denote drier conditions. Drought events were identified separately for each site and time scale. To benchmark the 2018–2022 sequence against the historical record, the site series of each sampling region were averaged into one regional series, so that each region yields a single event catalogue rather than one per site (Fig. 2, Table B1 in Appendix B2).



170 2.5 Species-specific climate–growth models

To account for long-term growth trends and estimate growth anomalies associated with moisture conditions, we fitted generalized additive mixed models (GAMMs) (Hastie and Tibshirani, 1986; Chen, 2000) to basal area increment (BAI). Models were fitted separately for each species to allow for species-specific growth dynamics and drought responses. To avoid calibrating the models on the focal drought sequence, model fitting was restricted to pre-2018 observations (1951–2017). The fitted models
175 were then used to generate expected growth under neutral moisture conditions for the entire study period, which served as the basis for the relative growth index and the derived drought-impact metrics described below (Sects. 2.5.1 and 2.6). This modeling framework is well suited to the hierarchical and unbalanced sampling design of our study (Tables 1 and 2), because it accommodates non-linear relationships while accounting for repeated measurements and site-level heterogeneity (Lin and Zhang, 1999).

180 For tree i in year t , BAI was modeled using a Gamma distribution with log link:

$$\text{BAI}_{i,t} \sim \text{Gamma}(\mu_{i,t}, \kappa), \quad \log(\mu_{i,t}) = \eta_{i,t}, \quad (7)$$

where $\text{BAI}_{i,t}$ is the observed basal area increment ($\text{cm}^2 \text{ yr}^{-1}$) of tree i in year t , $\mu_{i,t}$ is its conditional expectation, κ is the Gamma shape parameter (assumed constant within a species and estimated from the data), and $\eta_{i,t}$ is the linear predictor on the log scale.

185 The linear predictor included smooth functions of age and size, a species-level drought-response function, and a site-specific deviation in drought sensitivity:

$$\eta_{i,t} = \alpha + f_{\text{age}}(\text{age}_{i,t}) + f_{\text{size}}(\text{size}_{i,t}) + f_{\text{SPEI}}(\text{SPEI}_{\text{site}(i),t}) + f_{\text{SPEI,site}(i)}(\text{SPEI}_{\text{site}(i),t}) + u_{\text{plot}(i)} + u_{\text{tree}(i)}, \quad (8)$$

where α is the species-level intercept, i.e. the expected logBAI at average age and size under neutral moisture conditions. The smooth f_{age} describes the ontogenetic growth trend as a function of cambial age $\text{age}_{i,t}$ (years), while f_{size} absorbs the
190 geometric increase of BAI with stem size, $\text{size}_{i,t}$ being the reconstructed inside-bark stem radius (cm) of tree i at the start of year t (Sect. 2.3).

Water availability enters through $\text{SPEI}_{\text{site}(i),t}$, the July SPEI at a 12-month accumulation scale ($\text{SPEI-12}_{\text{Jul}}$) at the site in which tree i was sampled, i.e. the site-level series of Sect. 2.4 from which the drought events are also delineated. Its species-level effect is the smooth f_{SPEI} , common to all sites, and $f_{\text{SPEI,site}(i)}$ is a factor-smooth deviation from it for the site of tree i , so
195 that the realized response at a site is the sum of the two. Drought sensitivity is thereby allowed to vary among sites while poorly supported site-level deviations are shrunk toward the species mean. Finally, $u_{\text{plot}(i)} \sim \mathcal{N}(0, \sigma_{\text{plot}}^2)$ and $u_{\text{tree}(i)} \sim \mathcal{N}(0, \sigma_{\text{tree}}^2)$ are random intercepts for plot and tree identity, accounting for local heterogeneity and for repeated observations of the same tree.

$\text{SPEI-12}_{\text{Jul}}$ was selected *a priori* because it integrates moisture conditions during the early current growing season, when
200 most radial growth occurs, with hydroclimatic conditions during the preceding autumn, winter, and spring that influence water availability in the current year. Summer-centered 12-month drought metrics are commonly used in dendroecological studies (Trifković et al., 2022; Akhmetzyanov et al., 2023; Kröner et al., 2024). We also evaluated alternative SPEI formulations in a



sensitivity analysis (Appendix C2) and found that the main anomaly patterns were largely unaffected by the exact choice of the SPEI driver.

205 Residual temporal dependence within tree-ring series was modeled using a first-order autoregressive AR(1) structure, allowing residuals from adjacent years to be correlated. This accounts for non-independence within growth series and is consistent with the biological memory often observed in radial growth (Klesse et al., 2023). Further implementation details and diagnostics are provided in Appendix C.

2.5.1 Neutral-moisture predictions and relative growth index

210 Using the fitted GAMMs, we predicted expected growth for each observation under neutral moisture conditions by setting $\text{SPEI-12}_{\text{Jul}} = 0$ while holding all other covariates unchanged. This yields the expected BAI for tree i in year t under climatically neutral moisture conditions:

$$\widehat{\text{BAI}}_{i,t}^{(0)} = \widehat{\text{BAI}}_{i,t} \big|_{\text{SPEI-12}_{\text{Jul}}=0}. \quad (9)$$

We then defined a relative growth index as

$$215 \quad \text{RI}_{i,t} = \frac{\text{BAI}_{i,t}}{\widehat{\text{BAI}}_{i,t}^{(0)}}. \quad (10)$$

Under this definition, $\text{RI}_{i,t} = 1$ indicates growth equal to the expected growth under neutral moisture conditions, values below 1 indicate growth suppression, and values above 1 indicate above-expected growth. Thus, RI expresses observed growth relative to a counterfactual baseline for the same tree-year observation, while holding age, size, plot and tree effects, and the site-specific climate-response structure constant. Because tree growth can also be influenced by factors other than drought, 220 including competition, pests, or nutrient limitation, RI should not be interpreted as a pure no-stress baseline.

2.5.2 Rolling-window anomaly metrics

To place growth reductions during 2018–2022 in a longer historical context, we calculated growth anomalies over annual ($L = 1$) and five-year ($L = 5$) windows. For each tree, the anomaly was defined as the ratio of observed to expected BAI summed over the window:

$$225 \quad \text{RI}_{i,t}^{(L)} = \frac{\sum_{k=0}^{L-1} \text{BAI}_{i,t-k}}{\sum_{k=0}^{L-1} \widehat{\text{BAI}}_{i,t-k}^{(0)}}, \quad (11)$$

where t is the final year of the window. A ratio of 1 indicates growth equal to that expected under neutral moisture conditions, whereas values below 1 indicate reduced growth.

To summarize, the log-transformed ratios were averaged across trees within each plot–species unit. For species-level summaries, the resulting plot-level values were then averaged across plot–species units, giving each unit equal weight regardless 230 of the number of trees sampled. Plot- and species-level means were back-transformed and expressed as percentage deviations



from expected growth as

$$\text{dRI}^{(L)} = 100 \left[\exp(\overline{\ln \text{RI}^{(L)}}) - 1 \right]. \quad (12)$$

This geometric averaging treats proportional increases and decreases symmetrically and limits the influence of unusually large positive anomalies. Percentile ranks compare each recent anomaly with anomalies calculated at the same aggregation level and window length over the 1951–2024 record.

2.6 Drought-event impacts on radial growth

The rolling-window metrics summarize growth anomalies across the full study period. To understand how much growth was depressed in relation to drought severity, we performed a mixed-model analysis linking individual drought events to tree growth during those events. Drought events were delineated from the site-specific SPEI-12 series (Sect. 2.4). Because events are delineated in months whereas RI is annual, each event e was mapped to the set of calendar years $\mathcal{Y}_e$ spanned by its start and end months, and the growth response was taken as the lowest annual anomaly within that set:

$$\min \text{RI}_{i,e} = \min_{t \in \mathcal{Y}_e} \text{RI}_{i,t}. \quad (13)$$

Because drought events delineated at SPEI-12 span at most two calendar years, this minimum is taken over one or two annual values, limiting any influence of event length on the minimum.

We then fitted species-specific linear mixed-effects models relating minimum growth during an event to drought severity and to whether the event overlapped the recent drought sequence (2018 onward):

$$\ln \min \text{RI}_{i,e} = \beta_0 + \beta_1 z(S_e) + \beta_2 I_{2018+}(e) + b_e + b_{\text{plot}(i)} + b_{\text{tree}(i)} + \varepsilon_{i,e}, \quad (14)$$

where $z(S_e)$ denotes event severity standardized within species and $I_{2018+}(e)$ is an indicator for events overlapping 2018 or later. Random intercepts for event, plot, and tree identity accounted for repeated observations and the hierarchical sampling design. The coefficient β_2 estimates the difference between recent and historical events at a given severity: negative values indicate additional growth suppression during recent events, and positive values indicate less suppression.

2.7 Distance-decay of spatial synchrony

Spatial synchrony quantifies the extent to which geographically separated populations co-fluctuate due to shared environmental forcing (Walter et al., 2017). Tree-growth synchrony has been used to infer the spatial scale of common climate limitation and to diagnose changes under warming (Tejedor et al., 2020).

The spatial synchrony was assessed for the three species with sufficient plot replication: European beech (*Fagus sylvatica*, FASY), Scots pine (*Pinus sylvestris*, PISY), and oak (*Quercus* spp.). Here, the two oak species were pooled because each was represented in too few plots to characterize distance-decay separately and because their plot-level anomaly series showed comparable decay behavior. For each plot, we constructed annual plot-level growth-anomaly series by averaging the tree-level $\ln(\text{RI})$, and computed the Pearson correlation coefficient between the plot-level anomaly series using pairwise complete



observations within the 1951–2024 analysis period. For comparison, we computed analogous inter-plot correlations for the climatic driver using plot-level SPEI-12_{Jul} series. The distance decay was then summarized by Spearman rank correlation between pairwise r and inter-plot distance.

3 Results

265 3.1 Hydroclimatic severity and persistence of the 2018–2022 drought episode

To put the tree-growth responses into context, we first evaluated all regional drought events across the six sampling regions using SPEI accumulation scales of 3, 12, 24, and 48 months. Figure 2 visualizes the duration and intensity characteristics of all identified events between 1951 and 2024 for each region and accumulation scale and highlights the start year of the three most severe events.

270 At SPEI-3, the most recent severe event lasted 6 to 8 months and was ranked 1st to 3rd in terms of severity and first to fourth in terms of duration across the six sampling regions (see Table B1). This was the 2018 drought in five regions and the 2022 drought in the West-High region. At SPEI-12, the 2018 drought was ranked as the most severe in four regions, but was surpassed by both the 2022 drought in West-High and the 1959 drought in East-High. In terms of mean intensity, however, these recent events ranked second in five of the six regions, again behind the 1959 drought. Therefore, at these short accumulation
275 scales, the recent droughts rank among the most extreme during the study period beginning in 1951, though they are not unprecedented in every region.

At longer accumulation scales, however, the 2018–2022 drought period clearly departs from earlier historical events. As illustrated by the SPEI time series in Fig. B1, a number of repeated short-term deficits during 2018–2022 merge progressively into a sustained multi-year moisture deficit. Accordingly, at both 24- and 48-month accumulation windows, the recent multi-
280 year drought period ranks first for severity and duration in all six sampling regions, and first for mean intensity in all cases except West-High at SPEI-24 (rank 2 of 26). Especially at the longest accumulation window, drought duration ranges from 65 to 94 months and far exceeds that of any other event on record. Notably, in one region the prolonged deficit already began two years earlier in 2016 (West-High). Overall, the results indicate that, in terms of its combination of persistence, severity, and duration at longer accumulation scales, the dry hydroclimatic episode 2018–2022 is unmatched in the post-1951 climate
285 record.

3.2 Growth responses during drought events

3.2.1 Growth anomalies

Growth anomalies showed that the persistent 2018–2022 water deficit translated into both strong annual and sustained cumulative growth reductions, but with marked differences among the species. We used 2019 as the annual benchmark because it
290 represents the year with the highest growth impact across most of the sampled stands, and the five-year window 2018–2022 to summarize the cumulative impact of the recent drought sequence (Fig. 3).

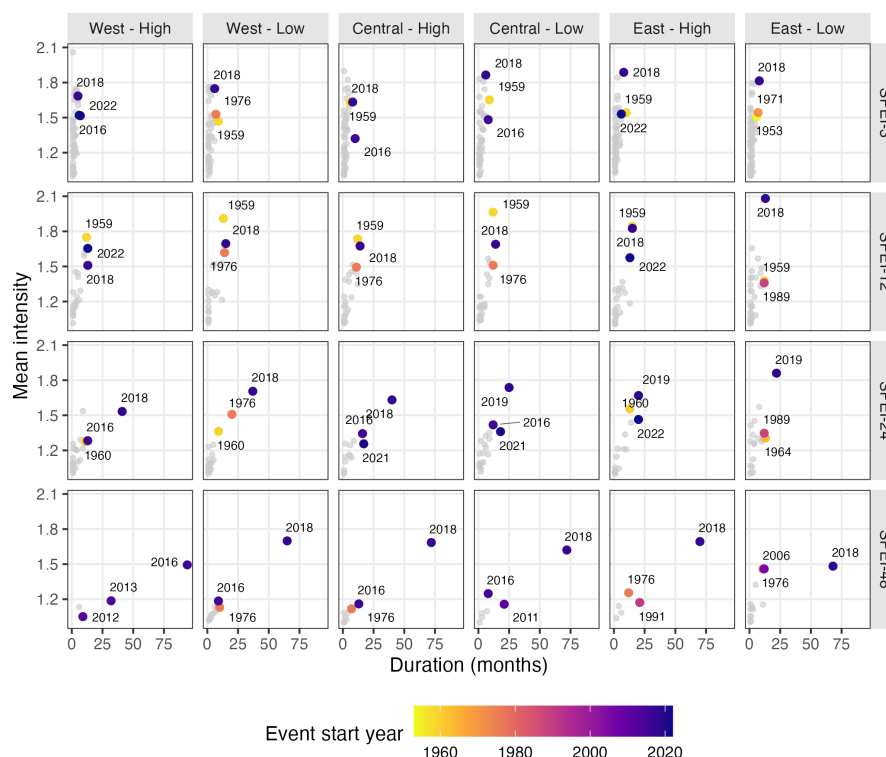


Figure 2. Duration–intensity characteristics of drought events at accumulation timescales of 3 to 48 months for each region. Grey points show all events identified between 1951 and 2024, coloured points mark the three most severe events (largest cumulative SPEI deficit, Sect. 2.4), per region and scale, labeled and coloured by event start year. Intensity is the mean deficit during the event ($-\text{mean SPEI}$).

Annual growth anomalies in 2019 were negative across all focal species, ranging from -21% to -42% , and fell into the upper tail of the observed species-specific distribution (79th to 93rd percentiles, Fig. 3). Douglas fir (PSME) differed from the other species in showing a strong response already in 2018 (-57% , 92nd percentile), earlier than in the other species. Its 2019 anomaly was still severe but, unlike in the other species, its strongest single-year deficit occurred in 2022 ($\approx -66\%$; cf. Fig. 4). When integrated across 2018–2022, the recent drought sequence produced some of the most severe five-year growth deficits in the record for European beech (FASY, P94), Scots pine (PISY, P94), pedunculate oak (QURO, P93), and Douglas fir (PSME, P99). For Douglas fir this was the most extreme five-year deficit in its own record, although that ranking rests on short chronologies (median 61 years, Table 2). By contrast, the species mean for sessile oak (QUPE) was much closer to zero ($\approx -6\%$), placing the recent episode near the center of the empirical distribution (P55).

These cumulative differences reveal contrasting temporal response patterns among species (Fig. 4). The annual $\text{SPEI-12}_{\text{Jul}}$ trajectory indicates pronounced drought conditions in 2019 and 2022, separated by partial relaxation in 2020–2021 and followed by recovery toward positive values by 2024. Beech (FASY) and pine (PISY) remained mostly below expected growth throughout 2018–2022, indicating sustained multi-year suppression. For beech, the variation of plot-level trajectories is es-

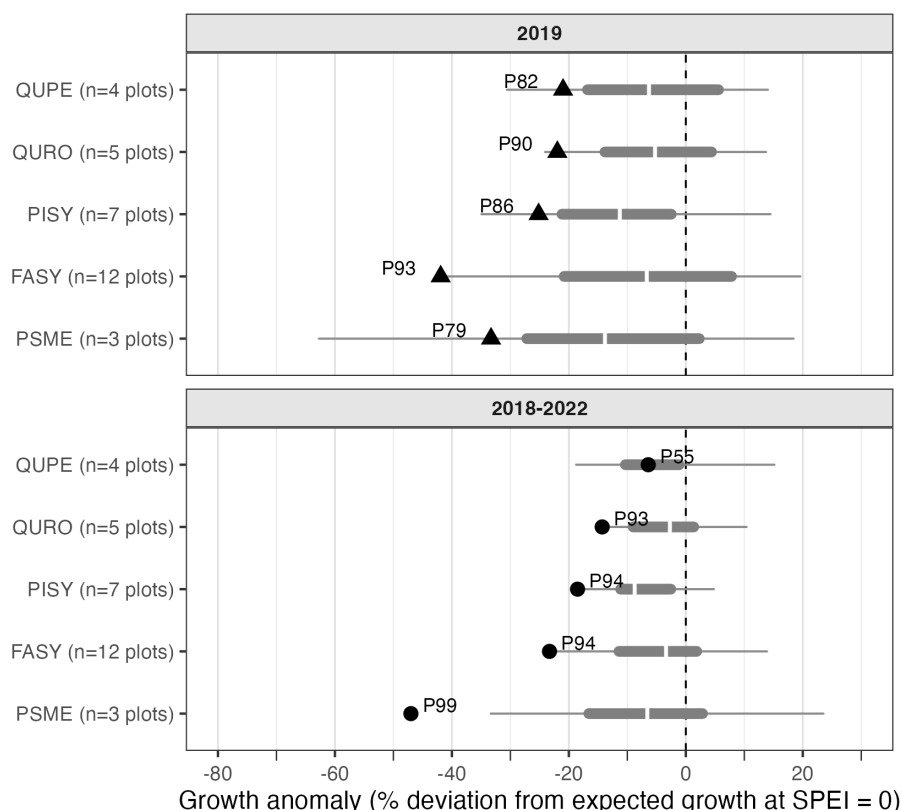


Figure 3. Rolling-window growth-anomalies during the recent drought sequence. Growth anomalies are expressed as percentage deviations from expected growth under neutral moisture conditions ($\text{SPEI-12}_{\text{Jul}} = 0$) and summarized for each species across the sampled plots. Box-plots show the species-specific historical distribution of rolling-window anomalies, with whiskers spanning the 5th–95th percentile range. The upper panel shows annual anomalies (L1), with 2019 highlighted as the main response year following the onset of the 2018 drought. The lower panel shows five-year rolling anomalies (L5), with the 2018–2022 window highlighted as the cumulative recent drought sequence. Labels indicate the percentile rank of the highlighted anomaly within that species’ own historical distribution, where higher values denote rarer, more severe deficits. For species abbreviations, refer to Table 2.

305 pecially strong in 2022, with some plots showing renewed declines while others returned to partial recovery, also visible in
 2020–2021. Pedunculate oak (QURO) also showed persistently negative but more moderate anomalies. Among the sampled
 sessile oak (QUPE) plots, short-term recovery, e.g., in 2021, was more evident than in QURO, although this pattern was not
 consistent across plots. Douglas fir (PSME) was distinct in showing strong suppression already early in the drought sequence,
 slight recovery during the intervening years, and a renewed, exceptionally strong decline in 2022. It is the only species that
 310 experienced larger growth reductions in 2022 than in 2019.

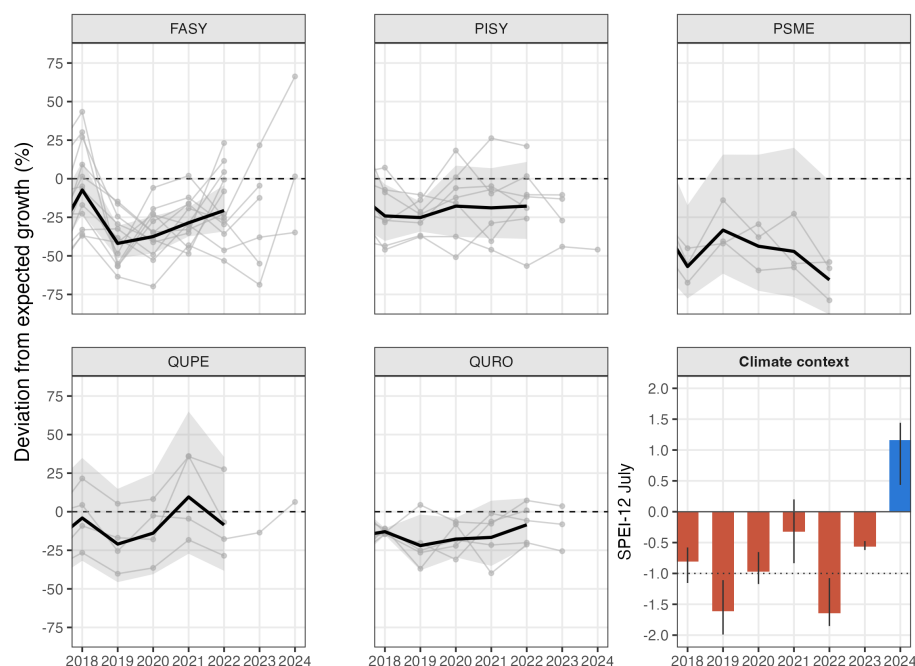


Figure 4. Plot-level annual growth anomalies from 2018 to 2022 (and later years where available), expressed as percent deviation from expected growth under neutral moisture conditions ($\text{SPEI}-12_{\text{Jul}} = 0$). Thin grey lines show plot–species units, the thick black line the species mean through 2022 with its 95% confidence interval (grey band), and the dashed line zero anomaly. Species panels are labeled by abbreviation (Table 2). The lower-right panel gives the climate context, where bars are the annual median of the $\text{SPEI}-12_{\text{Jul}}$ across sampling regions, whiskers the regional minimum and maximum, and the dotted line the drought threshold $\text{SPEI} = -1$.

3.2.2 Relationship between radial growth and drought severity

To test whether the recent drought sequence reduced growth more than expected from past droughts, we modeled the log-transformed minimum relative growth during each event as a function of drought severity, with an additive term distinguishing events from 2018 onward. Across all species, more severe drought events were significantly associated with lower relative growth (Table E1). However, the strength of this relationship differed among species, being steepest for Douglas fir (PSME, $\approx -14\%$ per standard deviation of event severity) and weakest for pedunculate oak (QURO, $\approx -6\%$), as shown in Figure E1 and Table E1.

Figure 5 shows the model results for the two species with the strongest replication, European beech (FASY) and Scots pine (PISY). For beech, the recent-period effect on minimum relative growth at a given severity was -11.1% (95 % CI $[-20.8, -0.3]$), indicating additional suppression relative to historical events. The corresponding estimate for pine was -5.9% $[-15.8, +5.2]$, with an interval spanning zero. Douglas fir showed a larger negative period effect (PSME -25.1% $[-42.8, -2.1]$). Its interval excluded zero, but the estimate requires caution because the species was represented by only 3 plots and 45 trees and the model had a singular fit, with plot-level variance estimated as zero. Sessile oak showed a positive period effect (QUPE

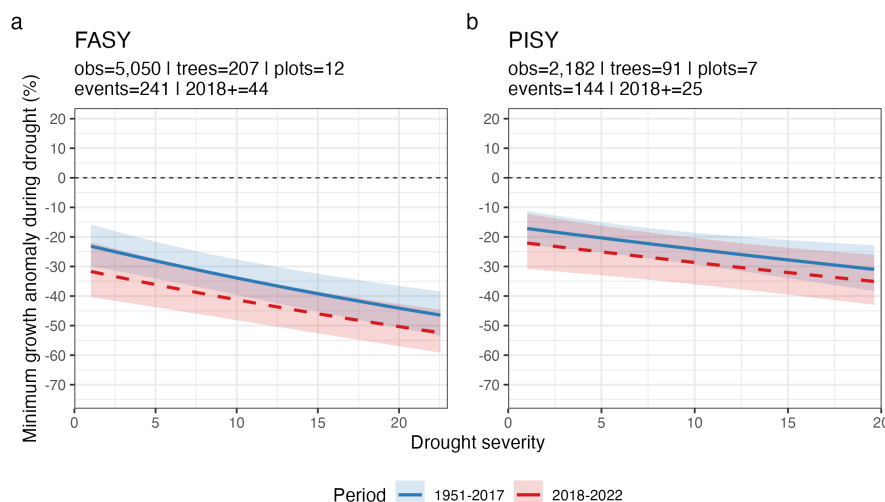


Figure 5. Predicted drought impact on radial growth for (a) European beech (FASY) and (b) Scots pine (PISY). Lines show the predicted minimum growth anomaly during a drought event as a function of event severity, with 95% confidence intervals (shaded); blue solid for 1951–2017, red dashed for 2018–2022. Models were fitted to $\ln \text{minRI}$ (Eq. 14). Predictions are back-transformed and expressed as percent deviation from expected growth under neutral moisture conditions. Values below the dashed line at 0 % indicate growth suppression during the event. Panel subtitles report sample sizes (observations, trees, plots, total events, and post-2018 events).

+17.4% [+0.4, +37.3]), indicating less growth suppression at a given severity during recent events, while the period effect
325 for pedunculate oak remained unresolved (QURO -5.8% [$-13.6, +2.8$]; Table E1).

3.3 Spatial heterogeneity and synchrony of drought impacts

Despite strong regional climatic forcing, plot-level trajectories during 2018–2022 (Fig. 4) revealed substantial heterogeneity within species. To ask whether such divergence is a general feature of growth along the transect rather than a peculiarity of this event, we quantified how similarly trees grew from year to year at different plots, and whether that similarity declined with
330 distance. Applying the same comparison to the drought index (SPEI-12_{Jul}) shows what to expect if growth simply tracked the regional climate signal (Fig. 6). In beech, pine and oak alike, pairs of plots shared far less of their year-to-year growth variation than of their climate: even neighboring plots a few hundred meters apart, exposed to virtually identical weather, grew together only moderately ($r \approx 0.4$ – 0.7). Growth similarity also declined with distance in beech and oak (Spearman $\rho = -0.77$ and -0.67 , 66 and 36 plot pairs), whereas pine growth was already weakly correlated at short distances and changed little
335 along the transect ($\rho = -0.27$, 21 plot pairs). The distance-decay coefficients and fits in Fig. 6 are descriptive summaries rather than formal tests, because each plot enters multiple pairs and the pairwise correlations are therefore not independent.

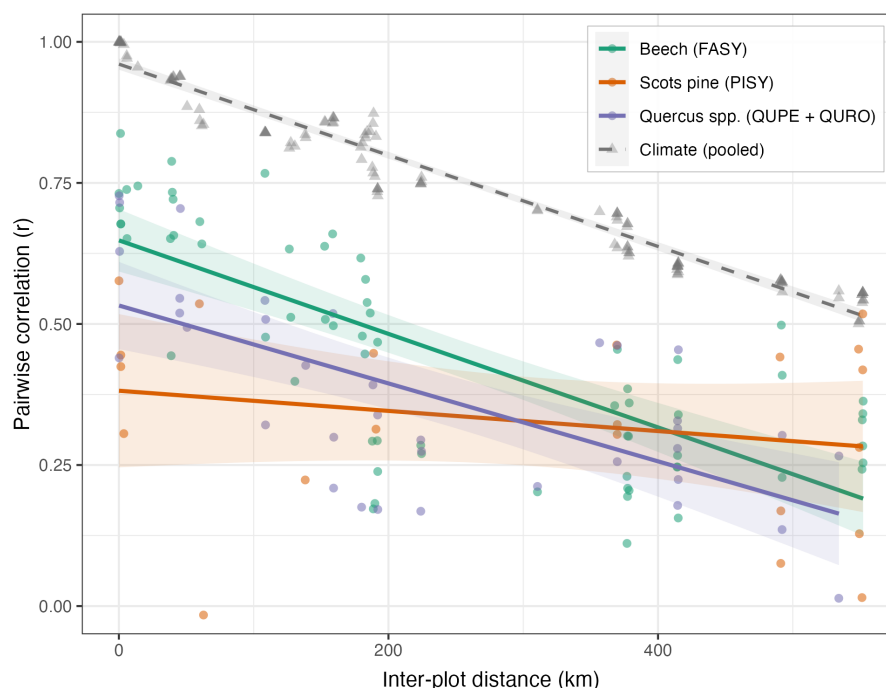


Figure 6. Distance-decay of spatial synchrony in growth anomalies compared to the climatic driver for the entire study period 1951–2024. Pairwise synchrony (Pearson’s r) as a function of inter-plot distance (km) for European beech (FASY), Scots pine (PISY) and oak (*Quercus* spp., QUPE + QURO combined), alongside the pooled climatic driver (SPEI-12_{Jul}). Points are individual plot pairs and lines are linear-model fits with 95 % confidence bands (shaded).

4 Discussion

4.1 The 2018–2022 sequence as a persistent drought regime

The 2018–2022 period in Central Europe was an exceptional sequence of compound hot-dry events, driven by recurring precipitation deficits, high temperatures, and elevated atmospheric evaporative demand (Markonis et al., 2021; Bevacqua et al., 2024; Rakovec et al., 2022). How exceptional it appears, however, depends on the timescale over which water deficits are accumulated. At SPEI accumulation scales of 3 and 12 months, which isolate individual dry spells, the recent events remained comparable to earlier severe droughts such as 1959 or 1976 in parts of the transect. At the 24- and 48-month scales, which integrate across successive years, the event overlapping 2018–2022 ranked first for severity and duration in all six regions, and first for mean intensity in all but the West–High region at SPEI-24 (Table B1, cf. Fig. 2), although in the West–High region the 48-month deficit had already set in by 2016. What was unprecedented was not the intensity of any individual dry summer, but rather the failure of the water balance to recover between them. Water deficits accumulated faster than stores were replenished over multiple years, leading to the depletion of deeper soil water and groundwater (Boeing et al., 2022; Pohle et al., 2025).



These rapidly recurring stress sequences under warmer atmospheric conditions reduce the time available for hydrological and biological recovery, so annual growth anomalies may reflect both current-year stress and carry-over effects from preceding dry years (Anderegg et al., 2015; Kannenberg et al., 2019; Schnabel et al., 2022). This matters especially for radial growth, where wood formation depends on cambial activity and turgor as well as carbon supply (Cabon et al., 2020; Peters et al., 2021; Zweifel et al., 2021) and where incomplete recovery between events can prolong suppression after the climatic deficit eases (Hagedorn et al., 2016; Gessler et al., 2017).

Consistent with this, growth remained below the expected growth under neutral moisture during the partial hydroclimatic relaxation of 2020–2021 for four of the five species means and at most individual plots, with only sessile oak briefly approaching its expected growth in 2021 (Fig. 4). The 2018–2022 sequence therefore illustrates how forest drought impacts are less well attributed to discrete events than to cumulative drought regimes, in which repeated exposure and incomplete recovery jointly determine growth responses. Distinguishing acute drought stress from persistent drought sequences is thus essential for assessing forest impacts, particularly as back-to-back and multi-year droughts are projected to become more likely in Europe under continued warming (Schumacher et al., 2024; Suarez-Gutierrez et al., 2023).

4.2 Strong but locally filtered growth impacts

Four of the five species recorded some of the strongest five-year growth deficits since 1951 during 2018–2022. These losses were not, however, uniformly severe across the network. The plot-level percentile rankings (Appendix D) place the recent anomaly in the extreme tail of the local historical distribution at only some of the plots. Sessile oak (QUPE) shows this unevenness most clearly, with one plot growing above its expected growth throughout the recent period and a second recording a strong positive anomaly in 2021 (cf. Fig. 4). Averaged to species level, these gains offset the losses at the remaining plots: omitting the single above-expectation plot shifts the QUPE mean from -6.4% to -14.1% (Fig. D2). A near-neutral species mean can therefore conceal substantial deficits at individual stands rather than indicate an absence of drought impact.

Trees at neighboring plots experienced nearly the same weather, yet lost very different amounts of growth (Appendix D), and shared far less of their year-to-year growth variation than of their climate (Fig. 6). Most of that mismatch is already present between plots a few hundred meters apart. Part of this divergence follows from the trees themselves. The anomalies are already expressed relative to expected growth at a given age and size and account for serial dependence between years, but they do not absorb differences in age-dependent drought sensitivity, competitive status, or crown condition. A large part, however, likely reflects how much water each stand could actually reach. A stand rooted in deep, water-retentive soil, or with access to groundwater, draws down its supply more slowly through a dry period and therefore sustains cambial activity longer under the same climatic deficit than a stand on shallow or freely draining soil (Weigel et al., 2023; Walthert et al., 2021; Putzenlechner et al., 2023). Where trees stand densely, they draw on that same limited store simultaneously, which can deplete it earlier in the season and deepen the growth loss (Schmied et al., 2023; Castagneri et al., 2022).

The paired pedunculate-oak plots at Hinnensee illustrate this directly. The pair was established specifically to contrast proximity to groundwater, and the growth outcome followed that contrast: trees at PF12 fell 18.3% below their expected growth over 2018–2022, whereas those at PF13, only 156 m away and under effectively identical weather, stayed within 2.5% of ex-



pectation. The trees at PF13 therefore plausibly retained access to water that those at PF12 had already lost (Skiadaresis et al., 2019, 2021; Steger et al., 2024), although the low replication at PF13 (5 trees, median EPS 0.665, Table A1) makes the contrast
385 suggestive rather than conclusive. Regional drought indicators therefore remain well suited to identifying coherent exposure and benchmarking event severity, but translating regional severity into plot-scale impacts for unsampled stands will require additional information on local water availability and stand context.

4.3 Interpreting drought impacts from SPEI-based growth anomalies

The event-based models linked stronger SPEI-derived severity to lower minimum relative growth in all species, with the
390 steepest response in Douglas fir and the weakest in pedunculate oak (Table E1). For beech, recent events also fell significantly below the historical severity–impact relationship, with minimum relative growth -11.1% (95 % CI $[-20.8, -0.3\%]$) lower at a given severity. Douglas fir showed a larger negative effect of -25.1% (95 % $[-42.8, -2.1\%]$), although limited plot replication and a singular fit constrain the interpretation and generalization of this estimate. Sessile oak showed the opposite shift of $+17.4\%$ (95 % $[+0.4, +37.3]$), indicating less suppression during recent events at equal severity, whereas the intervals
395 for pine and pedunculate oak spanned zero.

These species contrasts may partly reflect differences in drought response strategy and rooting access. Scots pine has been described as a relatively conservative water user with strong stomatal control under drought, and its radial growth often responds closely to climatic water-balance indices such as SPEI (Irvine et al., 1998; Martin-Benito et al., 2013). This is consistent with the absence of an additional period effect in our models, although it does not imply that pine responses are fully explained by
400 SPEI alone. Oaks, particularly *Quercus robur* on sites with access to deeper soil water or groundwater, can buffer atmospheric and shallow-soil deficits through deeper water uptake and conservative stomatal regulation (Skiadaresis et al., 2019, 2021; Neuwirth et al., 2021; Niemczyk et al., 2024). Beech and Douglas fir, by contrast, appear more vulnerable to combinations of soil drying, heat, and high atmospheric demand. Recent studies identify heat and elevated vapor pressure deficit as important drivers of beech growth decline, while Douglas fir growth and water use are strongly constrained by atmospheric saturation
405 deficit and soil-water limitation (Leuschner and Bat-Enerel, 2024; Niemczyk et al., 2024; Leuschner and Meinzer, 2024; Niessner et al., 2024). For Douglas fir, stand age may sharpen this sensitivity further. Drought susceptibility in this species has been reported to be highest in young stands, where shallower rooting and lower stem water storage capacity provide little buffer against water deficits (Leuschner and Meinzer, 2024), and the Douglas fir stands sampled here are by far the youngest in our network (median chronology length 61 years, Table 2). Deeper rooting with age, however, only buffers a stand for as
410 long as water remains at depth to be reached. Where deficits persist across successive years and propagate into deeper soil layers (Boeing et al., 2022; Pohle et al., 2025), that advantage erodes, which tempers the expectation that older stands would have been substantially better buffered through a sequence of this duration. These differences may also extend to the timing of climatic sensitivity, with beech showing stronger responses to summer drought and oak responding more strongly to spring climatic conditions (Scharnweber et al., 2013; Engelmayer et al., 2026).

415 Two mechanisms could explain why recent drought events reduced beech and Douglas fir growth more than their SPEI severity alone would predict. First, SPEI integrates precipitation and potential evapotranspiration into a standardized climatic



water-balance metric, but it cannot fully resolve the independent physiological effects of heat, vapor pressure deficit, and short-term extremes, especially where PET is estimated from simplified meteorological inputs (Peng et al., 2024). Thus, recent droughts may have imposed higher atmospheric demand, heat stress, or soil-water limitation than implied by their SPEI severity alone. Second, the rapid recurrence of stress within the recent drought sequence may have left less time for recovery, so that impacts accumulated across events through legacies in carbon reserves, hydraulic function, and canopy condition that a single event-severity axis cannot capture (Anderegg et al., 2015; Kannenberg et al., 2019; Schnabel et al., 2022). Both mechanisms could cause an event-severity framing to under-represent realized impacts in these species, but the period coefficients do not distinguish between them. The contrasting positive effect in sessile oak also shows that recent events did not uniformly amplify suppression across species.

Several caveats bound this interpretation. The GAMM anomalies provide a baseline for expected growth under neutral moisture conditions while accounting for age, size, repeated measurements, and site-level variation in drought sensitivity, but they are not pure drought effects and may also carry signals of competition, stand structure, pests, management, or pre-drought vitality. The tree- and plot-level random effects and the smooth age and size terms reduce confounding by persistent and slowly varying structure, but they cannot exclude time-localized shocks. Yet, these caveats bear mainly on the magnitude of the anomalies rather than their direction. The negative sign of the response is well supported, because the 2019 and 2022 annual anomalies and the five-year cumulative anomaly remained negative for all species under every alternative SPEI driver tested (Appendix C2), and the negative species-level deficits were robust to omitting any single plot (Fig. D2). The exception is the near-neutral sessile oak mean, which, as described above, rests on a single above-expectation plot. Limited replication therefore constrains how far individual deficits can be extrapolated, but it does not undermine the consistently negative growth signal. Furthermore, sample depth declines after 2022 because chronologies end between 2022 and 2024 (Table 2), so any lagged response in 2023 is only partially represented. Since the timing of the 2022 drought also varied along the transect and some stands showed little or no growth response by 2022 (Fig. 4), such a lag would in any case not be expected in the same year at every plot.

5 Conclusions

Our analysis draws on 31 plot–species chronologies from more than 460 trees of five species, sampled along a west–east transect spanning the hydroclimatic gradient across Germany. Together, these records place the 2018–2022 drought sequence against seven decades of hydroclimate and growth variability, and resolve its impact both among species and among individual stands.

The persistence of the recent drought was matched by the magnitude of its growth impacts. At 24- and 48-month accumulation scales, the sequence is the most severe and longest event in the post-1951 record in every region examined, and four of the five species recorded among the strongest five-year growth deficits of the 1951–2024 analysis period. Event models indicated additional growth suppression at a given drought severity in beech and Douglas fir, although the Douglas fir result was



constrained by limited replication. Sessile oak showed less suppression than during historical events of equal severity, while
450 period effects remained unresolved for pine and pedunculate oak.

Those impacts were not, however, evenly distributed, nor proportional to the climatic signal. Losses differed among species, and among stands of the same species growing a few hundred meters apart under effectively identical weather. Species identity and local site context therefore governed how much growth a given stand actually lost, and a regional water-balance index such as SPEI is far better at identifying which forests were exposed than at predicting where growth was lost.

455 Because exposure and impact separate at distances below the resolution of the climate data, translating regional severity into growth losses requires local information on water availability and stand structure. Tree-ring networks such as this one provide the ground truth against which spatially distributed indicators can be calibrated. As global warming raises atmospheric evaporative demand and increases the recurrence of drought, water-balance indices alone may underestimate impacts under recurrent hot droughts, particularly for species such as European beech that are strongly affected by heat and high vapor-
460 pressure deficit.



Appendix A: Tree-ring dataset overview and chronology diagnostics

A1 Temporal distribution of the sampled trees

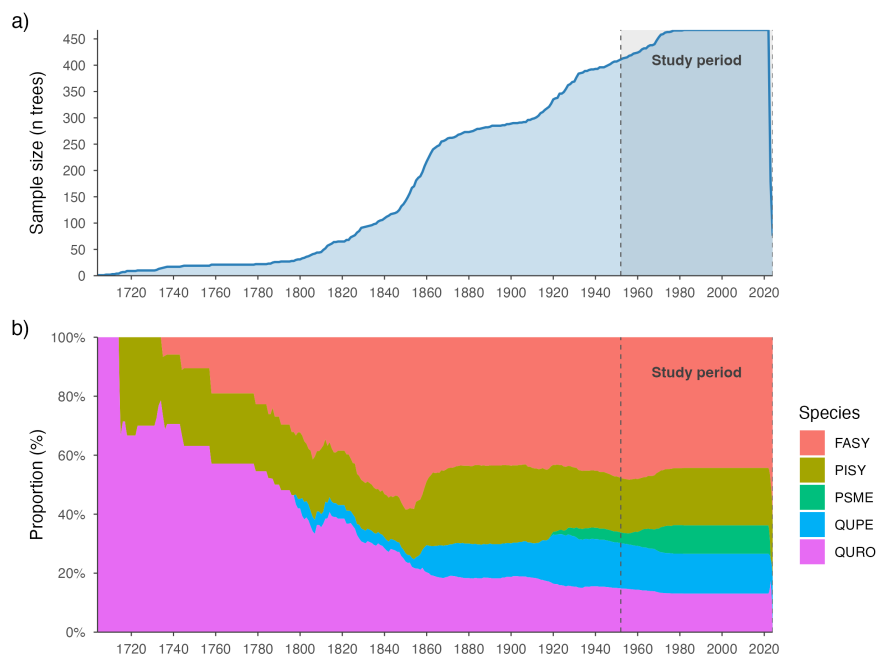


Figure A1. Temporal distribution of the sampled trees. (a) Cumulative sample size (number of trees) through time. (b) Relative species composition of the sample through time, expressed as the proportion of trees belonging to each species. Dashed vertical lines indicate the study period.



A2 Plot-level chronology metadata and descriptive statistics

Table A1. Plot-level metadata and descriptive chronology statistics for each sampled chronology. AGR, GLK, and NET are the 1963–2020 average radial growth, Gleichläufigkeit, and signal-strength parameter, respectively (Esper et al., 2001). Start abs. is the earliest measured ring year, Chron. start/end define the chronology interval, Length abs./chr. are the corresponding durations, Trees is the number of sampled trees, and EPS/rbar are median annual chronology reliability metrics. The table lists all 33 sampled chronologies. Two of them, the juvenile beech plots PF05 and SF04, were sampled beside the mature beech plots SF13 and SF08 and share their coordinates exactly; each juvenile plot is therefore treated as one plot–species unit together with its parent plot, so that the analyses rest on 31 plot–species units.

Plot code	Species	Forest type	AGR _{63–20}	GLK _{63–20}	NET _{63–20}	Start abs.	Chron. start	Chron. end	Length abs.	Length chr.	Trees	Median EPS	Median rbar
PF03	FASY	oak-beech forest	1.39	0.704	0.662	1852	1854	2022	171	169	15	0.919	0.444
PF05	FASY	mixed broadleaf forest	1.70	0.722	0.730	1917	1921	2024	108	104	15	0.911	0.412
PF08	FASY	beech-pine forest	1.01	0.744	0.605	1788	1804	2023	236	220	15	0.952	0.572
PF09	FASY	beech-pine forest	1.31	0.695	0.776	1798	1806	2023	226	218	15	0.938	0.522
SF02	FASY	lady-fern wood-rush beech forest	1.18	0.738	0.612	1829	1836	2022	194	187	15	0.930	0.478
SF04	FASY	wood-rush beech forest	1.77	0.688	0.638	1940	1948	2023	84	76	15	0.909	0.404
SF05	FASY	orchid beech forest	1.36	0.759	0.594	1813	1824	2022	210	199	15	0.946	0.572
SF08	FASY	wood-rush beech forest	1.52	0.708	0.627	1796	1803	2022	227	220	15	0.931	0.507
SF13	FASY	mixed broadleaf forest	3.33	0.722	0.540	1925	1926	2024	100	99	15	0.915	0.418
SF14	FASY	mixed beech forest with Douglas-fir	1.79	0.745	0.609	1908	1908	2024	117	117	20	0.962	0.566
SF18	FASY	high-canopy beech forest	1.55	0.762	0.580	1838	1848	2022	185	175	15	0.957	0.619
SF19	FASY	beech forest	0.87	0.720	0.588	1735	1758	2022	288	265	15	0.874	0.386
SF20	FASY	montane beech forest	1.28	0.745	0.521	1846	1848	2022	177	175	15	0.956	0.597
SF22	FASY	mixed pine-beech forest	2.05	0.717	0.550	1930	1942	2024	95	83	15	0.942	0.522
PF10	PISY	beech-pine forest	0.69	0.662	0.721	1745	1799	2023	279	225	15	0.914	0.488
PF11	PISY	beech-pine forest	0.63	0.631	0.917	1715	1718	2023	309	306	14	0.857	0.372
SF03	PISY	orchid beech forest	0.43	0.619	0.880	1846	1850	2022	177	173	15	0.891	0.375
SF06	PISY	pine plantation	3.20	0.733	0.558	1965	1966	2022	58	57	15	0.944	0.575
SF10	PISY	mixed pine-oak-beech forest	1.16	0.657	0.725	1852	1854	2023	172	170	15	0.884	0.384
SF16	PISY	melic grass oak forest	0.63	0.744	0.551	1860	1861	2022	163	162	15	0.958	0.617
SF23	PISY	mixed pine-beech forest	0.86	0.676	0.674	1855	1856	2024	170	169	15	0.927	0.489
SF11	PSME	Douglas-fir plantation	3.28	0.655	0.683	1956	1958	2022	67	65	15	0.898	0.386
SF15	PSME	mixed beech forest with Douglas-fir	2.68	0.754	0.556	1919	1920	2022	104	103	15	0.935	0.493
SF21	PSME	Douglas-fir plantation	4.76	0.784	0.442	1969	1969	2022	54	54	15	0.943	0.544
PF02	QUPE	oak-beech forest	1.40	0.712	0.556	1855	1857	2022	168	166	18	0.967	0.626
PF06	QUPE	mixed broadleaf forest	2.04	0.673	0.615	1904	1914	2024	121	111	15	0.935	0.555
SF12	QUPE	mixed beech forest with Douglas-fir	1.28	0.710	0.667	1912	1914	2022	111	109	16	0.928	0.464
SF17	QUPE	melic grass oak forest	0.97	0.722	0.567	1798	1812	2022	225	211	15	0.952	0.613
PF04	QURO	oak-beech forest	2.18	0.699	0.530	1843	1855	2023	181	169	11	0.921	0.528
PF12	QURO	oak-beech forest	1.31	0.651	0.600	1708	1718	2023	316	306	15	0.903	0.502
PF13	QURO	oak-beech forest	1.04	0.590	0.771	1704	1716	2023	320	308	5	0.665	0.293
SF01	QURO	oak-hornbeam forest	1.23	0.708	0.700	1832	1837	2022	191	186	15	0.927	0.486
SF09	QURO	wood-rush beech forest	1.70	0.642	0.616	1808	1811	2022	215	212	15	0.951	0.565



A3 Tree attribute distributions by species

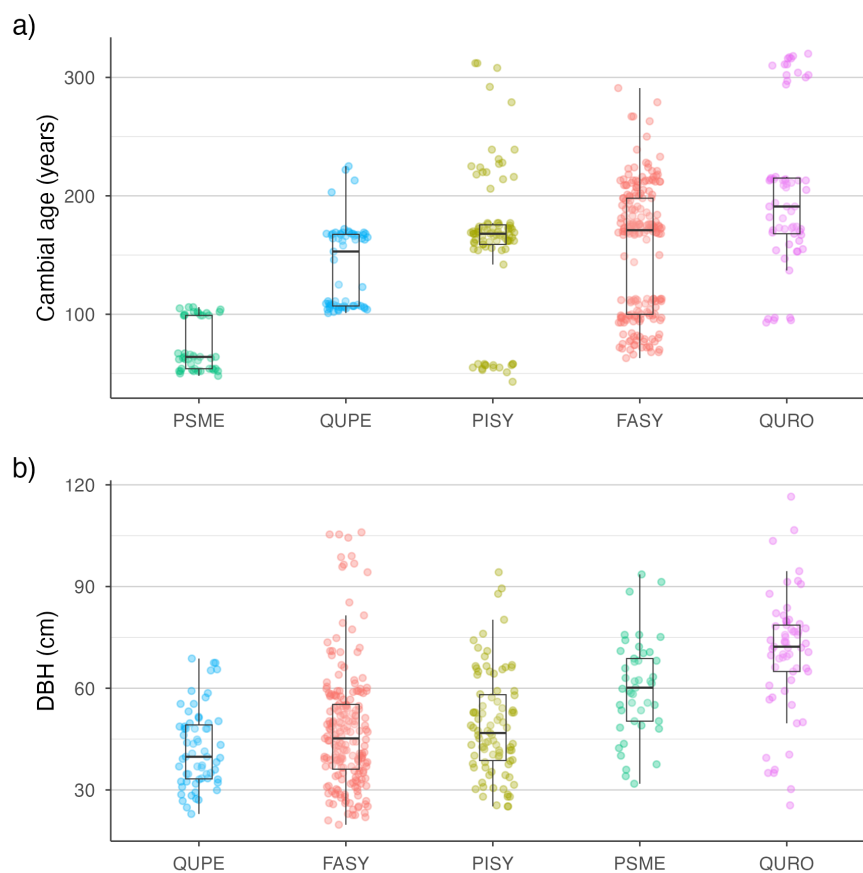


Figure A2. Tree attribute distributions by species. Panel (a) shows cambial age and panel (b) diameter at breast height (DBH). Points represent individual trees, and boxplots summarize the median, interquartile range, and spread within each species.



465 **A4 Plot-level chronology diagnostics**

Figures A3–A5 show the chronology diagnostics used to assess the quality of the tree-ring records using the R package `dplR`. For each plot chronology, tree-ring-width series were standardized with a 30-year smoothing spline (`dplR::detrend, method = "Spline", nyrs = 30`). The plotted chronology is the annual mean ring-width index (RWI) across all available trees, with shaded bands showing approximate 95 % confidence intervals from the among-tree standard error. Chronology reliability was evaluated from the standardized RWI series using 30-year running windows (`dplR::rwi.stats.running`). Windows were advanced annually, with a minimum overlap of 30 years, and correlations were computed after prewhitening. The plotted `rbar` is the effective mean interseries correlation, and `EPS` is the expressed population signal derived by `dplR` from the same running-window statistics. The figures are grouped by record length (Figs. A3–A5), with a common time axis within each group. The exact first and last ring years per series are given in Table A1.

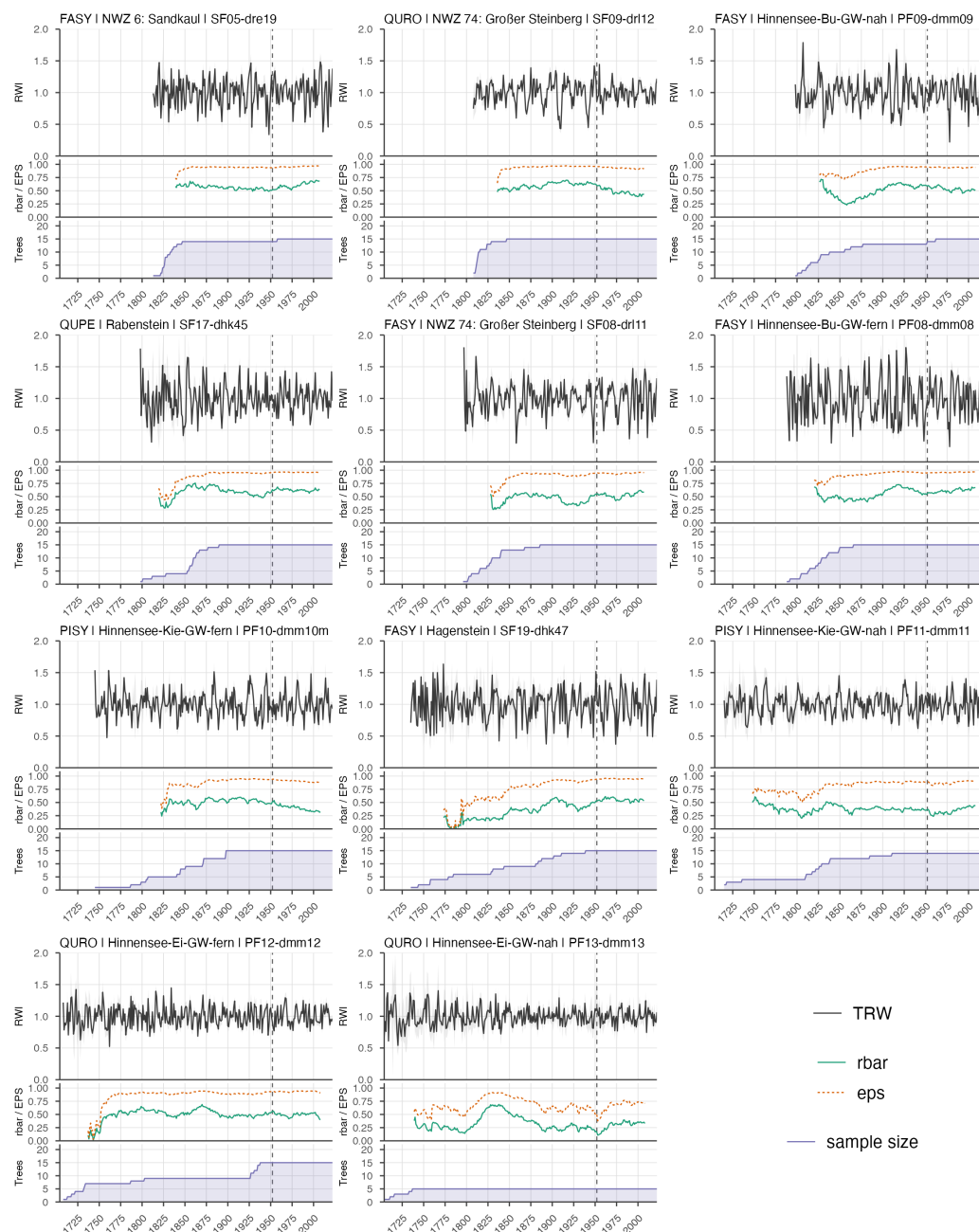


Figure A3. Plot-level chronology diagnostics (Part 1, 1704–2022). Each panel corresponds to one plot–species unit and shows, from top to bottom, the standardized tree-ring-width chronology (TRW), running interseries correlation (rbar; green) together with expressed population signal (EPS; orange dashed), and sample depth (number of trees; purple). Panel titles identify species and plot code. The dashed vertical line marks the start of the study period used for the climate–growth analyses.

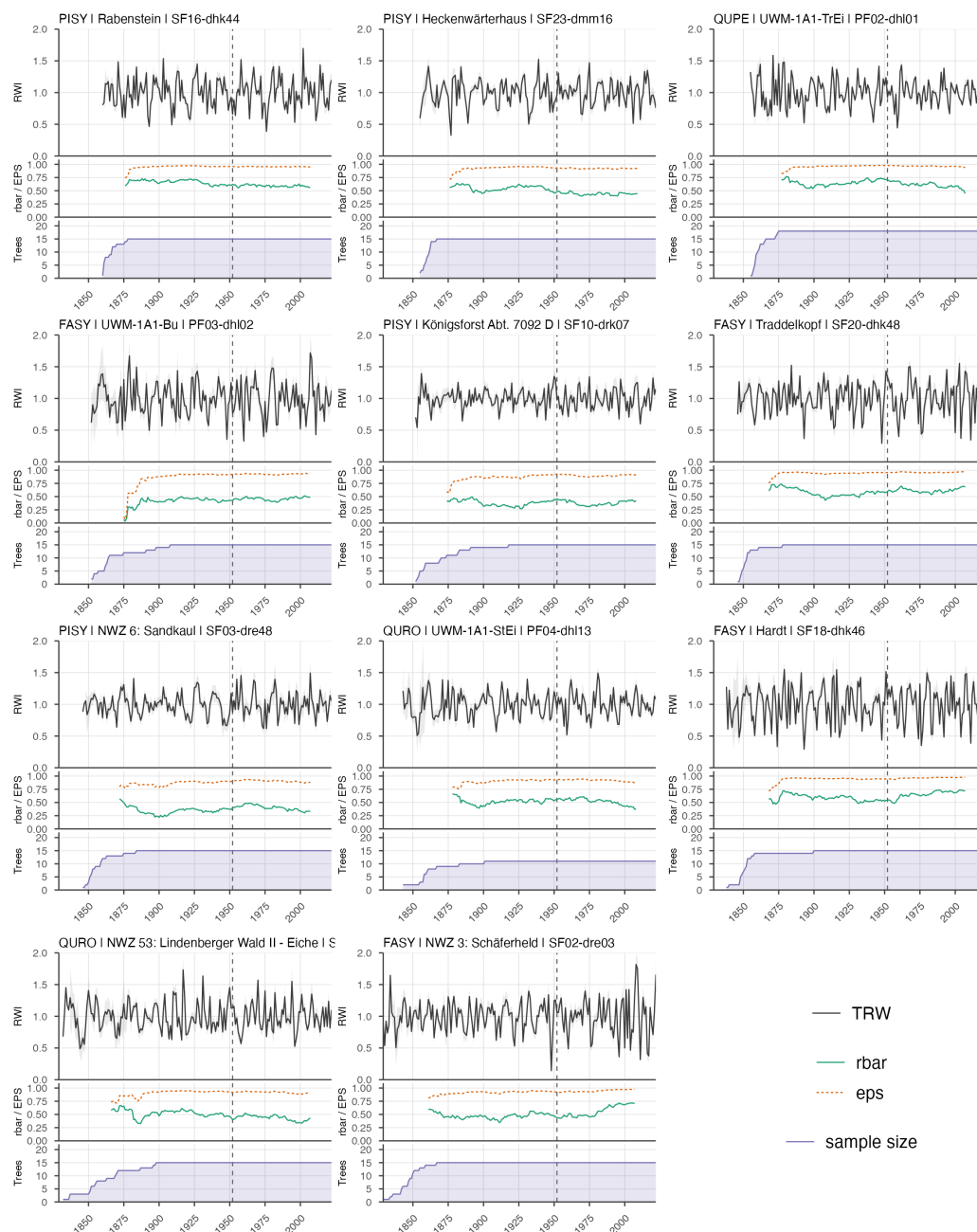


Figure A4. Plot-level chronology diagnostics (Part 2, 1829–2022). Each panel corresponds to one plot–species unit and shows, from top to bottom, the standardized tree-ring-width chronology (TRW), running interseries correlation (rbar; green) together with expressed population signal (EPS; orange dashed), and sample depth (number of trees; purple). Panel titles identify species and plot code. The dashed vertical line marks the start of the study period used for the climate–growth analyses.

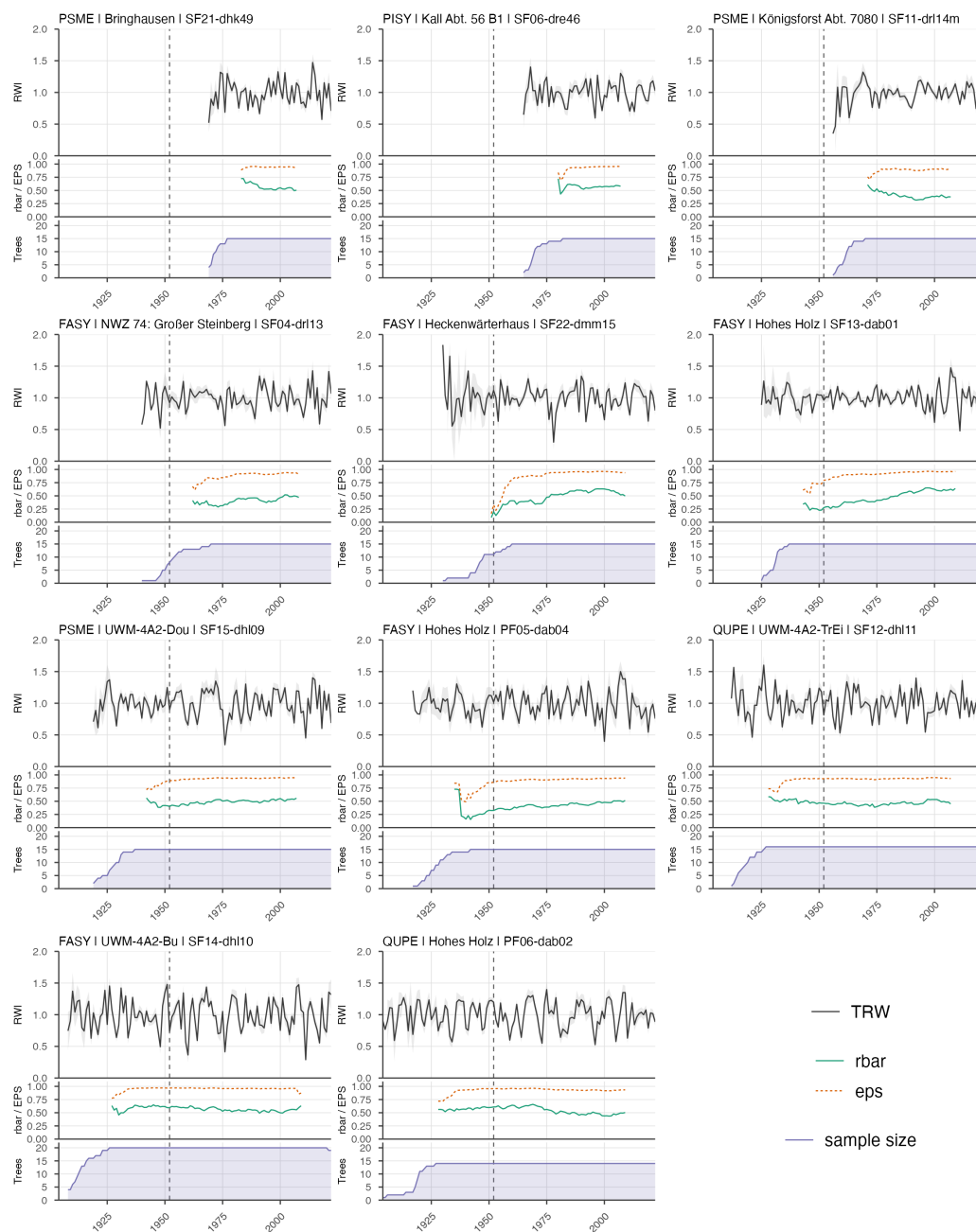


Figure A5. Plot-level chronology diagnostics (Part 3, 1904–2022). Each panel corresponds to one plot–species unit and shows, from top to bottom, the standardized tree-ring-width chronology (TRW), running interseries correlation (rbar; green) together with expressed population signal (EPS; orange dashed), and sample depth (number of trees; purple). Panel titles identify species and plot code. The dashed vertical line marks the start of the study period used for the climate–growth analyses.



475 A5 Quality control of core-based radius estimates

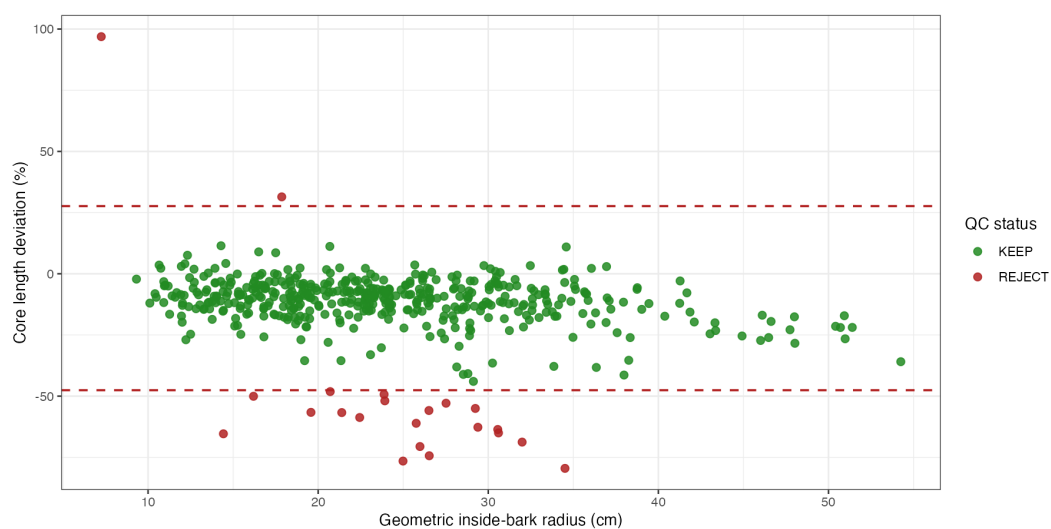


Figure A6. Quality control of core-based radius estimates. Each point represents one tree and shows the percentage deviation between the radial length represented by the tree-level ring-width series and the geometric inside-bark radius derived from manual measurements in the field. Dashed red lines indicate the exclusion thresholds defined as the sample median ± 5 median absolute deviations (MAD). Green points were retained for analysis and red points were excluded.



Appendix B: SPEI accumulation scales and drought-event ranking

B1 Dependence of drought characterization on SPEI accumulation timescale

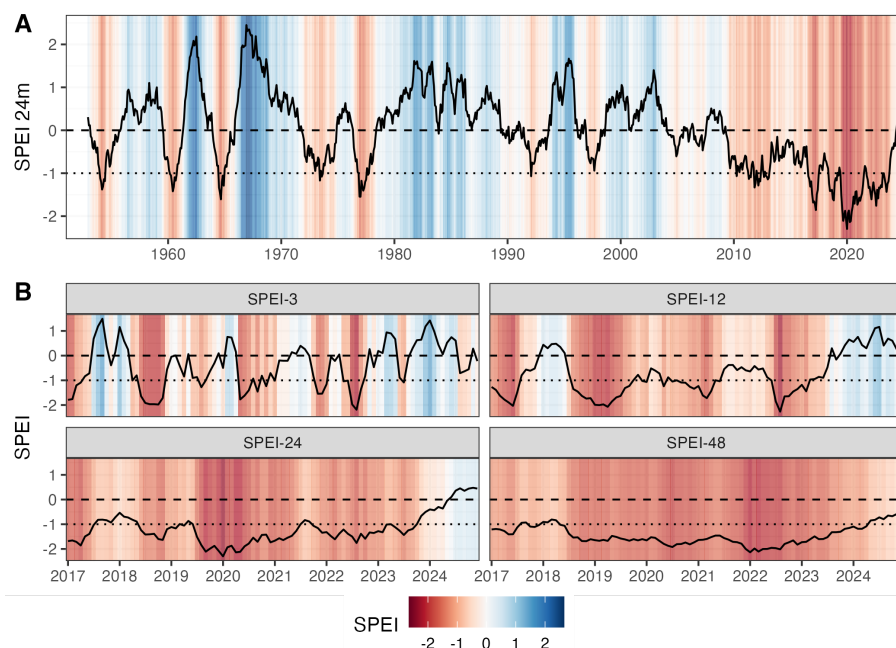


Figure B1. Dependence of drought characterization on SPEI accumulation timescale. (a) Full SPEI-24 time series for a representative region (1951–2024). (b) Zoom on 2017–2024 showing SPEI-3, SPEI-12, SPEI-24 and SPEI-48. Background shading indicates monthly SPEI values (colour scale); black lines show the SPEI time series. Dashed line marks normal conditions (SPEI = 0) and dotted line marks the drought threshold (SPEI = -1).



B2 SPEI-based event ranking

Table B1. Most severe drought event overlapping 2018–2022 by sampling region and SPEI accumulation scale. Events and ranks are derived from the sampling-region mean SPEI series, i.e. the same events shown in Fig. 2. Mean intensity is event severity divided by event duration, so larger values indicate stronger drought. Severity, duration, and intensity ranks are within sampling region $\times$ scale and are reported as rank/number of events since 1951.

Region	Scale	Dates	D_{mo}	I_{mean}	S_{rank}	D_{rank}	I_{rank}
Central–High	SPEI-3	2018-04 to 2018-11	8	1.63	2/52	2/52	7/52
Central–High	SPEI-12	2018-08 to 2019-09	14	1.67	1/24	1/24	2/24
Central–High	SPEI-24	2018-04 to 2021-07	40	1.63	1/14	1/14	1/14
Central–High	SPEI-48	2018-05 to 2024-04	72	1.68	1/9	1/9	1/9
Central–Low	SPEI-3	2018-06 to 2018-11	6	1.86	3/52	3/52	1/52
Central–Low	SPEI-12	2018-08 to 2019-09	14	1.69	1/26	1/26	2/26
Central–Low	SPEI-24	2019-07 to 2021-07	25	1.74	1/20	1/20	1/20
Central–Low	SPEI-48	2018-05 to 2024-04	72	1.62	1/7	1/7	1/7
East–High	SPEI-3	2018-05 to 2018-12	8	1.89	2/56	2/56	1/56
East–High	SPEI-12	2018-07 to 2019-09	15	1.83	2/24	1/24	2/24
East–High	SPEI-24	2019-02 to 2020-09	20	1.67	1/17	1/17	1/17
East–High	SPEI-48	2018-07 to 2024-04	70	1.69	1/6	1/6	1/6
East–Low	SPEI-3	2018-05 to 2018-12	8	1.81	1/63	1/63	1/63
East–Low	SPEI-12	2018-09 to 2019-09	13	2.08	1/31	1/31	1/31
East–Low	SPEI-24	2019-06 to 2021-03	22	1.86	1/19	1/19	1/19
East–Low	SPEI-48	2018-09 to 2024-04	68	1.48	1/13	1/13	1/13
West–High	SPEI-3	2022-05 to 2022-10	6	1.52	2/55	2/55	13/55
West–High	SPEI-12	2022-07 to 2023-07	13	1.65	1/24	1/24	2/24
West–High	SPEI-24	2018-02 to 2021-06	41	1.53	1/26	1/26	2/26
West–High	SPEI-48	2016-07 to 2024-04	94	1.49	1/4	1/4	1/4
West–Low	SPEI-3	2018-06 to 2018-11	6	1.75	3/46	4/46	3/46
West–Low	SPEI-12	2018-08 to 2019-10	15	1.70	1/21	1/21	2/21
West–Low	SPEI-24	2018-06 to 2021-06	37	1.71	1/22	1/22	1/22
West–Low	SPEI-48	2018-07 to 2023-11	65	1.70	1/11	1/11	1/11



Appendix C: GAMM implementation, diagnostics, and climate-driver sensitivity

480 C1 Model implementation and diagnostics

In the implemented workflow, the model for each species was fitted with `mgcv::bam()` using a Gamma distribution with log link, `method = "fREML"`, `discrete = TRUE`, and `select = TRUE`. The fitted model can be written in `mgcv` notation as

BAI ~

```
485 s(plot_code, bs = "re") +
    s(tree_id, bs = "re") +
    s(age, k = 5) +
    s(size, k = 5) +
    s(SPEI12_Jul_site, k = 6) +
490 s(SPEI12_Jul_site, site, bs = "fs", k = 5, m = 1)
```

where `SPEI12_Jul_site` is the site-level `SPEI-12Jul`. The factor-smooth interaction allows the `SPEI` response to vary among sites while shrinking poorly supported site-level deviations toward the species mean. Serial dependence was represented with an `AR(1)` structure within each tree-ring series. The correlation process was restarted at the first observation of each tree and after year gaps greater than one year. For each species, the `AR(1)` coefficient ρ was estimated from the weighted mean

495 lag-1 Pearson residual correlation obtained from a preliminary model fit without autocorrelation. Table C1 reports the resulting ρ values together with post-fit residual autocorrelation diagnostics, sample sizes, and grouping structure for each species.

Table C1. Diagnostics for the species-specific pre-2018 GAMMs used to estimate expected growth under neutral moisture conditions. ρ is the `AR(1)` coefficient used in the final fit, estimated from lag-1 Pearson residual correlation in a preliminary model. $r_{1,\text{std}}$ is the weighted lag-1 correlation of standardized residuals after refitting with `AR(1)`.

Species	ρ	$r_{1,\text{std}}$	R^2_{adj}	Dev. expl.	n_{obs}	n_{trees}	n_{plots}	n_{sites}
FASY	0.523	0.001	0.770	0.734	13,591	207	12	10
QUPE	0.500	0.015	0.789	0.774	4,158	63	4	3
QURO	0.530	-0.030	0.761	0.791	4,026	61	5	4
PISY	0.595	0.007	0.745	0.783	5,735	91	7	6
PSME	0.628	0.015	0.702	0.689	2,532	45	3	3

Table C1 summarizes the species-specific GAMMs trained on the pre-2018 period (1951–2017) and used to generate the expected growth under neutral moisture conditions baseline in the main analysis. Across species, model performance was consistently good, with adjusted R^2 values ranging from 0.70 to 0.79 and deviance explained ranging from 0.69 to 0.79. After



500 accounting for temporal dependence, weighted lag-1 correlations of standardized residuals were close to zero for all species ($r_{1,\text{std}} = -0.030$ to 0.015), indicating that the AR(1) structure adequately captured residual serial autocorrelation.

As an exemplar visual diagnostic, Figs. C1 and C2 show the `gratia::draw()` and `gratia::appraise()` output for the beech (*FASY*) model fitted with the same pre-2018 workflow. The `draw()` panel is restricted to the age, size, and SPEI smooths, because the plot and tree random-effect smooths are high-dimensional grouping terms and are already summarized by the model structure and support counts in Table C1. For beech, the global SPEI smooth indicates lower expected growth under dry conditions, while the factor-smooth term shows moderate site-level deviations around this species-level response. Apparent upward slopes toward dry conditions therefore indicate weaker-than-average drought sensitivity at a site, not a positive growth response to drought. The realized site response is the sum of the global smooth and the site deviation. Under drought conditions (SPEI < -1), this summed SPEI effect remains negative across sites. The `appraise()` panel provides complementary

510 Pearson-residual diagnostics based on simulated QQ reference intervals.

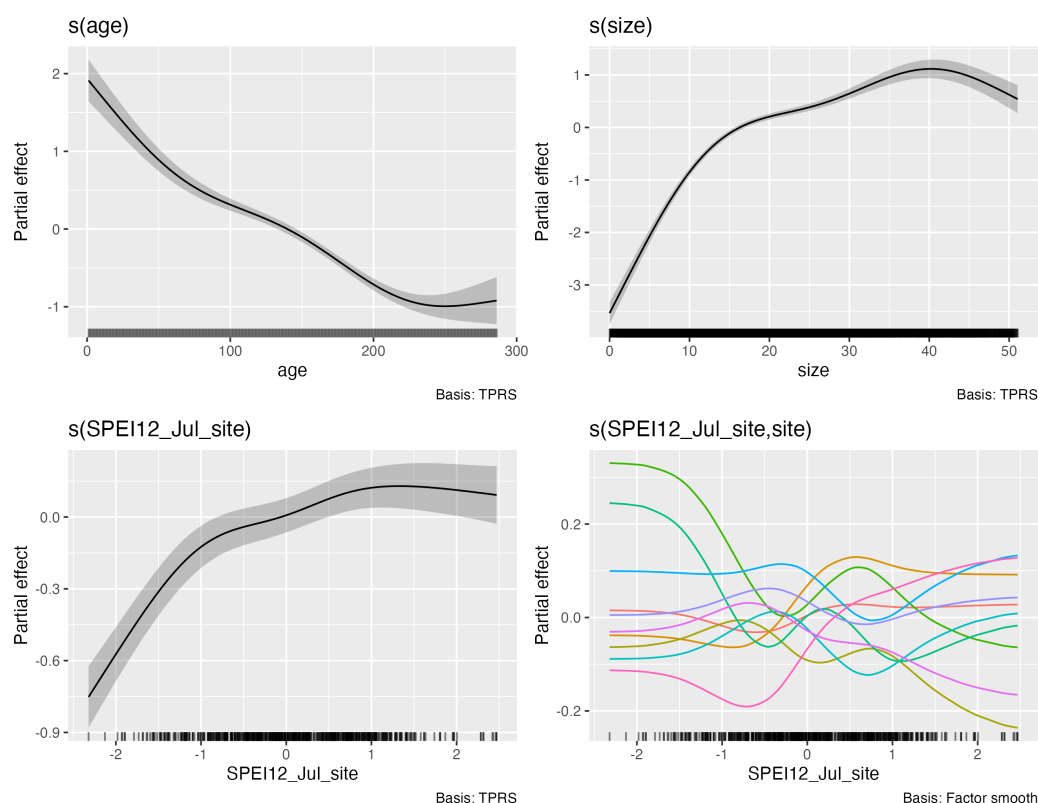


Figure C1. Exemplar `gratia::draw()` output for the beech (*FASY*) pre-2018 GAMM. Panels show the age, size, global SPEI12_Jul_site, and site-specific SPEI12_Jul_site factor-smooth terms as partial effects on the log-mean BAI (link) scale. Shaded bands show approximate uncertainty intervals for one-dimensional smooths, and rug marks indicate the observed covariate support.

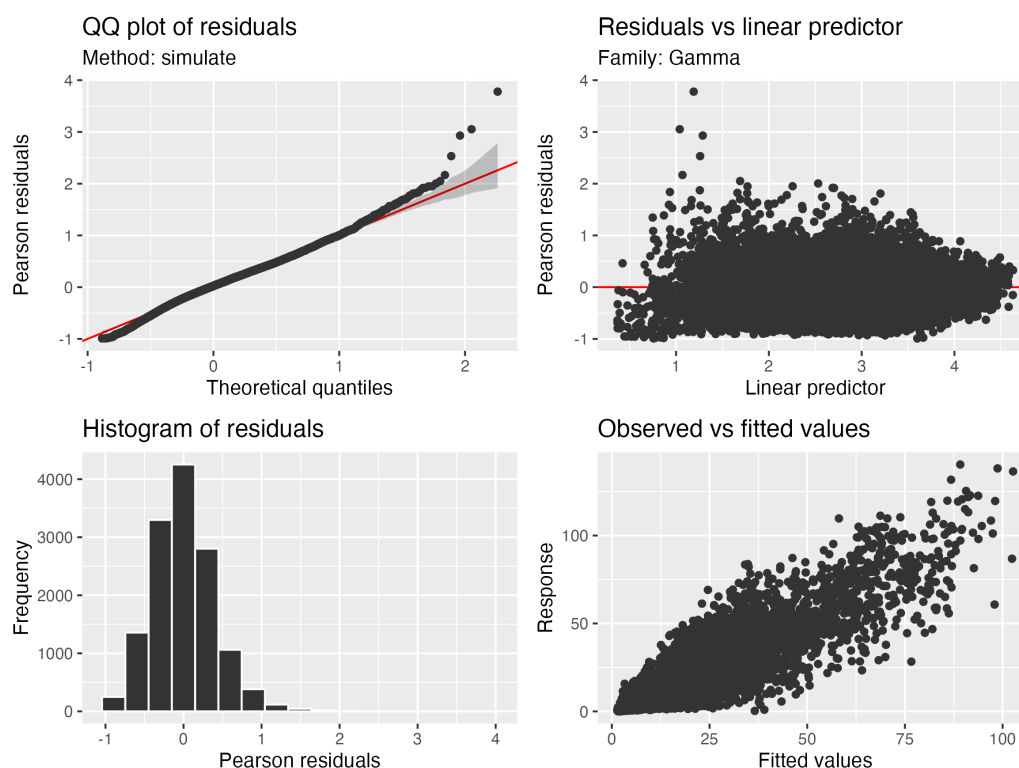


Figure C2. Exemplar `gratia::appraise()` output for the beech (FASY) pre-2018 GAMM, based on Pearson residuals and simulated QQ reference intervals. The panels summarize the QQ plot, residual distribution, residuals against the linear predictor, and observed versus fitted BAI values for the species-specific Gamma GAMM.

C2 Sensitivity analysis of the climate driver

The main analyses used SPEI-12_{Jul} as the climate driver because it captures moisture conditions during the early current growing season together with carry-over effects from the preceding autumn, winter, and spring (Sect. 2.5). To evaluate whether the main species-level anomaly conclusions depended on the exact drought-driver specification, we repeated the expected-growth and anomaly workflow using four nearby alternative SPEI formulations. The sensitivity analysis considered two kinds of deviations from the main driver SPEI-12_{Jul}: first, alternative summer reference months at the same 12-month accumulation scale (SPEI-12_{Jun} and SPEI-12_{Aug}); and second, alternative accumulation windows at the same July reference month (SPEI-3_{Jul} and SPEI-24_{Jul}). Across all tested drivers, both annual and cumulative anomalies supported the same qualitative interpretation as in the main analysis.

Across all alternative drivers, the qualitative interpretation remained unchanged (Table C2): annual anomalies in 2019 and 2022 remained negative for all focal species, five-year anomalies for 2018–2022 also remained negative, and *Pseudotsuga menziesii* (PSME) consistently showed the strongest cumulative growth reduction. Differences among drivers were mainly



Table C2. Sensitivity of species-level growth anomalies to alternative SPEI driver specifications. Values show percent deviations from expected growth under neutral moisture conditions, recalculated using alternative SPEI formulations. Reported are annual anomalies (L1) for 2019 and 2022 and the five-year cumulative anomaly (L5) for 2018–2022. Negative values indicate growth suppression.

Driver	FASY	PISY	PSME	QUPE	QURO
Annual anomaly (L1), 2019					
SPEI-12_{Jul} (main)	-41.9	-25.2	-33.3	-21.0	-22.0
SPEI-12 _{Jun}	-42.3	-21.4	-27.7	-18.0	-20.7
SPEI-12 _{Aug}	-39.5	-25.9	-31.6	-19.8	-22.8
SPEI-3 _{Jul}	-37.7	-24.1	-22.3	-17.1	-19.8
SPEI-24 _{Jul}	-41.2	-20.9	-29.2	-16.9	-21.3
Annual anomaly (L1), 2022					
SPEI-12_{Jul} (main)	-20.6	-17.8	-65.5	-8.6	-8.5
SPEI-12 _{Jun}	-21.2	-13.5	-62.6	-5.1	-7.0
SPEI-12 _{Aug}	-17.1	-18.6	-64.6	-7.1	-9.4
SPEI-3 _{Jul}	-14.5	-16.5	-59.4	-3.6	-5.8
SPEI-24 _{Jul}	-19.6	-12.9	-63.4	-3.8	-7.7
Five-year anomaly (L5), 2018–2022					
SPEI-12_{Jul} (main)	-23.3	-18.5	-47.0	-6.4	-14.3
SPEI-12 _{Jun}	-23.8	-14.4	-42.5	-2.9	-12.9
SPEI-12 _{Aug}	-20.0	-19.3	-45.6	-5.0	-15.2
SPEI-3 _{Jul}	-17.7	-17.3	-38.1	-1.6	-11.9
SPEI-24 _{Jul}	-22.4	-13.8	-43.7	-1.6	-13.6

quantitative rather than qualitative. These differences were largest for the weaker-response species, especially *Quercus petraea* (QUPE), and SPEI-3_{Jul} generally yielded somewhat smaller anomaly magnitudes than the 12- and 24-month formulations.

Overall, these results indicate that the comparative interpretation of species responses is robust to reasonable variation in drought-driver timing and timescale.



Appendix D: Plot-level severity and sensitivity of the 2018–2022 growth deficits

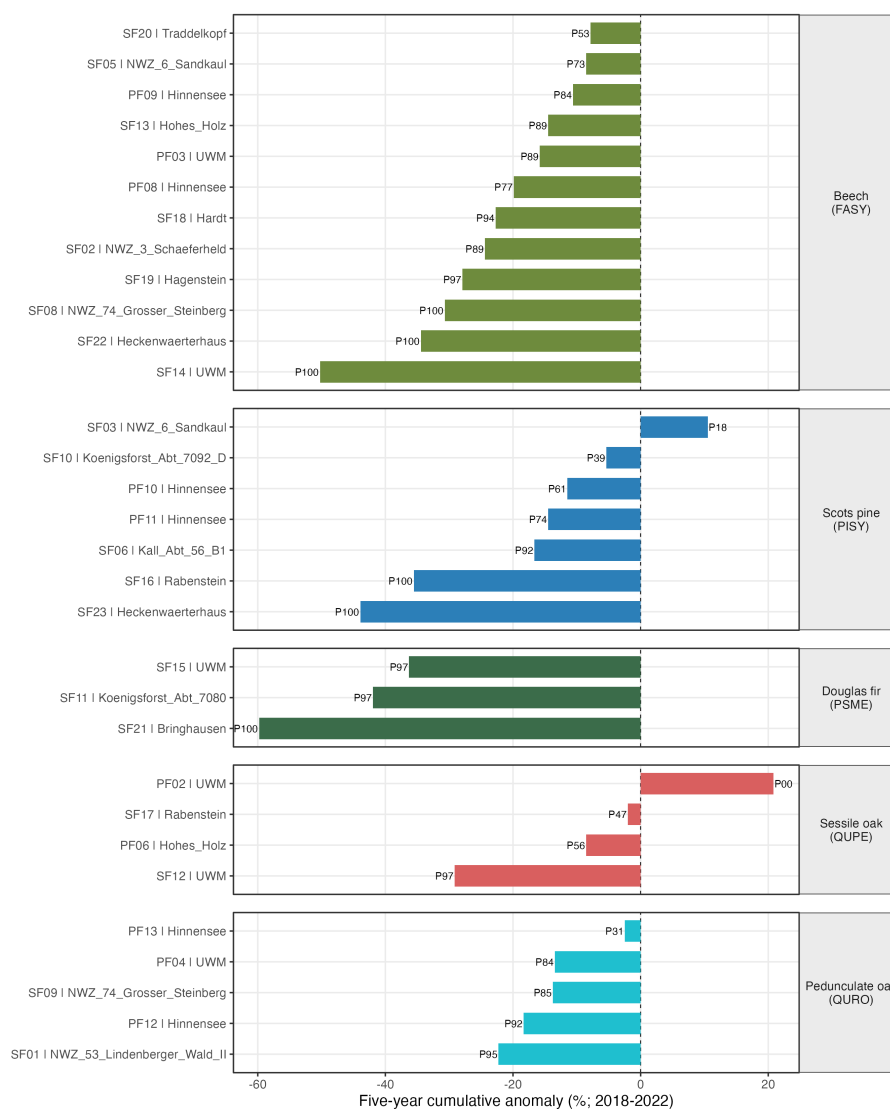


Figure D1. Plot-level five-year cumulative growth anomalies during 2018–2022. Bars show the cumulative anomaly (%) for each plot–species unit relative to expected growth under neutral moisture conditions, grouped by species. Labels (Pxx) denote the percentile rank of the 2018–2022 anomaly within the historical distribution of 5-year rolling anomalies for that plot–species unit, where higher values indicate rarer, more severe growth deficits.

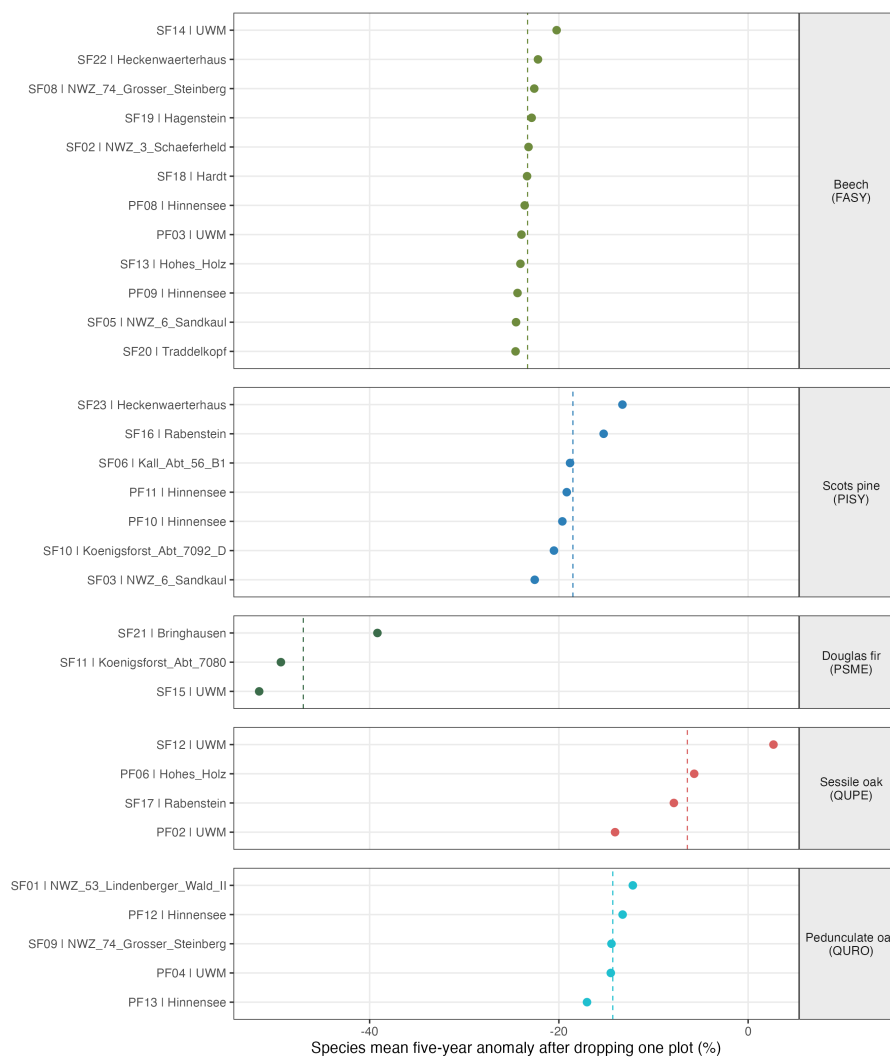


Figure D2. Leave-one-plot-out sensitivity of species-level five-year cumulative anomalies. Each point shows the species mean 2018–2022 cumulative anomaly recalculated after omitting one plot–species unit. Dashed vertical lines indicate the corresponding estimate obtained from the full dataset for each species. This sensitivity analysis shows how strongly the species-level summaries depend on individual plots.



Appendix E: Coefficients of the drought-event impact models

Table E1. Mixed-effects model results for drought event impacts on growth, fitted separately by species. Models relate the log-transformed minimum relative growth index observed during each drought event ($\ln \text{minRI}$) to standardized event severity (severity_z ; standardized within species) and a period indicator for events overlapping 2018+. All RI values use the expected-growth baseline from GAMMs calibrated on 1951–2017. Reported coefficients are fixed effects (estimate [95 % Wald CI]) on the log scale, so $100[\exp(\hat{\beta}) - 1]$ gives the percentage change in minRI . Sample sizes denote the number of tree–event observations, unique trees, plots, and events included in each species-specific fit.

Species	$\hat{\beta}_1$ (severity_z)	$\hat{\beta}_2$ (2018+)	n_{obs}	n_{trees}	n_{plots}	n_{events}	$n_{\text{events}, 2018+}$
FASY	−0.117 [−0.162, −0.072]	−0.118 [−0.234, −0.003]	5,050	207	12	241	44
QUPE	−0.099 [−0.158, −0.040]	0.161 [0.004, 0.317]	1,531	63	4	72	13
QURO	−0.059 [−0.092, −0.027]	−0.059 [−0.146, 0.028]	1,495	61	5	97	17
PISY	−0.064 [−0.106, −0.022]	−0.061 [−0.173, 0.050]	2,182	91	7	144	25
PSME	−0.153 [−0.264, −0.041]	−0.290 [−0.558, −0.021]	923	45	3	64	15

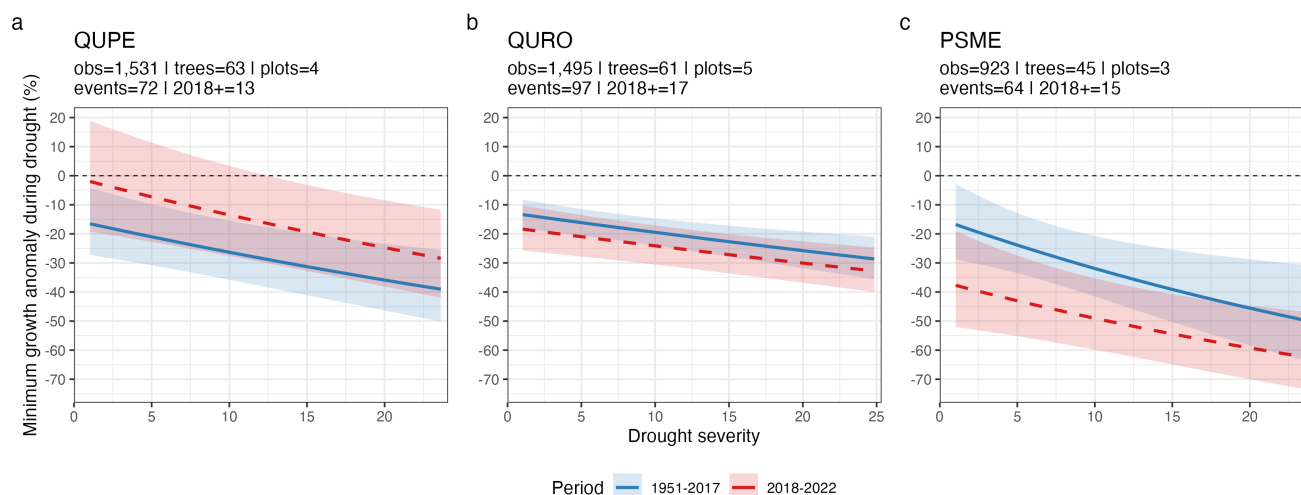


Figure E1. Predicted drought impact on radial growth for (a) *Quercus petraea* (QUPE), (b) *Quercus robur* (QURO) and (c) *Pseudotsuga menziesii* (PSME). Lines show the predicted minimum growth anomaly during a drought event as a function of event severity, with 95 % confidence intervals (shaded); blue solid for 1951–2017, red dashed for 2018–2022. Models were fitted to $\ln \text{minRI}$ (Eq. 14). Predictions are back-transformed and expressed as percent deviation from expected growth under neutral moisture conditions. Values below the dashed line at 0 % indicate growth suppression during the event. Panel subtitles report sample sizes (observations, trees, plots, total events, and post-2018 events).



530 *Author contributions.* FP, BN and AH conceived and designed the study. FP performed the analysis, developed the statistical models, and wrote the original draft. BN carried out the tree-ring measurements, crossdating, and chronology development. All authors contributed to the interpretation of the results and reviewed and edited the manuscript.

Competing interests. The authors declare that they have no competing interests.

Code and data availability. The tree-ring width measurements with their tree and plot metadata, the plot-level SPEI series, and all code to recreate all results, figures and tables are available on Zenodo (<https://doi.org/10.5281/zenodo.22979471>).

535 *Acknowledgements.* The research was funded by the Waldklimafonds (project MW3; grant agreements 2220WK86A4 and 2220WK86B4). The Waldklimafonds itself is funded by the German Federal Ministry of Food and Agriculture (BMEL) and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), and administered by the Agency for Renewable Resources (FNR). The research sites Hohes Holz, Hinnensee and Wüstebach belong to the framework of TERENO (Terrestrial Environmental Observatories), funded by the Helmholtz Association and the Federal Ministry of Education and Research (BMBF). The authors also
540 thank Dr. C. Lang (Nationalpark Eifel), Dr. A. Frede (Nationalpark Kellerwald-Edersee), U. Zimmermann and M. Schwabe (Nationalpark Mürzitz), Dr. M. Ellmer (Landesbetrieb Wald und Holz NRW), H. Römer (local forester), and many other forestry operations for their helpful cooperation concerning the field work and the necessary research permits."



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