SUPPLEMENTARY MATERIAL

Growth characteristics and drought vulnerability of southwest German spruce and pine

P. Römer*, E. Martínez del Castillo, F. Reinig, M.C.A. Torbenson, O. Konter, L. Klippel, U. Büntgen, and J. Esper (*University of Mainz; phiroeme@uni-mainz.de; +49-6131-3929891)

Table S1 Characteristics of the 46 TRW chronologies.

ID	Spec	**Elevation** [m asl]	**Lat** [°N]	**Lon** [°E]	n	$\bar{r}$	Period	MSL ± 1 SE	AGR ± 1 SE
1	PISY	106	49.33	8.38	97	0.61	1886–2013	118 ± 0.94	1.23 ± 0.04
2	PISY	118	50.12	9.01	94	0.52	1887–2016	77 ± 3.52	1.92 ± 0.05
3	PISY	130	50.02	8.20	91	0.52	1834–2013	163 ± 2.73	1.87 ± 0.05
4	PISY	139	50.01	8.19	96	0.39	1832–2016	116 ± 5.60	2.06 ± 0.06
5	PISY	140	49.98	8.68	94	0.53	1847–2015	154 ± 1.38	1.54 ± 0.03
6	PISY	140	50.01	8.19	74	0.51	1885–2018	119 ± 1.41	1.93 ± 0.05
7	PISY	140	50.01	8.19	101	0.38	1845–2019	153 ± 3.38	1.32 ± 0.03
8	PISY	150	49.95	9.00	70	0.54	1895–2014	104 ± 2.88	1.95 ± 0.06
9	PISY	230	50.46	8.22	54	0.35	1864–2017	136 ± 2.62	1.85 ± 0.08
10	PISY	320	50.42	7.26	41	0.56	1930–2020	78 ± 2.54	2.09 ± 0.08
11	PISY	334	50.70	8.23	113	0.52	1859–2012	143 ± 1.18	1.04 ± 0.03
12	PCAB	338	49.30	7.32	52	0.27	1940–2010	60 ± 1.71	2.23 ± 0.14
13	PISY	345	50.42	7.28	60	0.54	1929–2020	83 ± 1.50	2.02 ± 0.07
14	PISY	354	49.70	7.40	90	0.56	1881–2018	128 ± 1.04	1.31 ± 0.04
15	PISY	363	49.24	8.05	95	0.56	1879–2014	117 ± 1.67	0.96 ± 0.03
16	PISY	383	49.62	6.71	98	0.53	1903–2014	106 ± 0.73	2.66 ± 0.07
17	PCAB	400	49.34	8.11	59	0.38	1916–2013	80 ± 2.20	2.73 ± 0.10
18	PCAB	420	50.43	7.76	77	0.32	1913–2010	61 ± 2.85	3.46 ± 0.19
19	PCAB	420	50.43	7.76	80	0.51	1892–2010	105 ± 1.46	2.07 ± 0.06
20	PCAB	434	50.10	8.09	96	0.42	1864–2010	123 ± 2.88	1.38 ± 0.04
21	PCAB	440	50.81	7.97	90	0.48	1917–2010	82 ± 1.08	2.35 ± 0.07
22	PCAB	450	50.06	7.51	77	0.44	1910–2010	89 ± 1.56	2.67 ± 0.07
23	PISY	460	49.34	8.11	50	0.58	1892–2011	100 ± 4.04	1.38 ± 0.04
24	PISY	460	49.34	8.11	48	0.51	1880–2011	115 ± 2.50	1.03 ± 0.05
25	PCAB	463	50.11	8.09	81	0.45	1898–2010	81 ± 2.38	2.13 ± 0.09
26	PCAB	470	50.38	7.78	106	0.52	1915–2011	78 ± 2.74	2.10 ± 0.06
27	PCAB	472	50.10	8.11	98	0.47	1887–2013	88 ± 3.73	1.54 ± 0.05
28	PISY	490	49.34	8.11	80	0.36	1891–2011	81 ± 3.86	1.16 ± 0.13
29	PISY	490	49.34	8.12	46	0.49	1845–2011	139 ± 5.16	1.31 ± 0.06
30	PISY	490	49.35	8.11	39	0.48	1941–2011	75 ± 4.10	1.45 ± 0.06
31	PCAB	500	50.05	8.01	45	0.33	1873–2009	92 ± 6.00	1.22 ± 0.06
32	PISY	500	49.33	8.11	148	0.54	1870–2011	117 ± 1.81	1.06 ± 0.04
33	PISY	510	49.34	8.10	100	0.48	1899–2012	95 ± 1.58	1.41 ± 0.04
34	PCAB	518	50.20	6.91	97	0.51	1917–2016	71 ± 1.72	2.31 ± 0.08
35	PISY	518	50.07	7.51	63	0.50	1887–2016	117 ± 1.67	2.10 ± 0.07
36	PCAB	519	50.29	7.01	101	0.49	1945–2012	61 ± 0.70	2.83 ± 0.07
37	PCAB	530	50.69	8.16	92	0.51	1884–2012	85 ± 3.15	2.51 ± 0.13
38	PCAB	540	50.05	8.01	96	0.51	1925–2012	75 ± 2.19	1.99 ± 0.05
39	PCAB	550	51.08	8.04	91	0.53	1932–2011	74 ± 0.59	3.07 ± 0.06
40	PCAB	560	49.98	7.68	96	0.56	1925–2018	96 ± 1.19	2.05 ± 0.07
41	PISY	565	49.28	8.01	100	0.51	1864–2016	136 ± 1.65	1.17 ± 0.03
42	PCAB	632	50.22	8.43	99	0.52	1932–2020	77 ± 1.24	2.39 ± 0.06
43	PCAB	680	49.74	7.20	87	0.46	1886–2011	95 ± 4.10	1.90 ± 0.06
44	PCAB	690	50.27	6.38	94	0.49	1922–2011	61 ± 1.47	2.41 ± 0.07
45	PCAB	750	49.73	7.09	57	0.43	1916–2009	86 ± 1.16	2.75 ± 0.07
46	PCAB	819	50.22	8.45	60	0.51	1938–2009	65 ± 0.87	3.48 ± 0.09

Spec: *Picea abies* (PCAB) and *Pinus sylvestris* (PISY), **Lat:** latitude, **Lon:** longitude, **n:** number of series, **$\bar{r}$:** mean inter-series correlation between the 10SP series calculated for 1952–2009 CE, **Period:** chronology period at ≥ 10 series, **MSL:** mean segment length [years] ± 1 standard error (SE), **AGR:** average growth rate [mm/year] ± 1 standard error (SE) calculated over the first 60 years of cambial age.

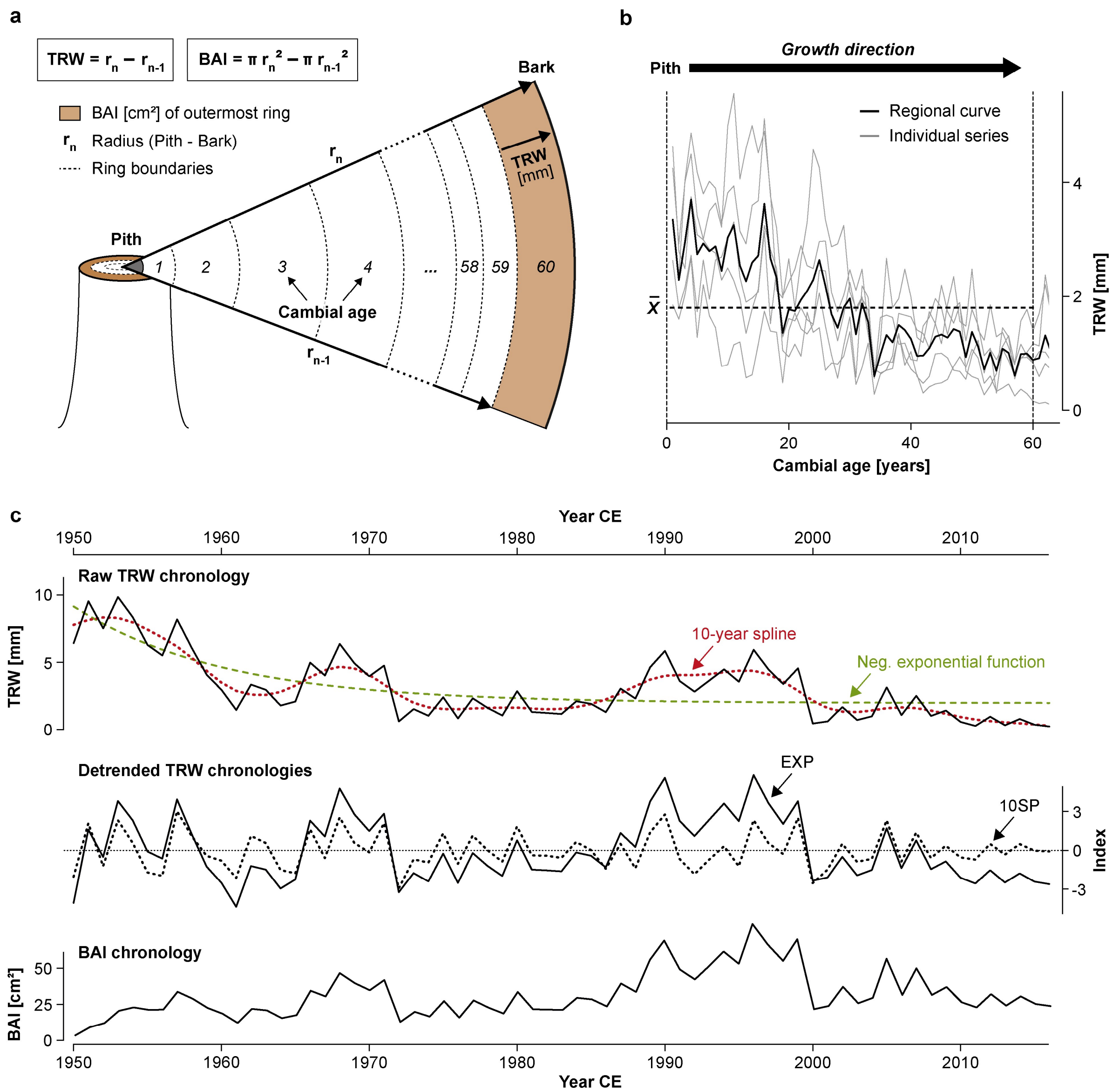

Fig. S1 Tree-ring width (TRW) and basal area increment (BAI) data. **(a)** Stem cross-section of a 60-year-old tree showing the two growth parameters. **(b)** The AGR of each site is calculated over the first 60 years of cambial age (highlighted by vertical dashed lines) as mean ($\overline{X}$; horizontal dashed line) of the regional curve. **(c)** Effects of standardization and BAI calculation. Top panel shows a raw TRW chronology together with a fitted 10-year cubic smoothing spline (red) and negative exponential curve (green). Middle panel shows the index chronologies after spline (10SP, dotted curve) and negative exponential detrending (EXP, solid curve). Bottom panel shows the BAI record derived from the TRW measurements using the equation shown in panel a.

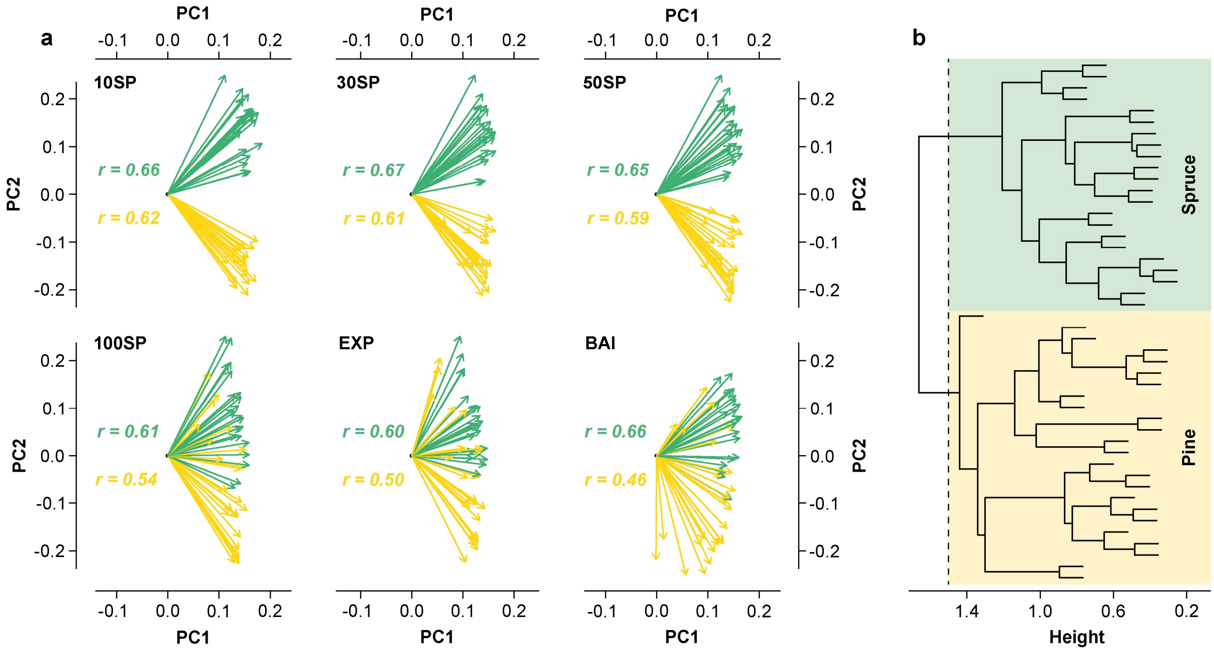

Fig. S2 (a) Principal Component Gradient Analyses (Buras et al. 2016) using 10-year (10SP), 30-year (30SP), 50-year (50SP), 100-year (100SP) spline, negative exponential (EXP), and basal area increment (BAI) chronologies (1952–2009 CE). Each arrow represents a spruce (green) and pine (yellow) site. R values indicate average intra-species correlations. **(b)** Hierarchical Cluster Analysis of the 10SP site chronologies. Note the distinct separation between spruce and pine in the 10SP data.

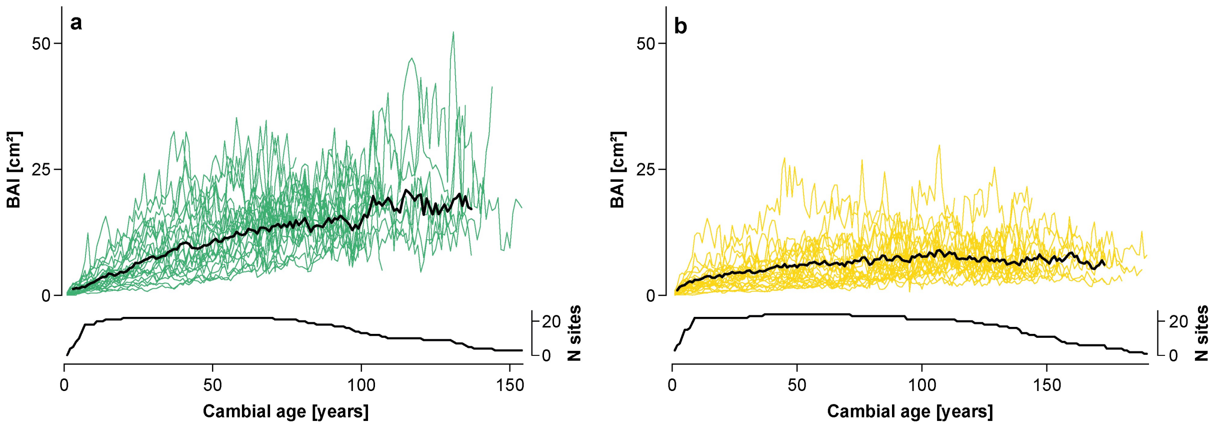

Fig. S3 Age-aligned basal area increment (BAI) chronologies of the **(a)** 22 spruce and **(b)** 24 pine sites truncated at < 10 series. Black lines represent species-specific means calculated for n ≥ 5 sites. Bottom panels show site chronology replications.

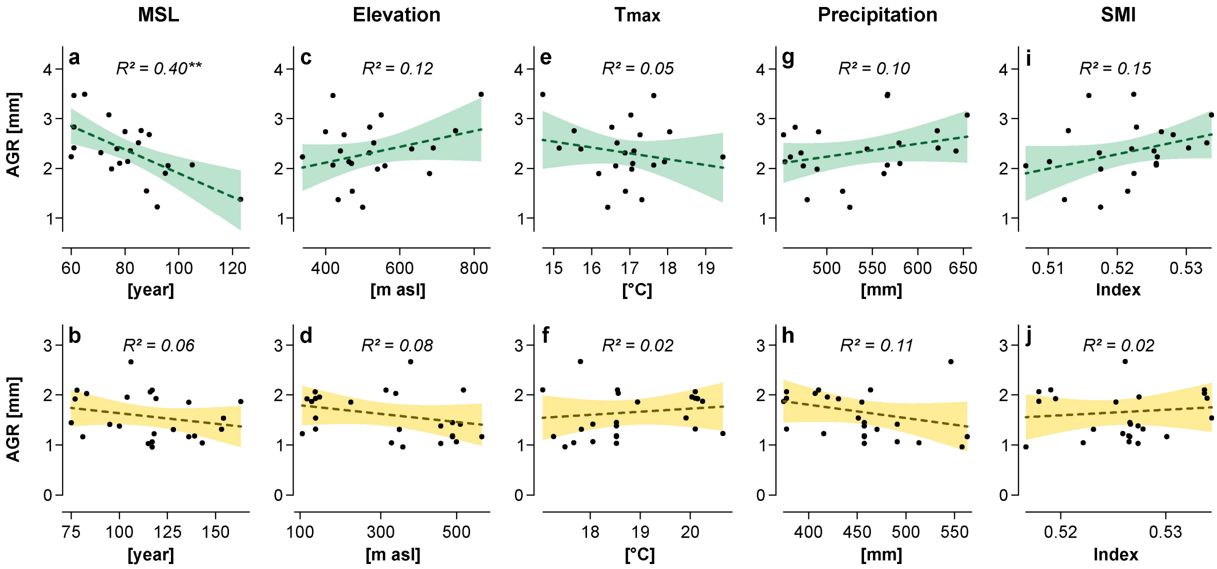

Fig. S4 Average growth rate (AGR) of spruce (top panels) and pine (bottom panels) as a function of **(a-b)** mean segment length (MSL), **(c-d)** elevation, **(e-f)** maximum air temperature (T_{max}), **(g-h)** precipitation totals and **(i-j)** soil moisture indices (SMI). The latter three variables are calculated for the growing season (April-October). Each dot represents one site. Dashed lines show linear trends. Colored areas are 95% confidence intervals of the regression slopes for spruce (green) and pine (yellow). Asterisks behind R^2 indicate $p < 0.05$.

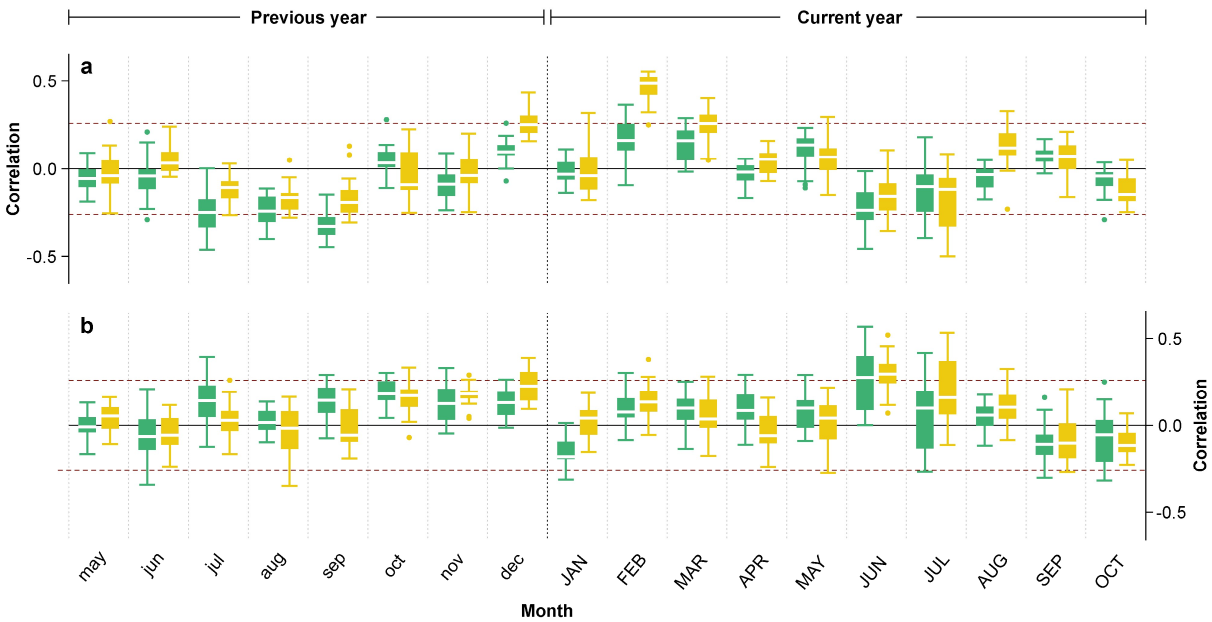

Fig. S5 Monthly climate-growth correlations for 1952–2009 CE. Distribution of bootstrap correlations of the 10SP TRW chronologies (spruce = green, pine = yellow) with **(a)** maximum air temperatures and **(b)** precipitation from previous-year (lower case letters) May to current-year (upper case letters) October. Boxplots show the median (white bar), 25%- and 75%-quartiles (box), min and max values within 1.5x the interquartile range (whiskers), and outliers (points). Dashed lines mark $p < 0.05$.

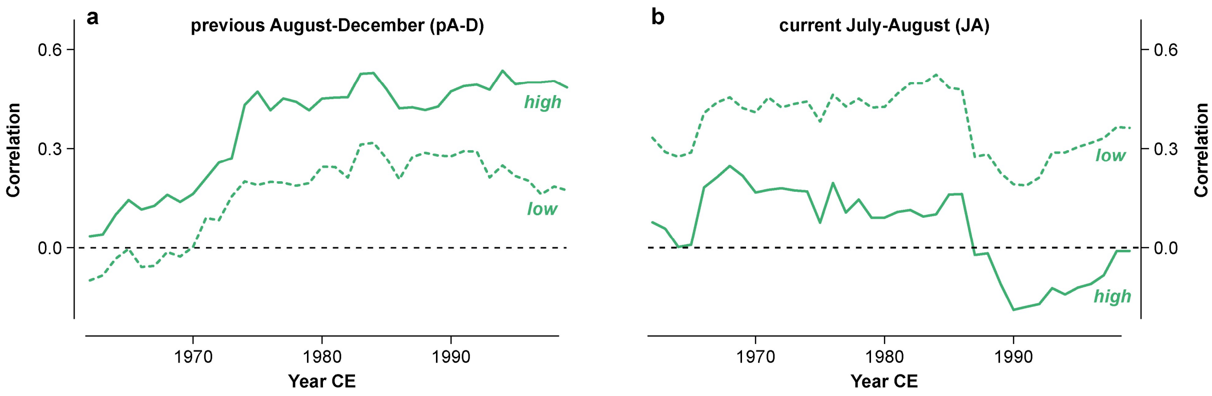

Fig. S6 Mean 21-year running correlations of spruce sites below 550 m asl (dashed curves) and above 550 m asl (solid curves) with **(a)** previous-year August-December (pA-D) and **(b)** current-year July-August (JA) soil moisture indices (10SP data).

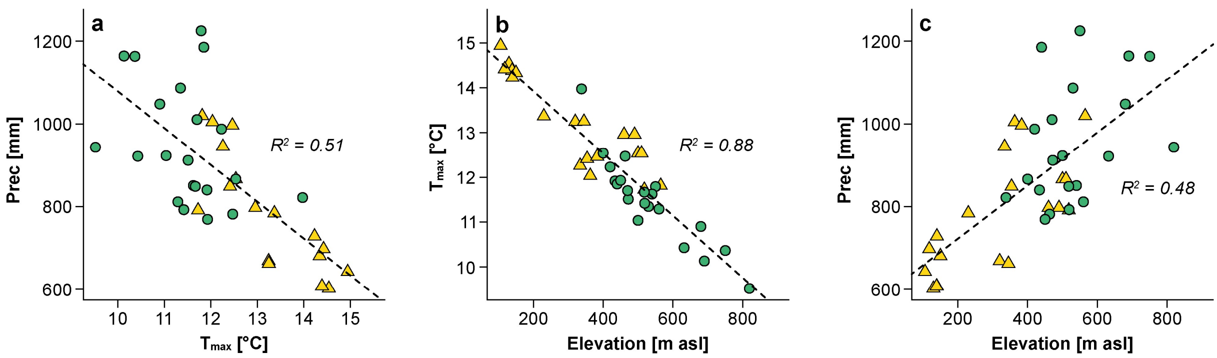

Fig. S7 Linear regressions between **(a)** annual maximum air temperatures (T_{max}) and annual precipitation (Prec), **(b)** elevation and T_{max}, and **(c)** elevation and Prec. Green circles represent the spruce sites, yellow triangles the pine sites.

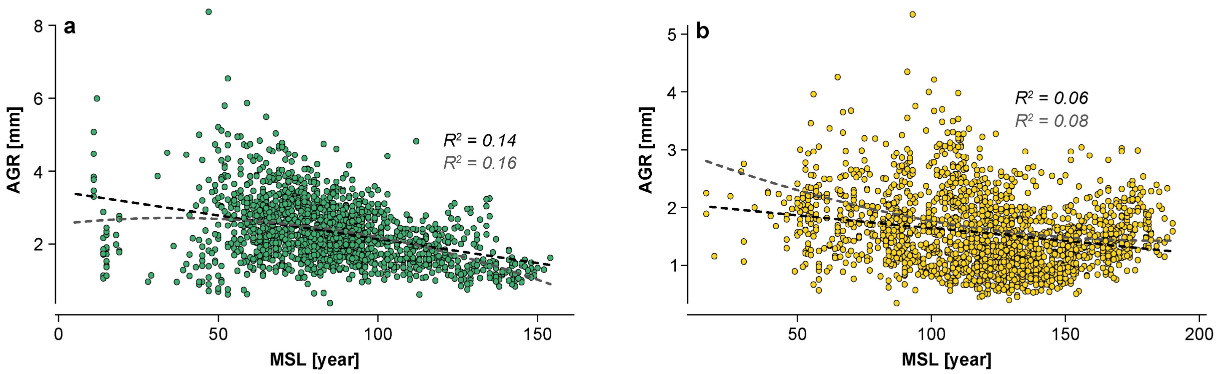

Fig. S8 Linear (black lines) and second-order polynomial (grey lines) regressions between mean segment lengths (MSL) and average growth rates (AGR) of the **(a)** 1831 spruce and **(b)** 1942 pine series. Each circle represents one series. All regressions are significant at $p < 0.001$.

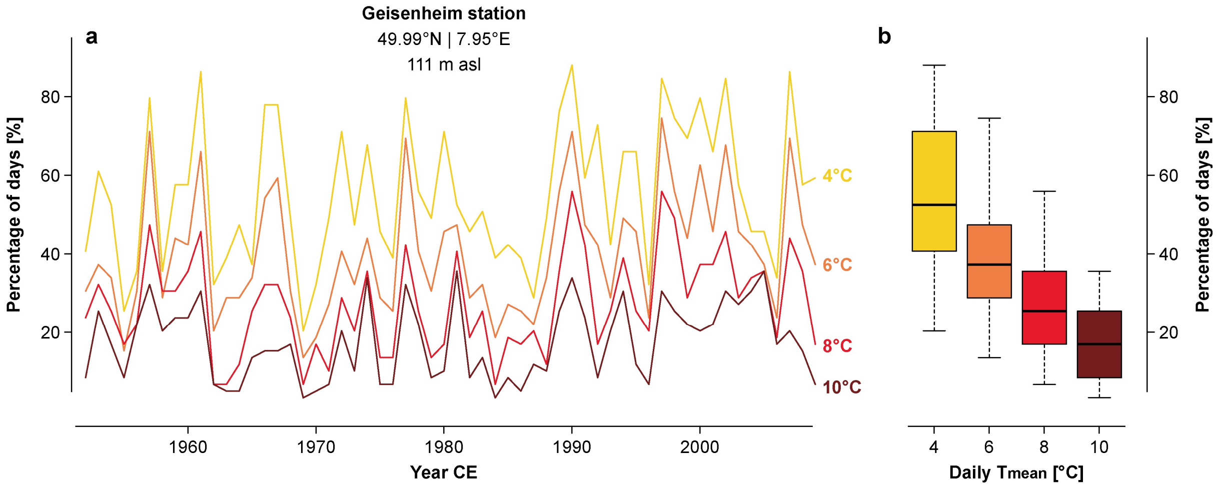

Fig. S9 (a) Percentage of February-March days exceeding daily mean temperatures (daily T_{mean}) of 4°C (yellow), 6°C (orange), 8°C (red), and 10°C (dark red) at the meteorological station in Geisenheim from 1952–2009 CE. **(b)** Value distributions of the various temperature tresholds from panel a. Boxplots show the median (black bar), 25%- and 75%-quartiles (box), and min and max values within 1.5x the inter-quartile range (whiskers). The climate station data was downloaded from the German Weather Service (https://cdc.dwd.de/portal/).

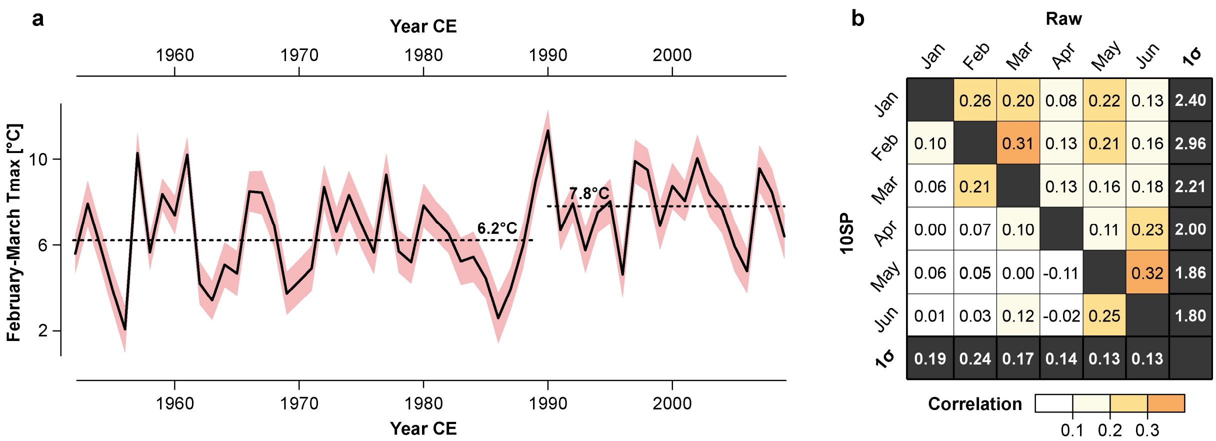

Fig. S10 (a) February-March maximum air temperatures (T_{max}) from 1952–2009 CE. Red shading represents ± 1 standard deviation of 24 grids covering the pine sites. Horizontal dashed lines show mean T_{max} from 1951–1989 CE and 1990–2009 CE. **(b)** Correlation matrix of the raw and high-pass filtered monthly T_{max} series (Jan-Jun). 1σ indicates one standard deviation of the T_{max} series.

Supplemental references

Buras A, van der Maaten-Theunissen M, van der Maaten E, Ahlgrimm S, Hermann P, Simard S, Heinrich I, Helle G, Unterseher M, Schnittler M, Eusemann P, Wilmking M (2016) Tuning the voices of a choir: detecting ecological gradients in time-series populations. PLoS ONE 11: e0158346. https://doi.org/10.1371/journal.pone.0158346