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500 years of regional forest growth variability and links to climatic extreme events in Europe

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Abstract
Climatic extreme events strongly affect forest growth and thus significantly influence the inter-annual terrestrial carbon balance. As we are facing an increase in frequency and intensity of climate extremes, extensive empirical archives are required to assess continental scale impacts of temperature and precipitation anomalies. Here we divide a tree-ring network of approximately 1000 sites into fifteen groups of similar high-frequency growth variability to reconstruct regional positive and negative extreme events in different parts of Europe between 1500 and 2008. Synchronized growth maxima or minima within and among regions indicate eighteen years in the pre-instrumental period and two events in the 20th century (1948, 1976) with extensive radial growth fluctuations. Comparisons with instrumental data showed that the European tree-ring network mirrors the spatial extent of temperature and precipitation extremes, but the interpretation of pre-instrumental events is challenged by lagged responses to off-growing season climate extremes. We were able to attribute growth minima in subsequent years to unfavourable August–October conditions and to mild climate during winter months associated with respiratory carbon losses. Our results emphasize the importance of carry-over effects and species-specific growth characteristics for forest productivity. Furthermore, they promote the use of regional tree-ring chronologies in research related to climate variability and terrestrial carbon sink dynamics.

Keywords: network, productivity, high frequency, extreme event, reconstruction, tree-ring, lag effect, autocorrelation

S Online supplementary data available from stacks.iop.org/ERL/7/045705/mmedia

1. Introduction

Climate fluctuations operating across multiple spatiotemporal scales are key drivers of ecosystem functions and thus are of crucial importance for quantifying terrestrial carbon cycle dynamics (Beer *et al* 2010). Over recent decades, unprecedented (Frank *et al* 2010) and steady (Foster and Rahmstorf 2011) warming trends were observed worldwide, accompanied by severe climate extremes (Stefanon *et al* 2012). The warmer base climate has enhanced the occurrence probability and intensity of heat and drought events (Ballester *et al* 2010, Simolo *et al* 2011) with a five to tenfold increased likelihood of extreme temperatures in Europe anticipated by the mid 21st century (Barriopedro *et al* 2011). However, projections of precipitation extremes are less certain (Orlowsky and Seneviratne 2012) and trends in the occurrence of strong climate anomalies vary regionally and seasonally (Lupikasza *et al* 2011) complicating understanding of the consequences for terrestrial ecosystems and related services for human societies (Schröter *et al* 2005).

European forests normally act as a net carbon sink (Luyssaert *et al* 2010) with increased productivity reported over the past 50 years due primarily to warming and CO_2 fertilization (Bellassen *et al* 2011). However, extreme climate events like the 2003 summer drought may temporarily turn ecosystems into carbon sources (Ciais *et al* 2005) adding uncertainties to their fates particularly given the projected increases in extreme events. Furthermore, the susceptibility of forests to temperature and precipitation extremes varies regionally (Lindner *et al* 2010) and depends upon species-specific climate responses (Lebourgeois *et al* 2010, Friedrichs *et al* 2009, Babst *et al* 2012). Lastly, carry-over effects from the previous growing season significantly influence growth performance (Fritts 1976, Frank *et al* 2007a) and may thus mitigate or enhance impacts of seasonal climate extremes on forest productivity—an issue not considered in most ecophysiological investigations.

Extensive and precisely dated empirical datasets are required to quantify large-scale forest ecosystem performance before, during and after extreme climate events. Measurements of the annual radial growth increment (tree-rings) offer such possibilities by allowing forest growth to be related to climate variability at local (Panayotov *et al* 2011), regional (Neuwirth *et al* 2007) and continental (Briffa *et al* 2002) scales. Furthermore, tree-ring chronologies can preserve growth variations over decades to millennia (Büntgen *et al* 2011) and thus can record adequate numbers of extreme events, which are rare by definition (Battipaglia *et al* 2010). Yet, effects from climate extremes occurring outside the main growing season, which may indirectly influence radial growth via nutrient storage (Kreuzwieser and Gessler 2010), altered phenological phases or changes in growing season length (Moser *et al* 2010), are usually more difficult to detect in the respective annual ring. Such climatic events may be recorded as carry-over effects leading to a strong growth reaction in the following year (Fritts 1976), however, the exact circumstances leading to lagged growth extremes have not yet been fully clarified on a large scale (Wettstein *et al* 2011). Improved understanding of both the immediate and lagged consequences of extreme events are crucial for interpreting growth anomalies during the pre-instrumental period as well as reducing uncertainties in ecosystem projections.

Here, we employ a continental scale tree-ring network (Babst *et al* 2012) to assess and reconstruct years with extremely high or low forest growth in different parts of Europe. We divide the network into sectors of similar annual variability and calculate mean tree-ring chronologies reflecting forest growth anomalies over the past five centuries. Furthermore, we compare extreme growth years at approximately 1000 sites to temperature and precipitation anomalies across Europe and test, if tree-ring networks reflect the spatial extent of climate extremes. Thereby we address extreme growth between 1500 and 2008 at sites predominantly sensitive to temperature, precipitation and mixed climatic influences. Additionally, we employ monthly temperature and precipitation data in extreme years to differentiate climate conditions leading to contemporaneous growth extremes from those conditions causing anomalous growth also or only in the subsequent year.

2. Materials and methods

2.1. Tree-ring and climate data

We used a large tree-ring width (TRW) network of approximately 1000 sites (Babst *et al* 2012) of the most abundant species to assess annual forest growth variability across Europe. For the assessed time periods, all TRW chronologies had a minimum sample replication of five series and an expressed population signal (EPS) above 0.85 (Wigley *et al* 1984) making the network well replicated over the past five centuries. To isolate extreme growth years in tree-ring data, it is necessary to remove low-frequency signals, including the biological age trend (Fritts 1976) and long-term growth changes (Esper *et al* 2002). This was accomplished using a spline detrending with a 50% frequency cutoff response at 30 years which preserves inter-annual to decadal variability in the resulting standard chronologies.

For climatic analyses, we derived monthly temperature and precipitation data from a fine-spatial (1×1 km) resolution gridded climatology spanning the 1901–2006 period (see Babst *et al* 2012 for a description). These instrumental data were detrended analogously to the tree-ring data to extract higher frequency variability.

2.2. Regional tree-ring width chronologies

We produced regionally representative tree-ring chronologies as the basis to assess and reconstruct growth extremes in different parts of Europe. Accordingly, we divided the European TRW network into fifteen groups of similar annual growth variability using a fuzzy clustering algorithm (Kaufman and Rousseeuw 1990), thereby disregarding any spatial information. The number of clusters was determined based upon sensitivity analyses of mean chronology inter-correlations (rbar) as well as cluster replication/spatial representation (appendix A). In contrast to a 'hard' *k*-means clustering which produces identical groups, the fuzzy approach additionally provides the degree of membership of a site to each of the fifteen clusters. Thus, when calculating representative mean curves, we were able to weight the

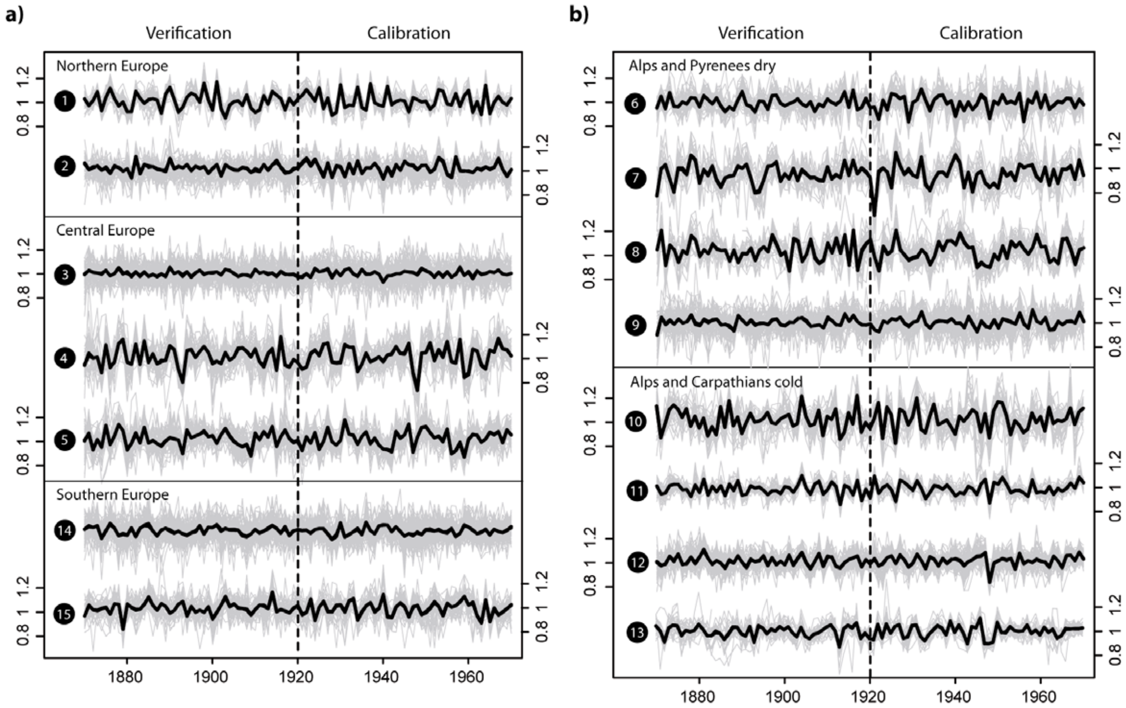

Figure 1. Calibration and verification period of fifteen high-frequency regional tree-ring chronologies (black mean curves) arranged according to sub-continental regions.

influence of each site on the resulting regional tree-ring chronologies (RTCs) by primary cluster membership to best represent the integrated forest area. Additionally, we accounted for changes in sample replication and rbar to minimize possible variance artefacts related to changes in the network composition (Frank *et al* 2007b) and truncated RTCs where the replication dropped below five sites (figure 1). We assessed monthly climate sensitivities of each RTC between April of the year prior to ring formation and current September (appendix B). Furthermore, negative or positive growth extremes were defined when TRW was below the 5th or exceeded the 95th percentile over the cluster calibration (1920–70) and verification (1870–1919) periods (Stefanon *et al* 2012).

2.3. Spatial climate anomalies and lagged growth extremes

We compared growth extremes indicated by the tree-ring network to seasonal climate anomalies across Europe to assess common spatial patterns. This comparison was done at the site level since climate anomalies do not necessarily affect the entire areas represented by an RTC, which may therefore imprecisely reflect the spatial extent of e.g. heat waves. Each site of the tree-ring network was classified according to significant ($p < 0.05$) correlations with instrumental data as temperature ($r_{temp} > 0.273$, 232 sites), precipitation ($r_{precip} > 0.273$, 216 sites), or mixed ($0.273 > r_{temp,\ precip} > -0.273$, 544 sites) sensitive. The mixed category contains sites which are neither strongly temperature nor water limited during the April–July period which was identified as the primary season influencing forest growth integrated over Europe (appendix B). Lagged growth extremes in the following year, however, cannot be explained by April–July climate anomalies only. Thus, we employed monthly temperature and precipitation indices in conjunction with a simple decision tree model (figure C.1) to distinguish climate conditions leading to immediate growth extremes from those conditions causing lag effects. Subsequently we use the following abbreviations to distinguish different types of extreme responses: C-EX = growth extreme in the current year; CL-EX = growth extreme in the current and in the following year; L-EX = growth extreme in the following year.

3. Results

3.1. Regional forest growth variability

We produced fifteen RTCs representing high-frequency growth variability of forests across Europe over the past 200–800 years. These contain between 41 and 103 site chronologies with mean inter-site correlations usually above 0.3 (see table D.1). Each RTC integrates a confined latitudinal, longitudinal and altitudinal space which emerged from a clustering solely based on annual radial growth variability (figure 2). While the represented areas overlap considerably, the majority of RTCs are dominated by no more than two species (table 1). The separation of RTCs primarily emerges from differing growth patterns under normal climatic conditions. RTCs may, however, respond synchronously to climate extremes within and among regions indicating years with extensive productivity maxima or minima.

Table 1. Species composition (%) of the fifteen RTCs grouped by region (NE = northern Europe; CE = central Europe; AL = Alps low elevation; AH = Alps high elevation; SE = southern Europe). The eight most frequently represented tree species are shown individually while further species (mostly southern European pines) are summarized under the 'other' category.

RTC	NE		CE			AL				AH				SE	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Abies alba	0	0	1	0	0	95	7	2	15	0	0	0	0	16	4
Picea abies	0	10	15	7	0	1	29	6	13	0	20	93	98	20	4
Pinus sylvestris	100	76	25	5	0	1	37	6	17	0	2	1	0	8	42
Larix decidua	0	2	10	2	0	0	10	5	2	84	2	4	2	2	0
Pinus cembra	0	2	2	0	0	0	0	0	2	0	74	0	0	1	0
Fagus sylvatica	0	0	5	75	0	1	17	5	17	14	0	0	0	0	0
Quercus robur	0	4	31	2	64	0	0	5	13	2	0	2	0	10	0
Quercus petraea	0	0	7	9	36	0	0	6	4	0	0	0	0	3	0
Other	0	6	4	0	0	2	0	65	17	0	2	0	0	40	50

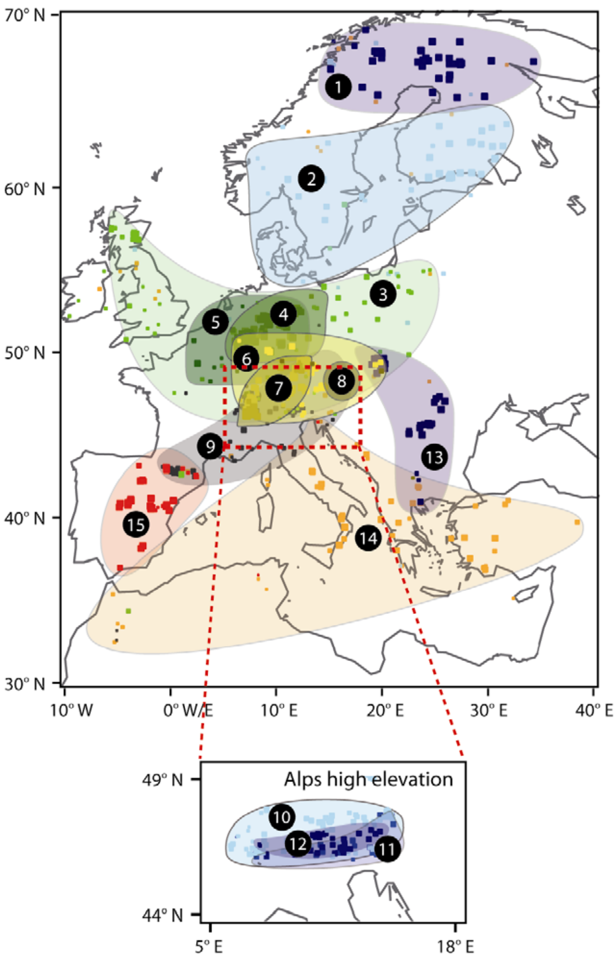

Figure 2. Geographic space represented by the fifteen regional tree-ring chronologies (RTCs). Rectangles indicate the location of individual sites and their size corresponds to membership strength. For better visibility, the high-elevation Alpine RTCs 10–12 are shown in a separate inset.

3.2. Extreme growth events between 1500 and 2008

We reconstructed positive and negative growth extremes across Europe over the past 500 years based on RTCs (figure 3). In northern Europe, both RTCs show eleven common extreme events before 1901 and one event during the early instrumental period. Sequential extreme years occurred on four occasions in northern (1641/42, 1644/45, 1693/94, 1695/96) and once (1695/96) in southern Scandinavia. In central Europe, conditions in 1834 and 1976 provoked a synchronous response of all RTCs. RTC 5 shows successive growth peaks in 1823/24. Within the Alpine region, RTCs are often synchronized. For the high-elevation Alpine groups, periods of frequent extreme years occurred in the 18th and 19th centuries while during the instrumental period, common growth peaks were less frequent (1913 and 1948). In southern Europe, RTCs show three positive (1762, 1846, 1885) and two negative (1600, 1725) common extreme years in the pre-instrumental period. RTC 15 indicates four occasions of subsequent growth extremes in 1600/01, 1648/49, 1762/63 and 1770/71. Combined RTCs highlight eighteen years during the pre-instrumental period and two years during the instrumental period (1948 and 1976) where forest growth was extremely high or low over large areas in Europe (figure 3 bottom).

3.3. Climate and growth anomalies in space and time

We assessed the spatial extent of forest growth extremes between 1500 and 2008 by mapping their annual occurrence and sign together with the expected climate sensitivity. Maps for each year during the full time period are provided in the supplementary material (available at stacks.iop.org/ERL/7/045705/mmedia). Direct comparisons with April–July climate anomalies were performed over the instrumental period (1901–2006) with a focus on 1976 and 1948 (figure 4)—the most extreme years in the RTCs.

In 1976, exceptionally hot and dry conditions exceeding two standard deviations prevailed over central and western Europe. Furthermore, warm and wet conditions occurred on the Iberian peninsula whereas in Scandinavia and eastern Europe precipitation amounts were low. The growth impacts of this climate pattern largely agrees with the signals expected from the site specific climate responses. In central and eastern Europe, precipitation and mixed-sensitivity sites showed a negative growth extreme in response to intense drought, while mid-elevation mixed-sensitivity sites on the Iberian Peninsula benefited from warm and pluvial conditions. Most temperature sensitive sites in the Alps showed no strong

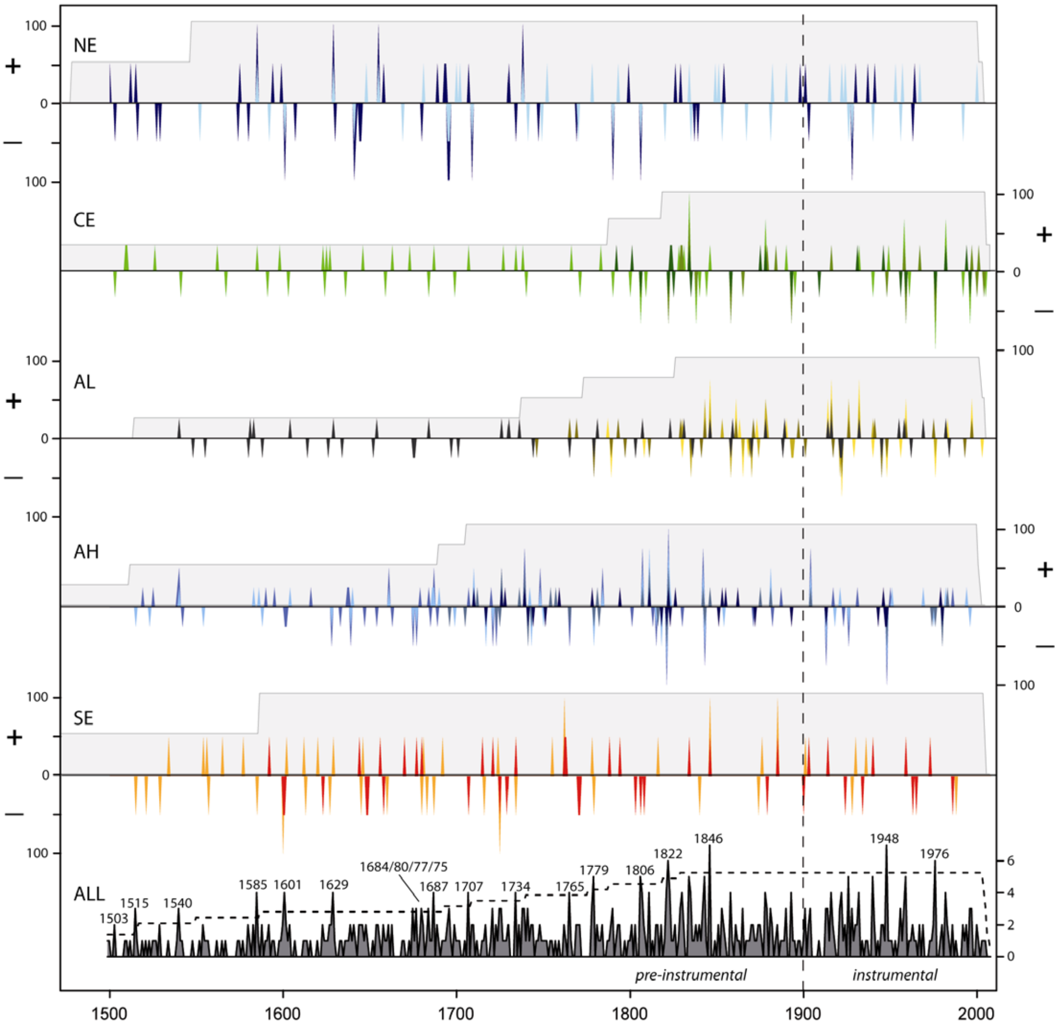

Figure 3. Reconstruction of years with extremely high (+) or low (−) growth rates between 1500 and 2008 in different parts of Europe (NE = northern Europe; CE = central Europe; AL = Alps low elevation; AH = Alps high elevation; SE = southern Europe). Colours correspond to cluster areas presented in figure 2. Peaks indicate the percentage of available RTCs (maximum indicated by grey shades) responding in each year. The bottom panel summarizes the number of RTCs with positive or negative extremes. A dashed line represents 33% of all available RTCs indicating years with extensive extreme events.

growth increase during the 1976 heat episode, likely due to legacies from low growth in 1974 (see small plot in figure 4) and 1975 (see supplementary material, available at stacks.iop.org/ERL/7/045705/mmedia). In 1948, low growth occurred at many precipitation and mixed-sensitivity sites in central Europe and the low-elevation Alps, suggesting drought. This signal, however, appears to result from lagged effects driven by the previous summer drought. In 1947, low growth of forests in southern, southeastern and central Europe reflected the dry conditions whereas high-elevation sites in the Alps benefited from warm temperatures (see small plot in figure 4 and supplementary material, available at stacks.iop.org/ERL/7/045705/mmedia). Positive growth was also observed in Great Britain due to enhanced moisture availability as well as in Scandinavia likely attributable to the expansive warmth in this year.

In the pre-instrumental period, spatial patterns of reconstructed growth extremes become less distinct with decreasing site replication back in time. Yet—while we refrain from making direct comparisons with early instrumental data (e.g. Böhm *et al* 2010)—it is clear from our results that climatically driven and spatially pervasive extensive growth extremes occurred in Europe during the past centuries.

3.4. Contemporaneous and lagged growth extremes

We employed the European tree-ring network and monthly instrumental data in an attempt to distinguish between climate conditions leading to contemporaneous growth extremes (C-EX) and those causing lag effects (CL-EX, L-EX). A separate assessment at temperature, precipitation and mixed sensitive sites, however, did not produce robust results due to the rare occurrence of CL-EX situations during the instrumental period. Thus, we combined temperature and precipitation limited sites where we compiled monthly indices of the respective limiting climate factor in all extreme growth years. Thereby we distinguished between C-EX, CL-EX and L-EX events and calculated bootstrapped means (Boos 2003)

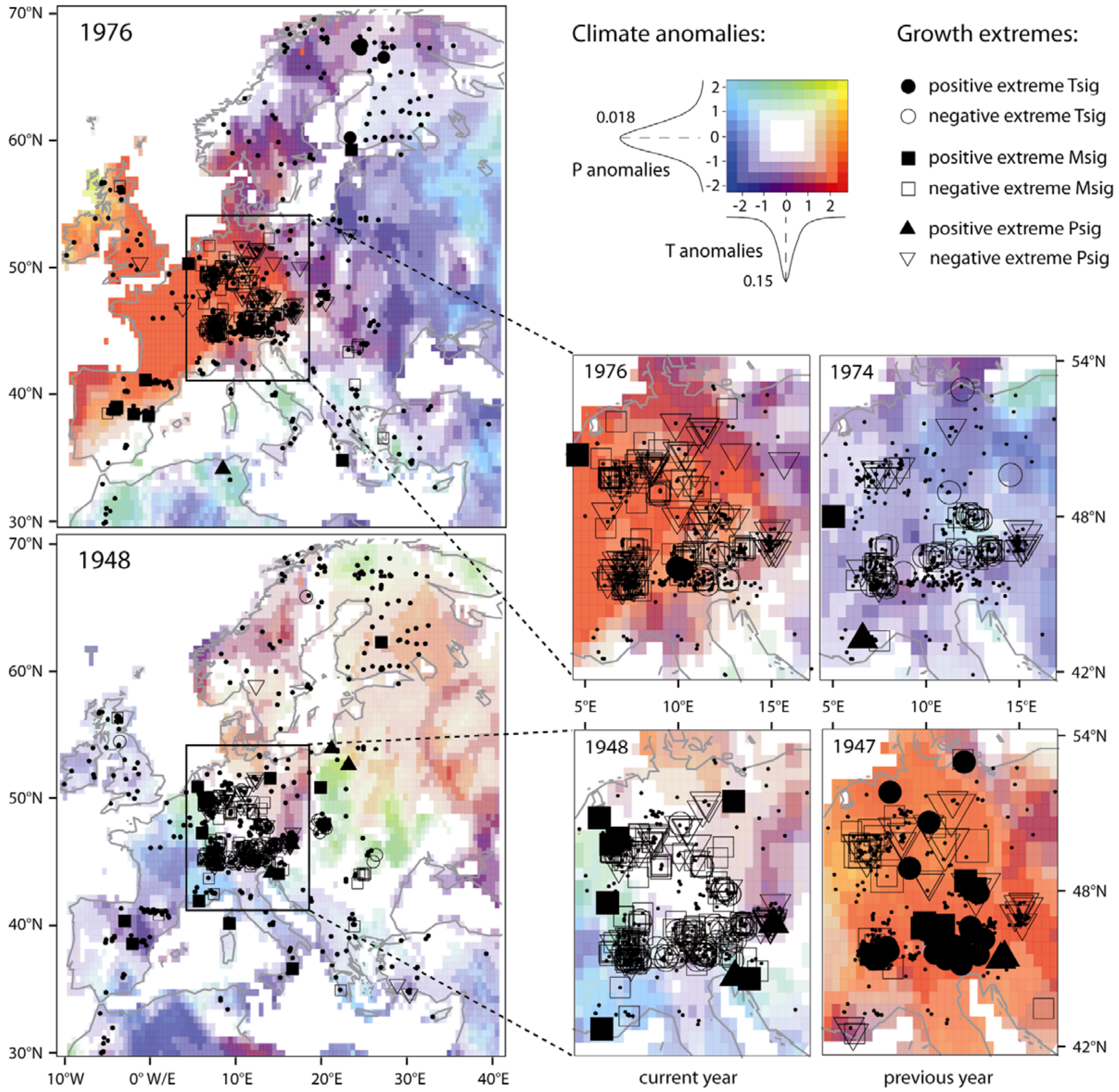

Figure 4. European maps showing positive and negative growth extremes at temperature (Tsig), mixed (Msig) and precipitation (Psig) sensitive sites in 1976 and 1948. Small plots showing central Europe and the Alps at higher spatial resolution have been added for the current and previous years. Small symbols mark isolated growth extremes while large symbols indicate extreme growth also in the subsequent year. Dots point out available sites. April–July temperature and precipitation anomalies derived from CRU TS 3.0 global datasets (0.5 × 0.5° spatial resolution; Mitchell and Jones 2005) are visualized using a bivariate colour scale (numbers indicate standard deviations). The probability density functions of T and P anomalies during the instrumental period (1901–2006) are displayed.

of the monthly climate indices leading to each of these three growth extreme types. Figure 5 shows the 95% confidence intervals of the means of monthly climate indices causing positive and negative growth extremes, as well as normal growth.

The robust patterns in the seasonal course of temperature and precipitation variations revealed significant differences in climate causing isolated and lagged growth extremes. C-EX growth responses (both positive and negative) are generally triggered by anomalous climate during the April–July season. In particular, ideal conditions in July lead to enhanced growth, while productivity drops depend upon a broader season. Negative CL-EX and L-EX events on the other hand are related to August–October climate. This relationship indicates, that unfavourable late summer to early autumn conditions leads to lower forest productivity in the following year. Additionally, reduced growth limitations in winter (December–February) contribute to low growth in the subsequent summer if previous growing season climate was moderately (negative L-EX) or strongly (negative CL-EX) disadvantageous. Positive L-EX events are caused by two consecutive growing seasons with beneficial climate conditions while no clear pattern leading to positive CL-EX events was found.

4. Discussion

Understanding the impacts of climate extremes on European forests requires information on tree growth at large scales. The RTCs developed in this study integrate high-frequency

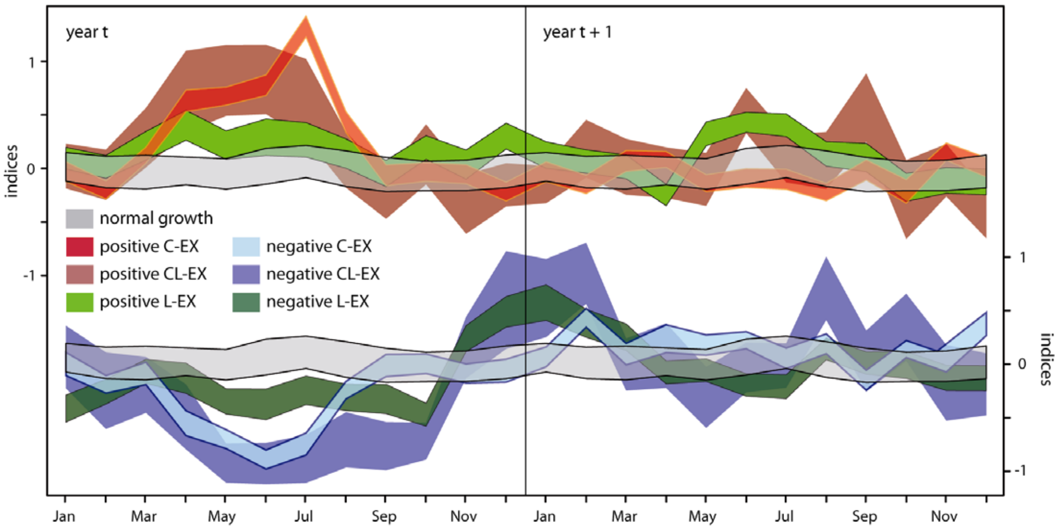

Figure 5. Monthly climate indices at combined temperature and precipitation limited sites causing normal or extreme growth reactions. Replications are: 178 negative and 142 positive C-EX events; 19 negative and 18 positive CL-EX events; 65 negative and 123 positive L-EX events. The replication of randomly chosen normal growth events equals the mean occurrence of extremes = 90 events.

forest growth variability over extensive areas and cover longer time periods than many of the individual site chronologies. Thus, our data provide a suitable basis for the assessment of past extreme events and comparison with other data streams such as climate variability, productivity measurements from vegetation models (e.g. Kaplan *et al* 2012), forest inventories (Corona and Marchetti 2007) or crop harvest data (Mozny *et al* 2012). Several RTCs—and reconstructed extreme years (see 'all' category in figure 3)—are dominated by individual tree species emphasizing species-specific growth characteristics under comparable climatic conditions. Thus, growth extremes of underrepresented tree species, and the extent to which mixed forests may be more resilient towards climatic extreme events, are not fully assessable using the current network. RTCs represent surprisingly confined areas, even though no spatial information was considered in the underlying grouping. Thus, forest productivity in the respective areas is expected to follow similar climatic drivers. Over long periods, however, the climate sensitivity of forests may shift due to low-frequency trends such as the 20th century warming (Lloyd and Bunn 2007, Andreu *et al* 2007) or changes in the atmospheric composition (Phillips *et al* 2008). Even though the magnitude of such variations in external forcing likely varies on a continental scale, we observed synchronous growth extremes between 1500 and 2008 within and among regions. This suggests that annual growth changes during the calibration and verification periods of RTCs were reasonably consistent with inter-annual to multi-decadal growth variability over five centuries.

We identified extremely high and low growth across Europe between 1500 and 2008 (see supplementary material available at stacks.iop.org/ERL/7/045705/mmedia). Large-scale growth extremes are rare due to the offsetting responses of temperature, precipitation and mixed-sensitivity sites as well as the physical modes of the climate system with contrasting regimes during summer in southern versus northern Europe (Trouet *et al* 2012, Casty *et al* 2007). Comparisons with climate anomalies during the 20th century suggest, that large tree-ring compilations mirror the spatial extent of temperature and precipitation extremes. A direct interpretation of pre-instrumental growth extremes is, however, complicated by seasonal variations in forests' climate responses (Babst *et al* 2012) and carry-over effects from the previous year (this study, Frank *et al* 2007a). Many regional dendroclimatological studies found positive correlations between radial tree growth and previous summer to autumn climate (e.g. Carrer *et al* 2010) and we observed a similar climate response of the fifteen RTCs (appendix B). It is important to note, however, that the species represented in our tree-ring network follow determinate growth mechanisms and therefore are significantly influenced by environmental conditions during bud formation (Borchert 1991). Carry-over effects from the previous growing season are likely enhanced compared to species which exert indeterminate growth, but testing this hypothesis would require a vastly enlarged network. For the major European tree species, our results emphasize the importance of lagged growth extremes, as evidenced by the growth anomalies during the 1947/48 and 1976 heat and drought events in central Europe and the high-elevation Alps respectively. Importantly, we were able to reveal how characteristic patterns in temperature and precipitation anomalies over the course of more than 18 months cause immediate or lagged growth reactions.

In our continental scale tree-ring network, we attributed growth minima in the subsequent year to negative August–October extremes of limiting climate parameters at temperature and precipitation responsive sites. This result emphasizes the influence of autumn climate on forest growth—a factor which is expected to become even more important due to changes in ecosystem respiration caused by warming trends (Vesala *et al* 2010). Furthermore, productivity in the subsequent year appears to be lower if growth limitations are reduced during the cold season. This signal presumably derives from enhanced respiratory carbon losses at temperature limited sites caused by warm conditions outside the main growing season (Piao *et al* 2008). These findings contribute to the mechanistic understanding of ring formation and also are relevant for terrestrial carbon sink estimates based on dynamic global vegetation models which currently do not sufficiently consider carry-over effects in simulations of ecosystem productivity (Sitch *et al* 2008).

5. Conclusions

High-frequency variability of European forest growth over the past 500 years is expressed by fifteen robust RTCs which are mainly separated by geographic position, climate response and species-specific growth characteristics. RTCs respond synchronously to extensive climate anomalies and indicate extreme years which are of particular interest for comparison with other data streams (e.g. crop yield). The spatial extent of strong climate anomalies is reflected by a continental scale tree-ring network, however, the direct attribution of past growth extremes to specific climatic conditions remains challenged by the intermittent occurrence of lagged responses to climate anomalies outside the current growing season. We could determine that negative lag effects are mainly caused by unfavourable August–October climatic conditions at temperature and precipitation limited sites. Our results demonstrate the merits of large empirical networks to assess the impacts of climate extremes on forest growth. In particular we provided the first continental-wide reconstruction of the timing and spatial manifestations of growth extremes during the past 500 years where the inter-annual terrestrial carbon balance was likely significantly affected. These are the first efforts to provide a long-term benchmark to place impacts of the recent extremes of 2003 in central Europe (Ciais *et al* 2005) and 2010 in western Russia (Stefanon *et al* 2012) in a long-term context and may trigger further use of tree-rings in studies related to carbon cycle dynamics and climate change.

Acknowledgments

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Appendix A. Number of regional tree-ring chronologies

To define the optimal number of regional tree-ring chronologies representing European tree growth, we performed a sensitivity analysis of changes in mean chronology inter-correlations (rbar) depending on the number of clusters chosen. Rbar increases until the tree-ring network is divided into 19 clusters, however beyond 16 clusters individual groups with very few sites and representing local conditions were obtained (figure A.1). Since our study requires robust regionally representative clusters we ended up dividing the tree-ring network into fifteen groups but tests showed that the overall results or conclusions are not sensitive to this choice. The cluster partitioning was determined over the 1920–70 period with maximum data availability and independently verified between 1870 and 1919.

Appendix B. Regional climate response

To assess the climate response of forests represented by RTCs, we generated cluster means from monthly temperature and

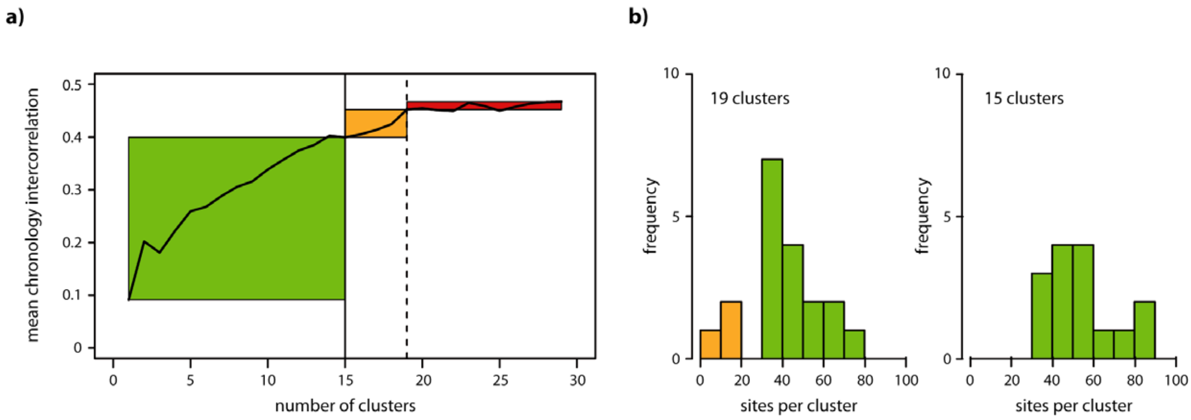

Figure A.1. (a) Sensitivity of mean chronology inter-correlations (rbar) to the number of clusters selected. (b) Distribution of the numbers of sites contained in 19 and 15 clusters respectively. Green areas mark a range of cluster numbers where the rbar is increasing while clusters are well replicated (>30 sites) and represent large areas. Orange areas indicate increasing rbars with simultaneously decreasing replication (>20 sites) and space represented. Red areas mark a range of cluster numbers with negligible increases in rbars.

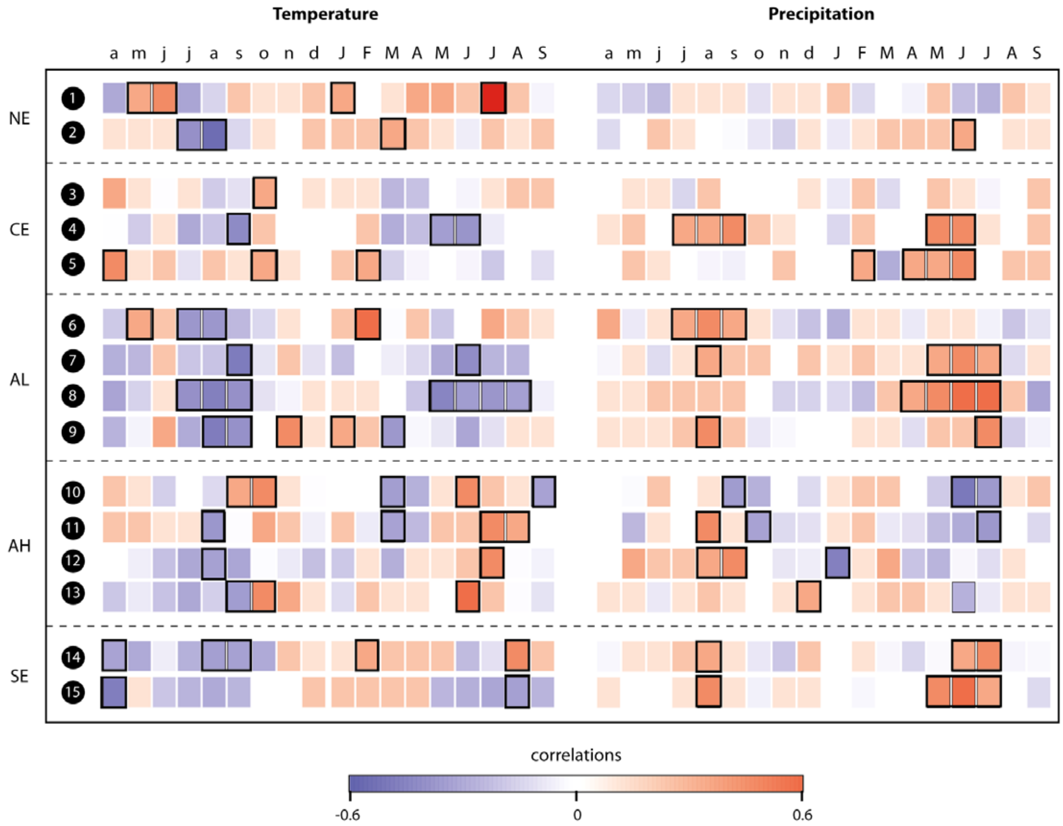

Figure B.1. Correlations between fifteen regional tree-ring chronologies (RTCs) and monthly temperature and precipitation data. Correlations are shown between April of the year prior to ring formation and current September. Black rectangles highlight significant months ($r > 0.273$, 95% confidence level). RTCs are grouped according to the geographic space covered (NE: northern Europe, CE: central Europe, AL: Alps low elevation <1300 m a.s.l., AH: Alps high elevation >1300 m a.s.l., SE: southern Europe).

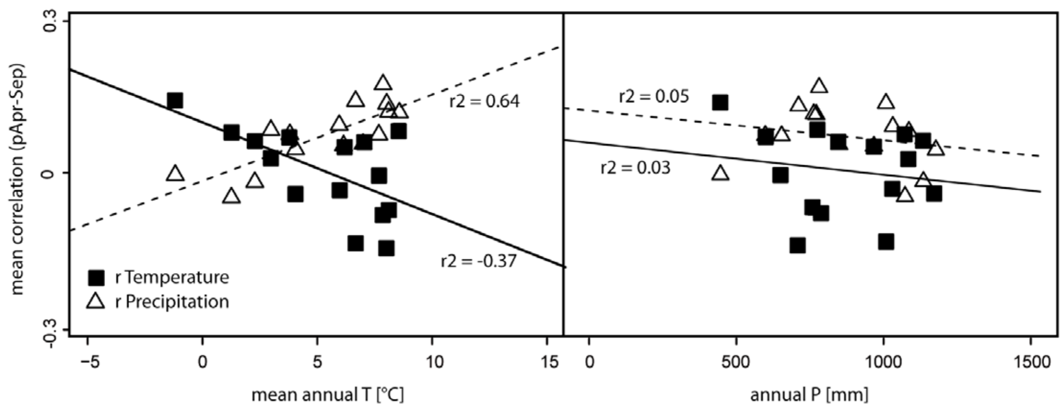

Figure B.2. Sensitivity of average pApr-Sep climate response of RTCs to mean annual temperature (left panel) and to annual precipitation (right panel).

precipitation data analogue to the calculation of RTCs. From monthly climate responses of clusters, we identified seasons which strongly influence forest growth in different parts of Europe. Additionally, we performed a linear regression analysis between the average previous April to current September climate correlations and mean annual temperature and precipitation of each cluster to identify the strongest common drivers of forest growth across the continent.

Results show that climate during the April–July season commonly influences forest growth across Europe. On a regional scale, however, the seasonality in the climate response varies strongly (figure B.1). July temperature is the strongest driver of forest productivity in northern Scandinavia (RTC 1) whereas in southern Scandinavia (RTC 2), spring to summer precipitation and spring temperature positively influence wood formation. Additionally, high temperatures during previous July–August hamper growth in this area. Forests in central Europe (RTCs 3–5) as well as at low to mid-elevation Alpine regions (RTCs 6–9) respond positively to April–July and in the case of RTCs 4 and 6 also to previous

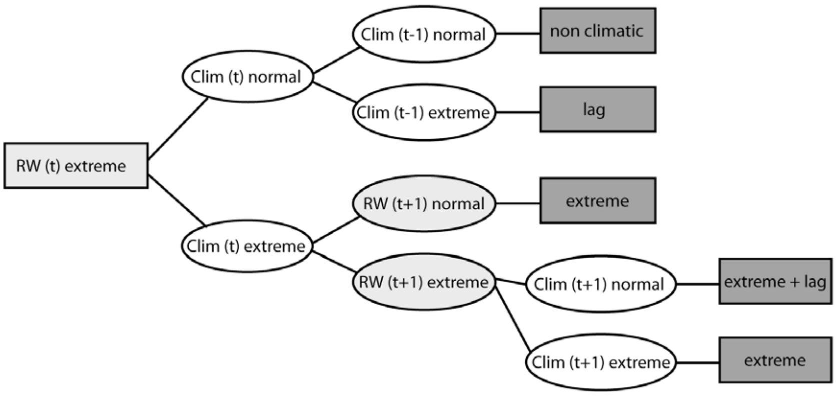

Figure C.1. Concept to distinguish between isolated growth extremes, growth extremes with lag effects, purely lagged extremes and growth extremes which are not related to climate extremes. Climatic (white) and growth (light grey) conditions are indicated with '*t*' representing the current growth year.

Table D.1. Properties of fifteen RTCs representing high-frequency European forest growth variability. The average elevation of RTCs are shown. Rbars represent the mean inter-chronology correlation between sites within clusters over the calibration and verification period.

Region	RTC	Countries	Elevation (m a.s.l.)	Nr. of cluster members	Chronology (repl. > 4)	Rbar calib.	Rbar verif.
Northern Europe	1	FIN, SWE, NOR	301	53	1481–2006	0.66	0.63
	2	FIN, SWE, NOR	373	66	1550–2003	0.23	0.17
Central Europe	3	POL, GER, GBR	619	99	1234–2008	0.09	0.07
	4	GER	365	55	1819–2005	0.48	0.40
	5	GER, FRA, NED	249	67	1788–2005	0.44	0.32
Alps and Pyrenees dry	6	CH, AUT, GER	958	73	1776–2004	0.43	0.38
	7	CH, GER	933	41	1829–2005	0.46	0.40
	8	AUT	470	46	1740–2007	0.49	0.50
	9	ITA, CH, ESP	1312	103	1517–2007	0.21	0.16
Alps and Carpatians cold	10	AUT, ITA, CH	1604	44	1382–2004	0.46	0.41
	11	AUT, ITA, CH	1915	51	1515–2003	0.62	0.53
	12	CH, AUT, ITA	1299	96	1693–2003	0.37	0.27
	13	SVK, ROM, BUL	1480	46	1709–2004	0.51	0.38
Southern Europe	14	TUR, GRE, ITA	1103	98	1438–2004	0.11	0.10
	15	ESP	1515	53	1587–2005	0.32	0.27

summer and early autumn precipitation. In addition, negative correlations with temperature during the same seasons are observed. High Alpine RTCs 10–13 generally react to more narrow time windows focusing on June–July of the current and August–October of the previous year. They benefit from warm current summer conditions while the response to previous autumn climate appears to be RTC and thus species specific. Southern European forests (RTCs 14–15) show a strong positive response to current May–June as well as to previous August precipitation. Considering the climate response of all RTCs, European forests mostly respond to the current June–August (temperature), April–July (precipitation), and the previous July–October (temperature and precipitation) seasons. Taking into account the average climate correlations over 18 months (pApr-Sep), we find that the temperature and precipitation responses of RTCs are highly sensitive to changes in mean annual temperatures and insensitive to changes in annual precipitation (figure B.2).

Appendix C. Decision tree model for lagged growth extremes

See figure C.1.

Appendix D. Description of regional tree-ring chronologies

See table D.1.

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