Climatic drivers of beech growth in the Vosges and Jura Mountains

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Introduction

Common beech (*Fagus sylvatica* L.) is one of the key tree species of Central European mixed mountain forests between 600-1400 m asl. This dominant broadleaf species is known to reflect distinct inter-annual signal strength over larger scales (Neuwirth et al. 2007). To date, various dendroclimatological and -ecological studies have assessed the growth response of beech (Biondi 1993, Dittmar & Elling 2007, Piovesan et al. 2003, Rozas 2001), with some emphasis on productivity changes under warming and/or drying climates (Leuzinger et al. 2005). More methodological approaches analyzed long-term trends in ring width (Badeau et al. 1995), physiological controls on wood density (Bouriaud et al. 2004), and vessel lumen size (Sass & Eckstein 1995) of the diffuse-porous beech. Additional effects of soil conditions and water control on beech growth have recently been analyzed (Granier et al. 2007, Thimonier et al. 2000).

Due to the increased climate sensitivity of beech trees that grow near their distributional boundary (Z'Graggen 1992), we here compiled tree-ring width (TRW) data from nine sites in the Vosges, Jura and Swiss northern pre-Alps. This network was analyzed to understand inter-annual to decadal-scale growth variations over space and time, and to reveal its responses to regional temperature and precipitation fluctuations over the past ~200 years.

Data and Methods

TRW series from the Jura Mts. and northern pre-Alps collected in the 1980s (Z'Graggen 1992) are re-used and combined with an update from the Vosges Mts. that extends until 2003. Data include ~28,600 annual measurements, derive from elevations between 560-1390 m asl, and roughly cover the region 46-48° N and 6-8° E (Fig. 1). Relevant information on the TRW site chronologies is summarized in table 1.

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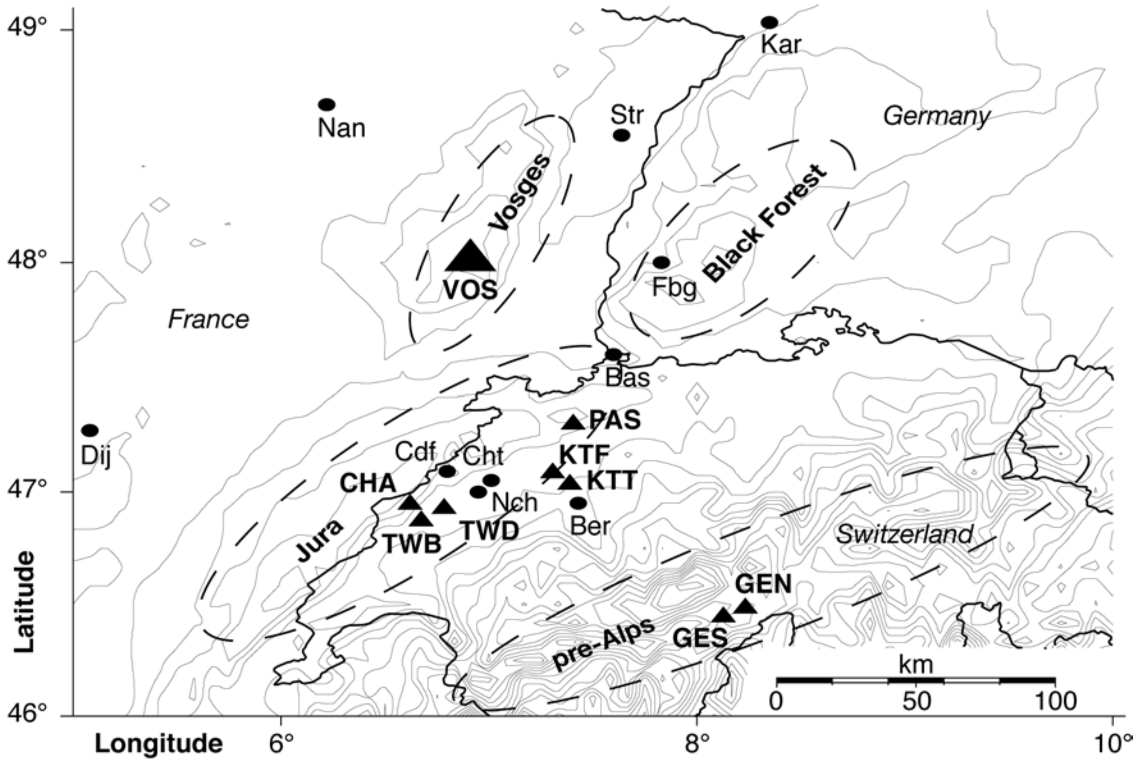

Figure 1: Location of the TRW sites (triangles) and instrumental stations (circles) used in this study. While each triangle represents one beech stand, the larger VOS triangle integrates samples from various stand locations along the Central Vosges Mountains.

Table 1: Characteristics of the site chronologies after spline detrending. Loc=Location (Lat/Lon), Ele=Elevation (m asl), Pep=Replication (Series), Per=Period, Per >5=Period >5 series, MSL=Mean Segment Length (Years), AGR=Average Growth Rate (mm/year), Lag-1=autocorrelation at year one. Bold chronologies were considered in the mean Swiss-French record.

Site	Loc	Ele	Rep	Per	Per >5	MSL	AGR	Lag-1
VOS	**48°00/6°90**	**1230**	**53**	**1781-2003**	**1781-2003**	**135**	**1.05**	**0.33**
TWD	47°05/6°90	560	24	1844-1987	1844-1987	121	1.59	0.45
TWB	47°05/6°80	630	26	1890-1987	1890-1987	78	2.24	0.28
PAS	**47°30/7°40**	**1080**	**24**	**1842-1987**	**1842-1987**	**130**	**1.11**	**0.28**
CHAS	**47°06/6°21**	**1370**	**24**	**1859-1987**	**1859-1987**	**93**	**1.59**	**0.42**
KTT	47°01/7°34	700	24	1825-1987	1825-1987	136	1.00	0.46
KTF	47°00/7°35	630	24	1879-1987	1879-1987	95	2.10	0.29
GENS	46°46/8°20	1390	23	1849-1987	1849-1987	95	1.34	0.43
GENN	**46°45/8°20**	**1320**	**24**	**1796-1987**	**1796-1987**	**144**	**1.10**	**0.25**

Raw measurements were first checked for dating errors on a site-by-site basis and individual spline detrending applied to remove non-climatic, tree-age related growth trends from the series (Fritts 1976). For the preservation of inter-annual to decadal scale variability, TRW series were individually detrended using cubic smoothing splines with 50% frequency-response cutoff equal $^{2}/_{3}$ the series length (Cook & Peters 1981). Indices were then calculated as residuals from the estimated growth curves after power transformation (details in Cook & Peters 1997). Mean chronologies were calculated using a bi-weight robust mean, with their variance stabilized using methods described in Frank et al. (2007b). Based on inter-series correlations between the nine site chronologies and elevation criteria, data from four sites (VOS, PAS, CHAS, GENN) were subsequently selected to develop a mean Swiss-French beech chronology (Fig. 2).

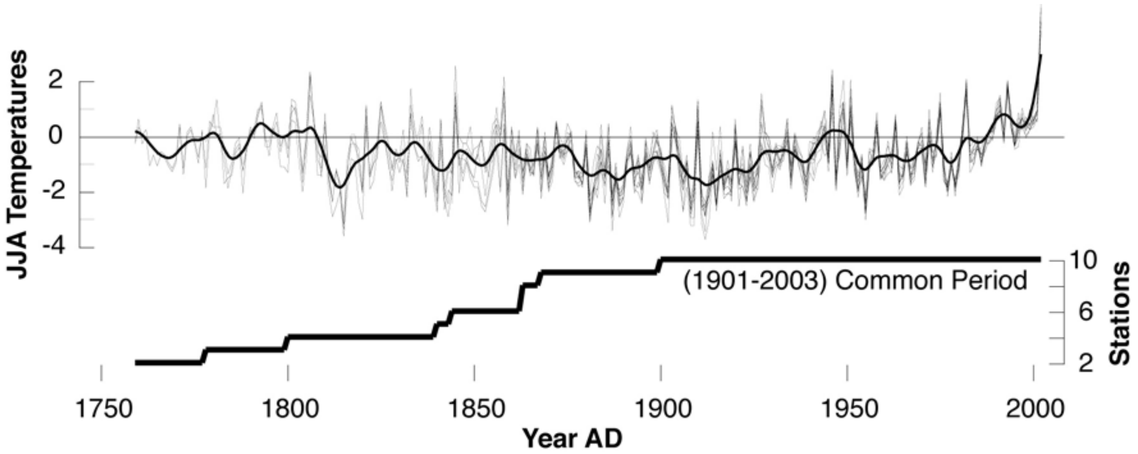

Figure 2: Summer (June-August) instrumental temperature data expressed as anomalies with respect to 1971-2000. Grand average correlation between the 10 stations for the annual, winter and summer data is 0.88, 0.93 and 0.94, respectively. Inter-station correlations range from 0.53 (Cht/Str) to 0.97 (Bas/Kar) for annual, from 0.81 (Chat/Str) to 0.99 (Kar/Str) for winter and from 0.88 (Nan/Nch) to 0.97 (Bas/Cht) for summer. Lag-1 autocorrelation of the mean summer (June-August) temperature record is 0.20. Smoothed mean curve is a 20yr low-pass filter.

Signal strength of this record (VOS-PAS-CHAS-GENN) was assessed using 'moving window' inter-series correlation (*RBAR*), and the Expressed Population Signal (*EPS*) computed along the time-series (Wigley et al. 1984).

For growth-climate response analysis, monthly temperature means and precipitation sums from 10 instrumental stations were employed (Fig. 1). Relevant information on these stations is summarized in table 2.

Table 2: Characteristics of the instrumental station data used in this study. Ele=Elevation (m asl), T-record=Period covered by temperature measurements (monthly), P-record=Period covered by precipitation measurements (monthly).

Site	Station	Country	Lon	Lat	Ele	T-record	P-record
Bas	Basel-Binningen	CH	7°60	47°60	316	1760-2003	1861-2003
Ber	Bern	CH	7°43	46°95	565	1760-2003	1856-2003
Cht	Chaumont	CH	6°99	47°05	1073	1864-2003	1864-2003
Dij	Dijon-Longvic	FR	5°08	47°27	227	1845-2003	1831-2003
Cdf	La Chaux de Fonds	CH	6°80	47°09	1018	1901-2003	1900-2003
Nan	Nancy-Essey	FR	6°22	48°68	217	1841-2003	1811-2003
Nch	Neuchatel	CH	6°95	47°00	485	1864-2003	1856-2003
Str	Strasbourg-Entzheim	FR	7°64	48°55	150	1801-2003	1803-2003
Fbg	Freiburg/Breisgau	DE	7°83	48°00	300	1869-2003	1869-2003
Kar	Karlsruhe	DE	8°35	49°03	112	1779-2003	1801-2003

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For further details including the reliability of early data and homogenization procedures, see Auer et al. (2007). Correlations between the proxy and target data were computed for an 18-month window from previous-year April to current-year September over the full 1806-2003 period of overlap. Four split periods of equal length were additionally used to detect temporal changes in climate sensitivity.

Monthly temperature means averaged from 10 instrumental stations (Fig. 1, Tab. 2) indicate high inter-annual to multi-decadal scale variability. June-August temperatures describe a decline from the beginning of the observations until the early 20th century (with superimposed depressions centered ~1785, 1816, 44, 88 and 1913), followed by increasing values peaking in 2003 (with superimposed depressions centered ~1940, 56, 78, and 1996) (Fig. 2).

Even though the common period covered by all stations is restricted to 1901-2003, the herein considered station measurements most likely provide reliable high-frequency variability back to 1760 (Auer et al. 2007), conditions worldwide limited to Central Europe. For a detailed summary of potential lower frequency uncertainties in early (<1850) instrumental station measurements that can systematically bias inferred relationships with tree-growth, see Frank et al. (2007b).

Monthly precipitation sums averaged from the 10 instrumental stations (Fig. 1, Tab. 2) indicate slightly lower inter-annual to decadal scale variability compared to the temperature variations. June-August precipitation portrays no longer-term trend over the past 200 years, but prominent decadal fluctuations (Fig. 3). These include below-average summer precipitation sums centered ~1838, 59, 70, 85, 1906, 23, the 1940s, 1962, 84 and 2003.

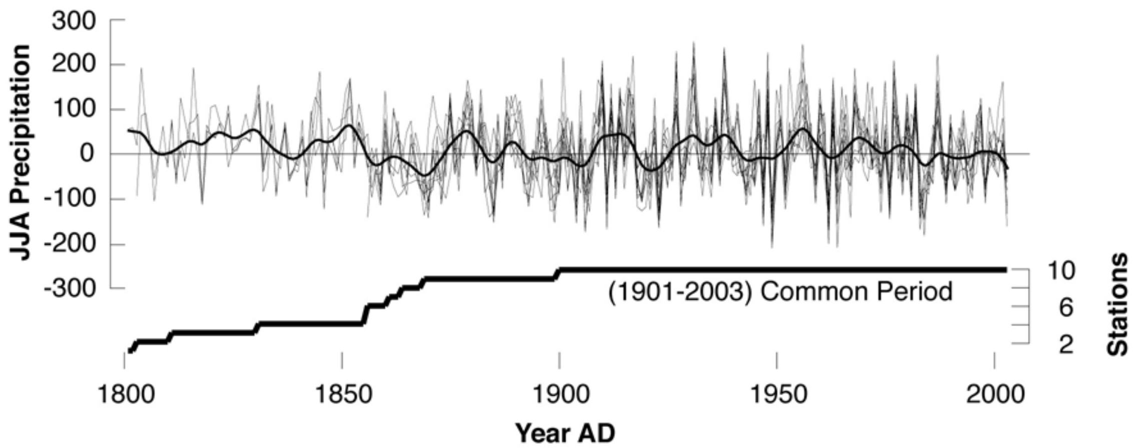

Figure 3: Summer (June-August) instrumental precipitation data expressed as anomalies with respect to 1971-2000. Average correlations between the 10 stations for the annual, winter and summer data are 0.77, 0.80 and 0.68, respectively (1901-2003). Inter-station correlations range from 0.57 (Kar/Nch) to 0.93 (Cht/Cdf) for annual, from 0.66 (Dij/Kar) to 0.95 (Cht/Cdf) for winter and from 0.45 (Dij/Kar) to 0.92 (Cht/Nch) for summer. Lag-1 autocorrelation of the mean summer (June-August) precipitation record is -0.10. Smoothed curve is a 20yr low-pass filter.

Results and Discussion

Mean correlation between the four TRW site chronologies (VOS, PAS, CHAS, GENN) is 0.47, and ranges from 0.27 between PAS and GENN to 0.61 between the VOS chronology

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and data from both PAS and CHAS. After combining measurements from these sites, a new mean chronology was developed that due to the sampling design (only living trees) and detrending method (individual series) only contains inter-annual to decadal-scale variability (Fig. 4a).

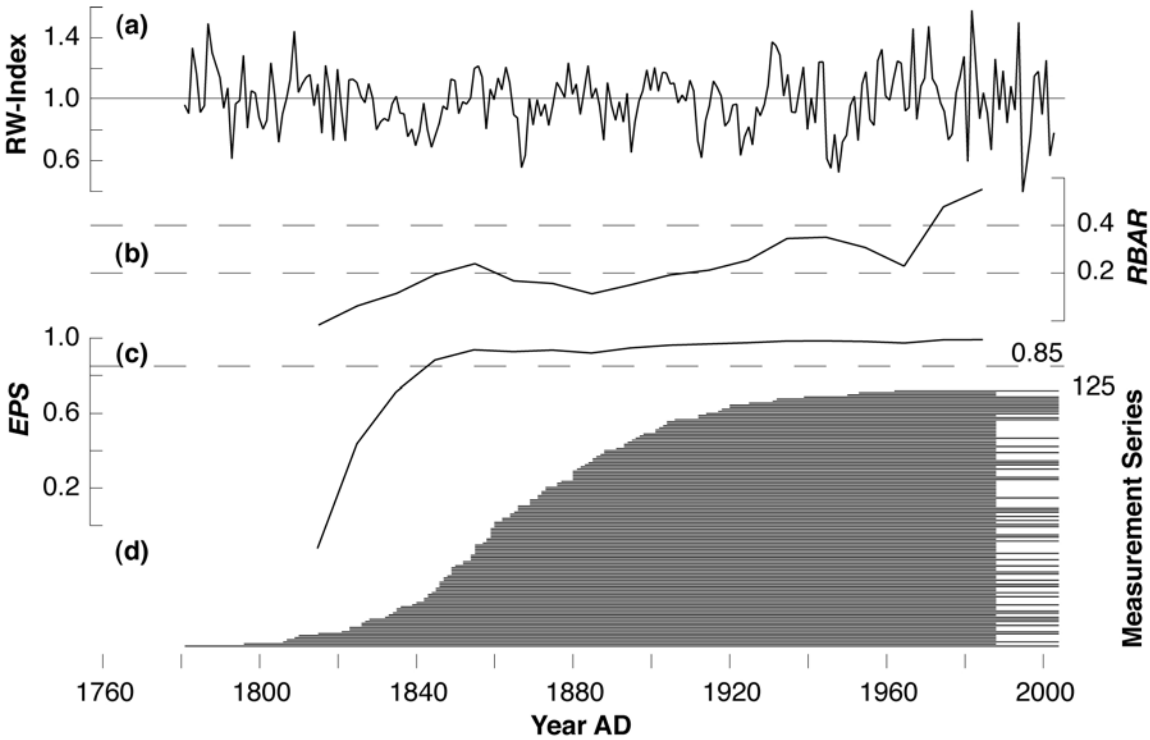

Figure 4: Characteristics of the (a) mean Swiss-French beech chronology and their (b) RBAR, (c) EPS and (d) replication. RBAR and EPS values were calculated over 30yr windows lagged by 20 years along the chronology. Lag-1 autocorrelation of the record is 0.24.

This novel Swiss-French mean record describes a slight upward trend from around the 1790s into the early 19th century, a well-known period of reduced solar activity and increased explosive volcanism (e.g., Büntgen et al. 2006a). Stronger decadal-scale fluctuations are revealed from around the 1840s to the 1920s, with episodes of high growth rates ~1860, 1880 and 1900. Distinct 20th century growth depressions occurred in the 1940s, 70s and 1990s. Abrupt growth reductions are found in 1793, 1867, 1895, 1913, 1923, 1948, 1981 and 1995; and positive anomalies in 1787, 1809, 1879, 1931, 1982, 1971 and 1994. In this regard, one must note that (artificial) variance changes i.e., increased variance before ~1830 and after ~1930, have not fully been removed. These are most likely related to the general decrease in sample size back in time, and the inclusion of juvenile and less correlating wood during the early 1830-1930 period (Fig. 4d), affecting the comparison of annual extremes over the past centuries. Interestingly, Biondi (1993) and Piovesan et al. (2003) both reported cross-dating difficulties related to the presence of very narrow, incomplete or even missing rings, especially near the pith. For a discussion and more methodological details on related variance stabilization techniques, see Frank et al. (2007a). Additional pruning at the end of each of the measurement series (i.e., some sort of agebanding methodology, Briffa et al. 2001) would result in a more even distribution of similar tree-ages along the record, and potentially help such affects to be diminished.

Hence, caution is advised with any interpretation of the new Swiss-French beech chronology, as various quality changes through time must be considered. Reasonable signal-strength is found for the past 150-200 years, as demonstrated by the *EPS* values above the commonly applied quality threshold of 0.85 until 1840 (Fig. 4b-c). Interestingly, the *RBAR* values constantly decrease back in time. Uncertainty during the chronology's first portion is most likely caused by low sample replication and should be considered (together with the observed variance changes) when comparing the proxy record with the instrumental target data.

Significant correlations between beech TRW and temperatures (using monthly means from previous year April to September of the growing season) are not obtained when computing over the full 1806-2003 period of proxy/target overlap (Fig. 5a). Highest correlations of 0.43 and 0.38 are derived from previous year April and current year August temperatures over the 1806-1855 and 1855-1904 periods, respectively. The most significant negative correlation (*r* =-0.46) is obtained with March temperature. The overall response to temperature describes no or negative relationships to previous year spring, generally negative correlations with previous year July-August and positive correlations with the previous autumn, and again no pattern with winter prior to the growing season. Overall negative correlations are found between March-June, followed by positive relationships for July-August. While correlations based on the four split periods indicate some noise, the overall response behavior is confirmed by the (relatively diminished) correlation results obtained from the full 1806-2003 period of proxy/target overlap.

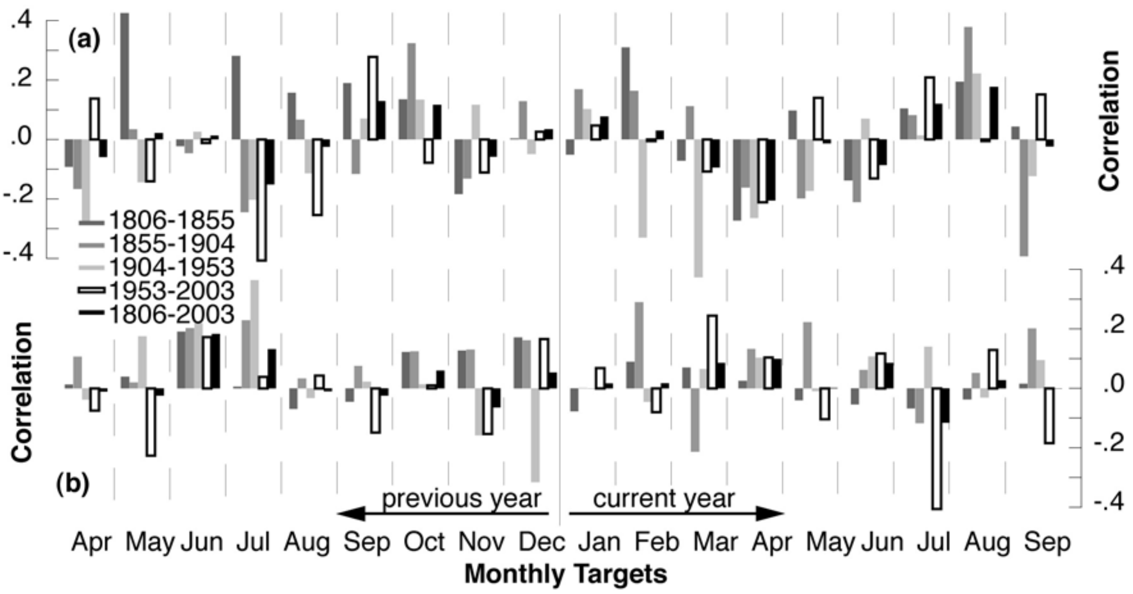

Figure 5: Comparison between the mean Swiss-French beech chronology and (a) monthly temperature means and (b) monthly precipitation sums from previous year April to current year September. Correlations were computed over the full 1806-2003 and four split periods of equal length. Significant levels are not provided as lag-1 autocorrelation varies between each monthly climate target and the different periods considered.

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In contrast, correlation analysis using monthly precipitation sums revealed overall less pronounced patterns in seasonal response (Fig. 5b). Some positive relationship is though indicated for previous year June-July, while negative correlations are found with July of the growing season. Besides (abiotic) shifts in growth responses to climate, which most likely result from changing temperature and precipitation regimes, (biotic) tree age-related changes in growth-sensitivity and/or response seasonality may account for some of the herein observed temporal variance. An overall response shift from former temperature to current precipitation (drought) sensitivity as reported from a spruce network (Büntgen et al., 2006b) is, however, not observed. Despite such temporal weakening in the growth/climate response of the mean Swiss-French chronology, some individual sites may show a more stable response behavior over time.

Comparison of the herein obtained TRW extremes with those reported from a beech network across the Bavarian-Forest and -Alps, reveals a high degree of temporal coherency between both regions, including growth depressions in higher altitudinal beech forests in the 1970s, 80s and 1995). Increased frequency of negative pointer years during the past three decades is also reported from an Italian high-elevation beech chronology (Piovesan et al. 2003). In this regard, Dittmar & Elling (2007) suggested reduced ecological fitness and stability of all age-classes, as low-elevation beech growth mainly suffered from below-average precipitation, whereas high-elevation beech growth was generally limited by pronounced temperature depressions. Interestingly, none of the meteorological and hydrological parameters is reported to significantly correlate with beech TRW at elevations ~1000 m asl; results that are (partly) confirmed by this study (Fig. 5).

Causes and scales of abrupt beech growth depressions are not fully understood. See Gessler et al. (2007) for potential risks of the European beech related to a warmer and dryer climate as projected for the future (IPCC 2007). In a free atmosphere experiment, Leuzinger et al. (2005) found a two-year sequence of reduced basal stem area growth of beech (and four other deciduous species), most likely caused by the severe summer drought of 2003 (Schär et al. 2004). Similar climatic conditions, i.e., negative water budget due to the precipitation/evaporation ratio, forced late summer soil desiccation and drought-induced growth reductions in the 1940s and 70s (Fig. 2). In this regard, one must note that beech has relatively shallow roots in comparison to oak (Leuschner et al. 2001a, b). Due to the complexity of cell length, wood anatomy and hydraulic properties such as elasticity of storage tissue and stomata control over tree water status (Hacke & Sperry 2001, Gessler et al. 2007), species-specific cavitation risk – even though the large oak early wood vessels are much more exposed to cavitation than the small beech vessels – is only weakly understood (Gessler et al. 2007, Leuzinger et al. 2005). Any argumentation towards vessel-size dependent drought-sensitivity could thus be misleading.

Three beech stands distributed across Central Europe showed most significant growth reductions in the year following the severe 2003 summer drought (Granier et al. 2007). Since beech is further assumed to allow water storage to be directly utilized for basal area increases (Bouriaud et al. 2004), growing season length and character may additionally impact annual growth rates. Nevertheless, one should consider that water storage can only last for a limited period (in the range of one day), and thus most likely becomes irrelevant during longer drought periods (Breda et al. 2006). A close relationship between photosynthetic production and TRW potentially allows some of the negative feedbacks of beech growth under a warming climate to be compensated, as related increases in radiation (and higher rates of photosynthesis) possibly promote vessel lumen formation, independent of any soil water deficit (Bouriaud et al. 2004). In contrast, one could argue that warmer summer temperatures and increased radiation don't necessarily have to cause an increase in photosynthesis rates, as the amount of summer radiation often excides the total of radiation usable for plants, which becomes even more critical for deciduas trees.

Further modifications of the generally observed drought-sensitivity of beech TRW may arise from the soil storage capacity at a given site (Garnier et al. 2007, Saas & Eckstein 1995), as soil water deficit can significantly hamper vessel formation (Aranda et al. 2000, Rozas 2001). In addition, various degrees of species-specific drought-sensitivity may result from differences in the adaptation rate of physiological parameters (Gessler et al. 2007, Peuke et al. 2002, Steppe & Lemeur 2007).

Conclusions

We compiled a network of nine TRW beech chronologies and instrumental station measurements for the Central northern pre-Alps and the past ~200 years. Growth-climate response analysis demonstrated the ability of inter-annual to decadal-scale variations in beech growth to reflect common climatic signals over a wider region. However, a distinct climatic driver (temperature or precipitation) was not found to dominate average beech TRW (~1000 m asl) when combining measurements from four sites distributed across the Vosges and Jura Mts.

In an attempt to further detail the 'complex' growth response of beech under potential future warming and induced drought stress, more local studies and more tree-ring data from heterogeneous sites e.g., high-to-low-elevation, dry-to-wet sites, juvenile-to-mature trees and additional climate parameters, e.g., reliable drought metric, water vapor and cloud cover data are required. Besides the spatial aspect, composite chronologies of living and historic material that may allow age-related detrending methods to be successfully applied and lower frequency information accordingly to be preserved, could further help benchmarking the extreme late 20th century conditions into a longer-term context. Such studies would subsequently provide useful insight on the role of forest growth in relation to estimates of large-scale biomass productivity and carbon sequestration.

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