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ORIGINAL ARTICLE

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Temporal instability in tree-growth/climate response in the Lower Bavarian Forest region: implications for dendroclimatic reconstruction

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Abstract This paper explores the temporal stability of growth/climate relationships in ring-width chronologies of Norway spruce [*Picea abies* (L.) Karst] and silver fir (*Abies alba* Mill) in the Lower Bavarian Forest region in southern Germany. These chronologies were compiled, using both historic and living tree-ring data, with the main aim of developing a dendroclimatic reconstruction for the region covering the last 500 years. Moving window correlation analysis shows that prior to the twentieth century, both species co-vary in a similar way (1480–1899 mean r =0.66). There is no significant correlation between the species chronologies since ca. 1930, which partly reflects anomalous growth trends in the fir chronology since ca. 1960. Multiple regression analysis was utilised to assess the ability of both species chronologies to model March–August precipitation. The precipitation signal of the spruce data was found to be both stronger than the fir data (1872–1930 calibration: r^2=0.45 vs 0.25) and more time stable. After ca. 1930, the fir chronology loses it ability to model March–August precipitation until there is no climate signal at all in the fir data in recent decades. The spruce data also express a later weakening in their climate signal in the mid 1970s. We present compelling evidence indicating that the anomalous trends observed in the fir data, since the mid 1960s, appear to be predominantly related to local SO_2 emissions from power plants and refineries. It is also likely that this local anthropogenic forcing is the cause of the weakening of the climate signal in the spruce data since the mid 1970s. The conclusions from this study are: (1) The fir tree-ring data cannot be used for traditional dendroclimatic calibration, although prior to the twentieth century the decadal variability in the fir data is very similar to spruce and so these data could be used to extend potential reconstructions in the future; (2) The recent decline and recovery event in the fir data appears to be unique to the twentieth century and is not part of a natural episodic phenomenon; (3) Traditional dendroclimatic calibration of March–August precipitation will be made using solely the spruce ring-width data. However, due to SO_2 forcing in recent decades, the calibration period will be shortened to the 1871–1978 period.

Keywords Dendroclimatology · Bavarian Forest · Germany · Response change · Forest decline

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Introduction

Between 1996 and 2001, historical tree-ring (TR) samples were taken from 40 buildings in towns of the lower Bavarian Forest Region (Fig. 1) to determine whether such data could be used to reconstruct past climates. By overlapping TR series from the historical material with series developed from low elevation living trees, composite living/historical chronologies were developed for Norway spruce [*Picea abies* (L.) Karst, 1456–2001] and silver fir (*Abies alba* Mill, 1233–1997) (Wilson 2003). In the Bavarian Forest, low elevation (<ca 700 m) spruce ring-width (RW) chronologies show a strong relationship with climate and respond positively to spring/summer precipitation (Dittmar and Elling 1999; Wilson and Hopfmueller 2001). The climate signal in fir is more complex and, compared to spruce, appears to be variable and more easily affected by non-climatic factors (e.g. site conditions, pollution etc.). Huber (1970) showed that fir TR series from southern Germany expressed a mixed climate signal and could not be used as proxies for one specific climate parameter. Elling (1993) quantified that healthy fir trees are less drought sensitive than spruce trees and that severe winter/early spring frosts could affect fir productivity for individual years. Recently,

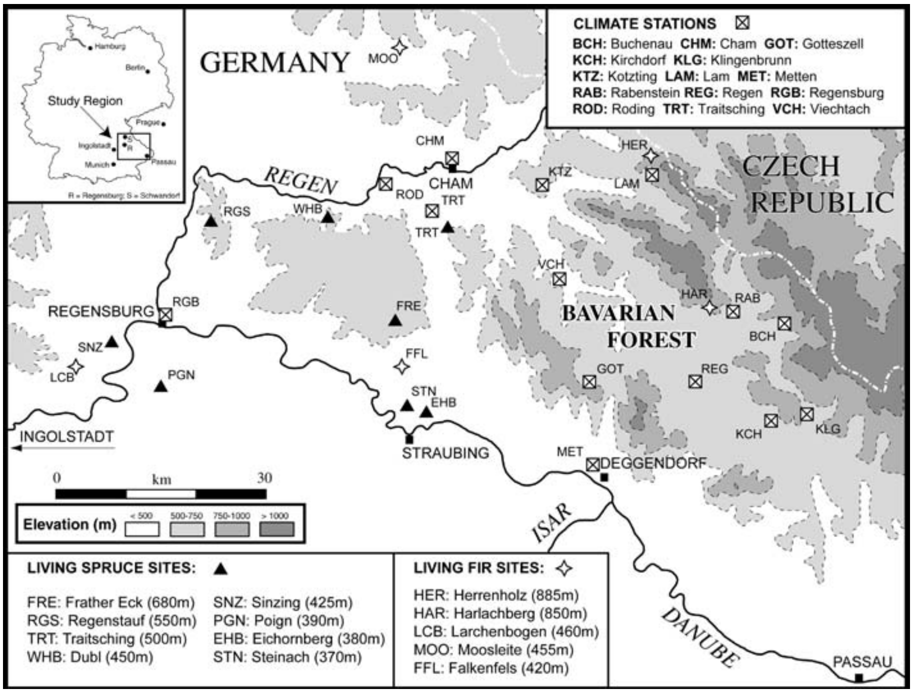


Fig. 1 Location map of living TR sites and climate stations

however, Brazdil et al. (2002), using fir RW data, have developed a March–July reconstruction of past precipitation in the Czech Republic suggesting that, in certain situations, fir could also portray a reasonably strong climate signal.

Preliminary comparison of spruce and fir chronologies from the Bavarian Forest shows that the fir data correlate well with low elevation spruce chronologies but not with higher elevation chronologies (>ca 1,050 m). Therefore, it is hypothesised that the RW series from fir and low elevation spruce sites express a similar climate signal. If this is the case, the combination of both the spruce and fir RW data (living and historical) should result in the development of a robust mean function showing common environmental forcing (presumably climate) for both species that could be used for the development of a spring/summer precipitation reconstruction. However, in recent decades in the Bavarian Forest, silver fir has shown highly anomalous trends in its RW series (Eckstein and Sass 1989; Kandler 1993) and an unstable relationship with climate through the twentieth century (Visser and Molenaar 1992a, 1992b).

James Hutton's principle of uniformitarianism is one of the fundamental keystones to any palaeoenvironmental study. In dendroclimatology, the uniformitarian principle implies that tree-growth/climate relationships modelled in the recent calibration period are stable through time so that we can infer the nature of past climate from tree-rings (Fritts 1976). There have been several recent studies that have demonstrated a reduction in tree sensitivity and/or a change in the response of tree growth to climate over the last 4–5 decades (Jacoby and D'Arrigo 1995; Briffa et al. 1998a, 1998b; Vaganov et al. 1999; Barber et al. 2000; Brazdil et al. 2002; Lloyd and Fastie 2002; Wilson and Luckman 2003). Such temporal instabilities in tree-growth/climate relationships have serious implications for the reconstruction of past climate. Therefore, the occurrence and possible causes of changes in growth/climate relationships must be explored to assess whether such changes are natural or are a result of anthropogenic forcing.

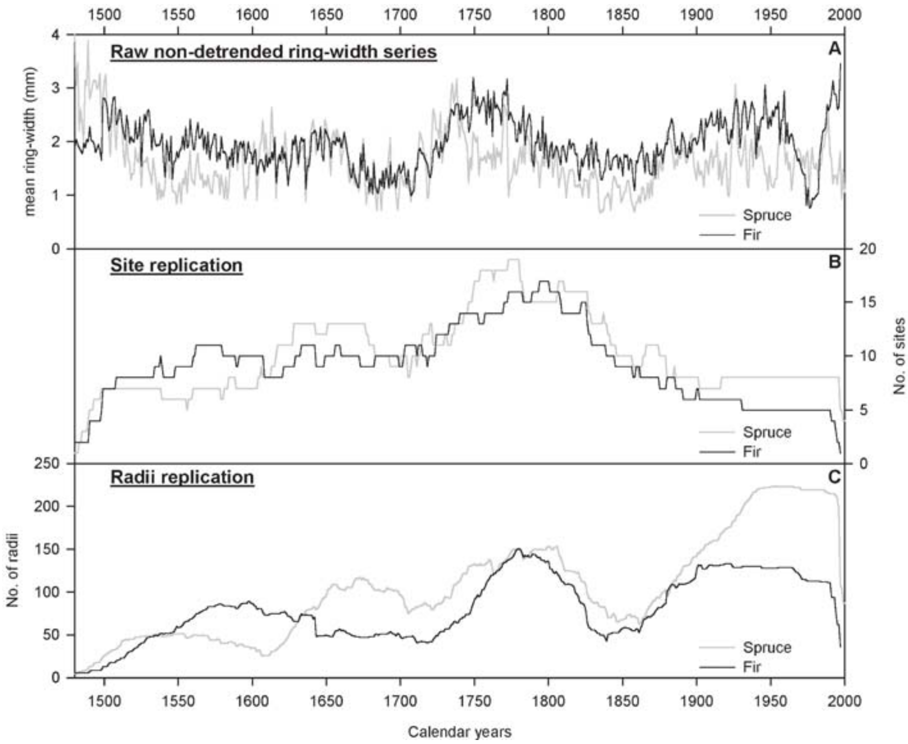
This paper examines whether RW series from spruce and fir can be used for dendroclimatic purposes in the Bavarian Forest region. It examines the temporal stability of the response of each species to climate through the period of available instrumental data and assesses the changing relationship between RW series of the two species over the last 500 years. Finally, conclusions are drawn as to the utility of each species for dendroclimatic reconstruction in the Bavarian Forest region.

Materials and methods

Tree-ring data and chronology development

Composite data-sets were developed for each species using cross-dated RW series from 31 buildings (40 construction phases) and eight living-tree sites for spruce and 29 buildings (41 construction phases) and five living sites for fir. The location and elevation of the living sites are shown in Fig. 1 and most of the historic samples were taken in and around the towns of Regensburg and Straubing. This relatively small region was targeted to maximise the probability that the sampled construction timbers originally grew in the local region (Wilson 2003). Figure 2a presents mean non-detrended chronologies for each series which highlight the anomalous pulse of low productivity and the period of recovery found in the fir data after 1960. The mean RW values in the mid 1970s are the lowest for the whole 500 year series, while the 1997 value is the highest. Obviously, some sort of disturbance event has affected the fir trees after 1960 which is not apparent in the spruce RW data.

Fig. 2. **A** Raw non-detrended site weighted RW chronologies for spruce and fir; **B** Site replication. A site is defined as either a living site or a construction phase within a building; **C** Radii replication



Much of the low frequency trends observed in the composite 'raw' chronologies in Fig. 2a are a result of the age related decline in the original measured RW series (Fritts 1976). In this study, a multi-stage standardisation procedure was utilised to remove this age related trend from individual series and develop a robust final mean index series for each species. Firstly, following techniques outlined in Cook and Peters (1997), the variance of the raw RW series was stabilised using an adaptive power transform, and the age related trend was detrended by subtracting a best fit 80 year cubic smoothing spline (Cook and Peters 1981) through the raw data. This method was used to remove the potential 'end effect' inflation of index values that can occur when using 'standard ratio' detrending (Cook and Peters 1997). For each site, the detrended series were averaged together using a biweight robust mean to diminish the effect of outliers on the mean function (Cook et al. 1990) and the site chronology variance was temporally stabilised using techniques outlined in Osborn et al. (1997). Finally, for each species, the overall historic/living chronologies were generated by averaging the site chronologies together. The Osborn et al. (1997) method was again used to help stabilise the variance through time in the final composite chronologies. This multi-stage standardisation procedure results in a composite chronology which is weighted equally to each site regardless of the replication of the sites themselves. The use of the 80 year spline for detrending ensures that the chronologies have a strong year-to-year and decadal signal while all potential centennial trends have been removed.

Climate data

As spruce growth at low elevations (<700 m) in the Bavarian Forest is limited by spring/summer moisture availability (Wilson and Hopfmueller 2001) and preliminary analysis has shown that fir TR data also portray a similar precipitation signal (albeit weaker than spruce), the analyses presented in this paper will concentrate only on the relationships between tree-growth and precipitation.

Precipitation data from 14 meteorological stations from the Bavarian Forest region (Fig. 1) were selected for analysis (Table 1). The data were provided by the German Weather Service. Although these data have been corrected for homogeneity problems (Herzog and Müller-Westermeier 1998), their homogeneity was verified by creating double mass plots (Kohler 1949) of cumulative precipitation between pairs of stations for each of the seasons. No serious homogeneity problems were detected (Wilson 2003).

Table 1 Precipitation records from the Bavarian Forest region

Meteorological station	Elevation (m)	Record length
Klingenbrunn	823	1911-2001
Buchenau	740	1891-2001
Kirchdorf	693	1899-1999
Rabenstein	690	1881-2001
Gotteszell	576	1913-2001
Regen	572	1899-2001
Lam	541	1901-2000
Viechtach	455	1901-2001
Traitsching	435	1900-1995
Kotzting	408	1901-2001
Cham	396	1879-2001
Regensburg	366	1871-2001
Roding	363	1895-2001
Metten	313	1879-2001

Principal component analysis (Baeriswyl and Rebetez 1997) was used to assess the signal homogeneity between the 14 precipitation records over their common period (1913–1995). Only one significant eigenvector was identified using both a correlation and covariance matrix for each of the four seasons (Wilson 2003). As these results indicate that the year-to-year variability is homogenous, the data from the 14 stations were averaged, using techniques outlined in Jones and Hulme (1996), to develop a regionally representative precipitation series.

The full length of the Bavarian Forest regional precipitation record is 1871–2001. However, the number of stations used to develop this series varies through time (Table 1) and the early less replicated period might not portray a robust average that represents the regional signal. The Expressed Population Statistic (EPS) (Wigley et al. 1984; Briffa and Jones 1990) was used to assess the theoretical number of climate series needed to acquire a robust mean function that represents the 'true' population signal. The mean between series correlation using the maximum overlap of all 14 records for each of the monthly series is 0.82. There is therefore a reasonably strong common signal between the precipitation records. The theoretical estimated minimum number of time series (n) needed to obtain an EPS of a particular value was calculated using:

$$n = \frac{(\bar{r} - 1)\mathrm{EPS}(x)}{\bar{r}\ (EPS(x) - 1)} \quad (1)$$

where the threshold value of EPS (x) is user defined and $\bar{r}$ is the mean between series correlation. An EPS value of 0.85 was chosen by Wigley et al. (1984) as a reasonable threshold for signal acceptance. Using this threshold, the estimated mean minimum number of climate series needed to develop a regional representative series is 1.2 (Wilson 2003). This means that theoretically, the period from 1871 to 1879 which is only represented by data from Regensburg (Table 1; Fig. 1) adequately portrays a representative signal for the region. Therefore, the tree-growth/climate analyses presented in this manuscript use the full period of the regional precipitation record.

Assessment of the between species common signal over the last 500 years

The long term common signal between the spruce and fir chronologies was assessed over their mutual well replicated period (1480–1997) using two techniques. Firstly, a running 30 year correlation window was used to calculate the common variance of both series through time. Periods of high correlation indicate a common environmental forcing, whereas periods of low correlation represent times when different factors were controlling the growth of each species. Secondly, to highlight the dissimilarities between the spruce and fir chronologies, a difference series (spruce minus fir) was generated after the series had been standardised to z -scores over the 1480–1997 period. This difference series highlights periods where productivity of one species was relatively higher or lower than the other. A moving 30 year window standard deviation series was also calculated from the difference series to quantify temporal variation between the two species chronologies.

Assessment of the temporal stability of tree-growth/climate relationships over the last 130 years

Wilson (2003) showed that the optimal season for dendroclimatic reconstruction using spruce is March–August precipitation. Preliminary analysis (not shown) also indicates that this is the case with the fir data although the strength of the relationship is weaker. The temporal stability of these relationships was assessed using two different approaches. Both utilise lagged independent variables to ensure that the potential effects of previous year's climate upon tree-growth is included in the models (Fritts 1976).

1. A calibration model was developed over the 1872–1930 period by independently regressing the species RW chronologies against lagged variables (t, $t+1$, and $t-1$) of March–August precipitation to predict RW index values from 1931–1997. The quality of the RW index predictions was verified against actual RW index values for the periods 1931–1963 and 1964–1997 using the Pearson product mean correlation (r) and the reduction of error statistic (RE; Fritts and Guiot 1990). The RE statistic determines whether predicted values provide a better estimate than simply using the mean of the dependent data in the calibration period (Cook et al. 1994). RE ranges from negative infinity to a maximum value of 1.0 which indicates perfect estimation. A positive value signifies that the regression model has some skill.
2. In this case, chronologies at t, $t+1$, and $t-1$ were regressed against mean March–August precipitation totals over moving 30 year windows (lagged by 5 years), for each species separately. Changes in the model R^2 and regression coefficients of each predictor (independent) variable were used to assess the temporal stability in the tree-growth/climate signal. This procedure is similar to that utilised by Visser and Molenaar (1992a) who used a Kalman-filter based regression model to study fir growth in the Bavarian Forest. Both approaches allow the regression coefficients to be time dependent and so enable the identification of growth/climate relationships that vary through time.

Results and discussion

Comparison between the species chronologies over the last 500 years

The signal strength of the standardised composite chronologies for both species was assessed using the EPS statistic calculated for 30 year periods lagged by 5 years (Fig. 3). For almost the whole 500 year period, the signal strength of the spruce chronology is above the 0.85 threshold defined by Wigley et al. (1984) as being acceptable for dendroclimatic purposes. The signal strength in the fir chronology is slightly weaker in the early and late sixteenth century, the first half of the eighteenth century and around 1850. However, the EPS values never fall below 0.7 and replication in most of these periods is high (Fig. 2). It is doubtful therefore that these periods of slightly weaker signal strength will affect the analyses in this study in any major way.

The post 1960 disturbance in the fir chronology is very clear (Fig. 3). This disturbance has been documented elsewhere for the Bavarian Forest (Eckstein and Sass 1989; Visser and Molenaar 1992a; Kandler 1993) but is not a symptom of a larger European synchronous phenomenon. The post 1960 'decline' is spatially diverse as it is particularly strong in north-west and north-east Bavaria but is weak or insignificant in the Bavarian Alps and south-west Bavaria (Elling 1993). The post 1980 fir recovery (Fig. 3) has not been well documented because most earlier studies in the Bavarian Forest used TR data that were sampled in the mid to late 1980s. The 1997 index value is, in fact, the maximum index value in the chronology. Given that detrending was undertaken by taking residual values from a flexible 80 year spline after appropriate power transformation (Cook and Peters 1997), the high index values in the 1990s are not a detrending artefact and represent a real recovery response after the mid 1970s disturbance.

The standardised difference plot shows that the maximum differences between the two species chronologies are in the twentieth century (Fig. 4a). This reflects the anomalous trends in the fir chronology. The plot of changes in the standard deviation of the difference series (Fig. 4b) clearly shows an increase in the variance of the difference between the species chronologies since ca. 1920. In fact an F -test comparing the variance means for the independent periods 1480–1886 and 1915–1983

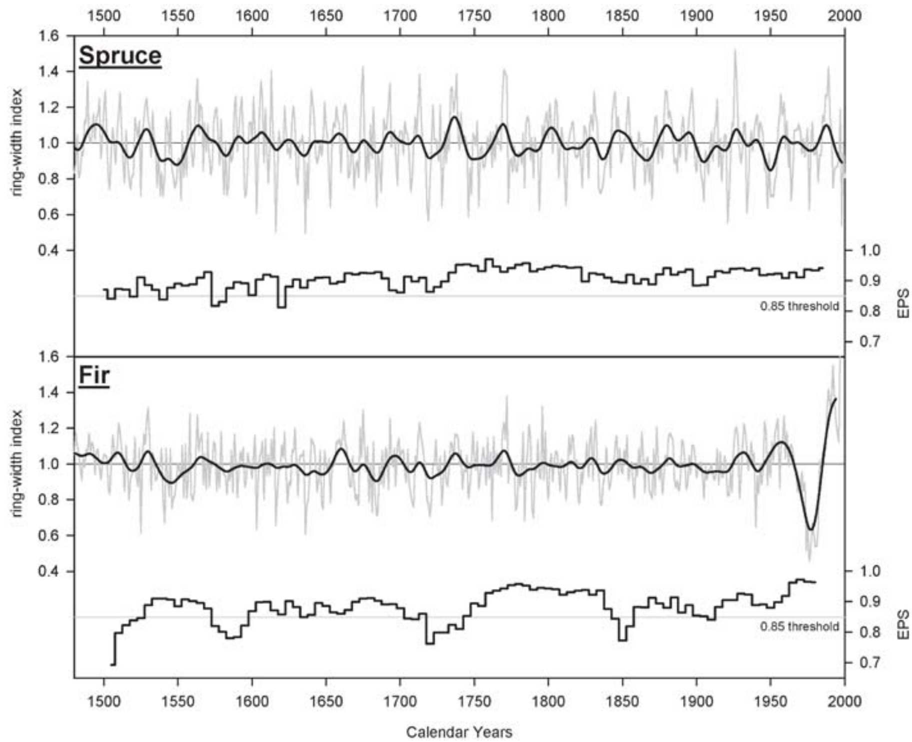


Fig. 3 Standardised living/historic composite chronologies for spruce and fir over the 1480–2000 period. The pre-1480 chronologies are not shown due to weak signal strength. The decadal variability is highlighted with a 20 year smoothing spline. EPS values are plotted for 30 year intervals lagged by 5 years. Replication of the series is shown in Fig. 2

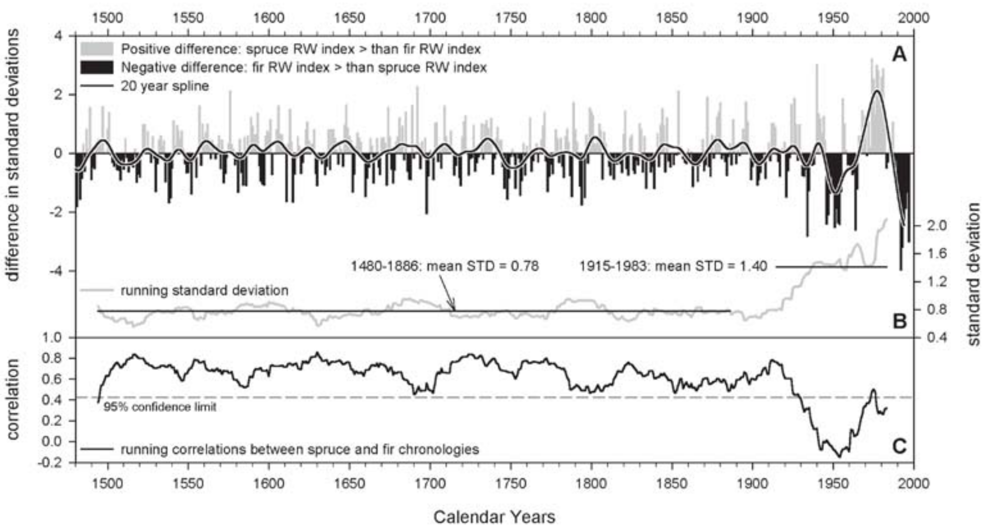


Fig. 4 **A** Difference plot between the low elevation composite spruce and fir chronologies. The original chronologies were standardised to *z* -scores so that the differences are expressed in standard deviations relative to the means of the original chronologies. The trend in the difference series is highlighted with a 20 year cubic smoothing spline; **B** Running 30 year standard deviation of the difference series. The mean standard deviation (STD) for the periods 1480–1886 and 1915–1983 are shown. An *F* -test shows that there is a significant difference at the 95% confidence limit between the variance means of these two periods; **C** 30 year running correlations between the spruce and fir chronologies. The 95% confidence limit has been adjusted for the loss of degrees of freedom due to mean autocorrelation of both series

shows that there is a significant difference at the 95% confidence level between the two periods. The moving window correlation results (Fig. 4c) support these variance results and show that since the ca 1930s the correlations between the two species are not significant at the 95% confidence limit.

The data presented in Figs. 2a, 3 and 4 indicate that the growth of fir in the late twentieth century is highly anomalous when compared with the previous 400 years. This severely constrains the potential for dendroclimatic reconstruction using these data. Therefore comparative

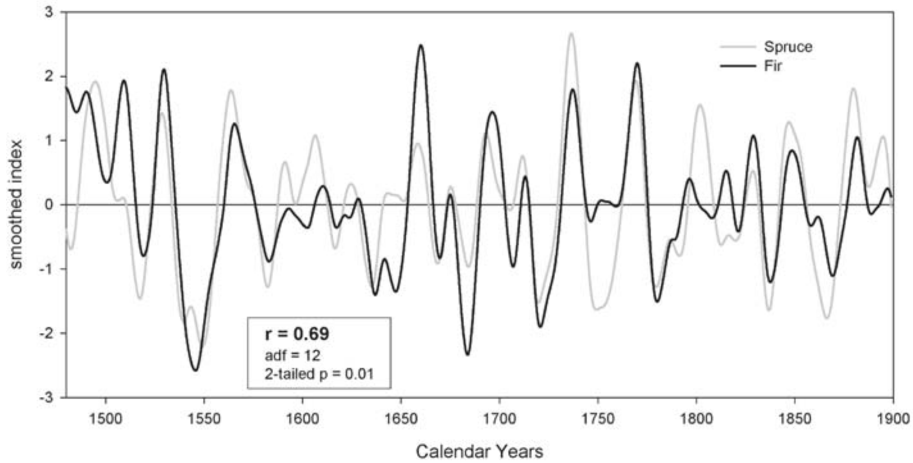


Fig. 5 Comparison between smoothed series (20 year cubic smoothing spline) of the spruce and fir chronologies over the 1480–1900 period. Both series were converted to *z* -scores to ensure equal variance of both series. Between series correlation =0.69 (P=0.01). *adf* adjusted degrees of freedom. The degrees of freedom were adjusted to account for the autocorrelation in the smoothed series so that the significance of the correlation coefficient could be assessed

analyses of these two chronologies are carried out separately for the periods before and after ca. 1870.

Between species comparison prior to the twentieth century

Well replicated composite chronologies for both species extend back to ca. 1500. However, the results of ongoing historical sampling/dating in the region suggest it will be difficult to extend the spruce composite chronology prior to 1500 with adequate replication for dendroclimatic purposes. However, it should be possible to develop a well replicated fir chronology that could span the whole of the last millennium. Some comparison of the common signal between both species therefore needs to be made to assess whether the fir data could also be used as a valid proxy for past spring/summer precipitation variability in the region.

Correlations between the chronologies are consistently significant at the 95% limit prior to the twentieth century. However, the correlations range between 0.37 and 0.86 with a mean of 0.66 over the 1480–1899 period (Fig. 4c). This implies a significant common signal of varying strength between the two species. Excluding the twentieth century, the periods of weakest correlation (<0.6) are the late fifteenth and sixteenth centuries, around 1700 and 1800 and ca. 1850–1890. Many of these periods also have high mean standard deviation values (Fig. 4b). The low correlations of the late fifteenth and possibly the late sixteenth centuries might be related to the weaker signal strength in the fir chronology for these periods (Fig. 3). Although the EPS values for both chronologies are reasonably high over the 1850–1890 period, this period is the overlap between the living and historic series in both chronologies and the lower correlations through this period might well reflect the 'noisy' nature of the overlap (Wilson 2003).

The weak between species common signal observed around 1700 and 1800, however, cannot be explained by low replication and weak signal strength in the chronologies. As both these periods of low correlation predate the era of significant atmospheric anthropogenic effects, these periods represent natural changes in the controls upon growth between the two species. These periods of low between species correlation, therefore, could reflect periods when the growth response of one or both of the tree species to climate changed. The period 1680–1700 has been reconstructed to be one of the coldest winter/spring periods over the last 500 years in central Europe (Pfister 1992, 1995; Brazdil 1992, 1996). Fir is known to be particularly susceptible to frost damage in winter and early spring (Elling 1993) and therefore might respond differently to these severe conditions. The reduction in correlation around 1800 does not however appear to coincide with an interval of particularly severe low temperatures (Brazdil 1992, 1996; Pfister 1992, 1995) except possibly for the 1816–1820 post-Tambora period (Briffa et al. 1998c; Briffa 2000).

Inferences about the effects of past climate on tree-growth prior to the instrumental record are difficult to quantify and caution is advised when interpreting these observations. Essentially, the sliding correlations and standard deviations in Fig. 4 suggest that there have been minor variations in the common year-to-year response of both species to climate since the late fifteenth century. However, such statistical measures are susceptible to outlier values and the periods of low correlations could also reflect that tree-growth/climate response was only affected for 1 or 2 years at a time. Figure 5 compares standardised smoothed series (20 year smoothing spline) of both species chronologies over the period 1480–1900. For most of the record there is a remarkable similarity in

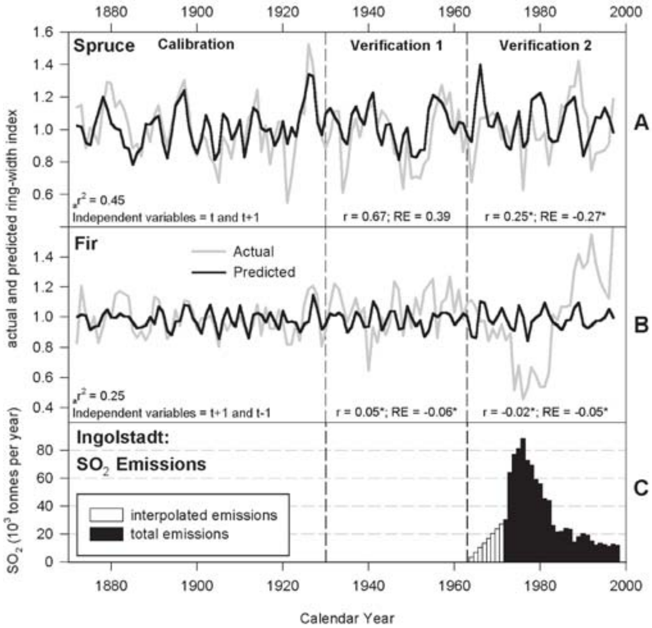


Fig. 6 1872–1930 calibration of RW index against lagged variables of March–August precipitation for spruce (**A**) and fir (**B**). RW index values are predicted for the periods 1931–1963 and 1964–1997 and verified against actual RW index values using the correlation coefficient and the reduction of error statistic (RE; Fritts and Guiot 1990). * = verification failed at the 95% confidence limit; **C** SO_2 emissions from the petrol refineries of Ingolstadt between 1964 and 1999 (after Elling 2000). The interpolated values are a linear interpolation between the first year of operation (1964) and the first year of measured emissions (1972)

decadal scale variability which suggests that at lower frequencies, both species respond in a similar way to climate. This would imply that although there might be mixed climate signals in either spruce or fir at a year-to-year scale, at lower frequencies, both species appear to express a similar environmental forcing. As the variability of spruce has been shown to compare well with March–August precipitation at decadal and lower frequency scales (Wilson 2003), these observations suggest that the fir data could also provide low frequency climatic information for past precipitation in the region.

Temporal stability of tree-growth/climate relationships over the last 130 years

Over the period 1872–1930, the lagged variables of March–August precipitation explain 45% and 25% of the variability in spruce and fir RW indices, respectively. These relationships were used to predict RW index values for both species from the precipitation records over the 1931–1963 and 1964–1997 periods (Fig. 6).

The predicted spruce index values verify well over the 1931–1963 period, but fail for the later period. The predicted fir index values fail verification for both periods. Silver fir is known to be sensitive to SO_2 emissions and is considered a bio-indicator for SO_2 dominated air pollution (Wentzel 1980). Fig. 6c plots total SO_2 emissions (Elling 2000) from oil refineries near Ingolstadt (see inset map Fig. 1). The sharp drop in actual RW index values in the fir data (Fig. 6b) coincides with the sharp increase in SO_2 emissions from the Ingolstadt refineries (r=−0.78 over 1964–1997). In fact, the lowest index value in the fir chronology (1976) coincides with the year of highest SO_2 emissions from Ingolstadt. It should also be noted, however, that 1976 was a particularly warm dry year and this will have undoubtedly had an effect on growth productivity for this year.

There has been much debate over the last 20 years about the major causes for the post 1960s 'decline' observed in silver fir from the Bavarian Forest Region (Eckstein and Sass 1989; Visser and Molenaar 1992a, 1992b; Kandler 1992a, 1992b, 1993; Elling 1993). No single factor was identified as causing this phenomenon which was thought to result from a complex amalgam of diseases, infestations and abiotic stresses (Kandler 1992b), although the primary cause was likely related to SO_2 emissions (Visser and Molenaar 1992a, 1992b; Elling 1993; Ellenberg 1996). The data presented in Fig. 6 strongly suggest that SO_2 emissions indirectly or directly impacted the productivity of Silver fir through the 1970s and early 1980s in the Bavarian Forest region. After the sharp decrease of tree productivity, when tree mortality was high, the observed 'explosive' recovery may represent a positive growth response of the trees to both opening of the canopy (due to the tree mortality) and the decrease in SO_2 levels. The year-to-year variability of the RW indices in this recovery period, however, cannot be modelled using climate variables (Fig. 6b) and there is no evidence that the growth/climate response of fir has returned to that of the pre-1930 period.

Two further points are worthy of discussion and need to be highlighted:

1. Although there is an obvious reduction of fir productivity after the 1960s, the response of fir to March–August precipitation changed much earlier and there is little similarity between the actual and modelled RW index values after 1940 (Fig. 6b). This response change is not related to the SO_2 emissions from Ingolstadt which started around 1964 (Fig. 6c). Some other external cause is implicated in this earlier response change. However, its effect is subtle as there is no obvious loss in tree productivity and the change is only in the response of the trees to climate.
2. The predicted RW indices for the spruce data in Fig. 6a fail verification over the second verification period. Previous studies in the region focused mainly on forest decline in fir which showed an obvious decrease in productivity through the 1970s. None of the studies in this region demonstrated a significant decline or changed response at low elevation spruce sites although a few studies did note symptoms of forest decline symptoms for spruce at high elevations (Eckstein and Sass 1989; Elling 1990; Sander et al. 1995). Although not specific to the Bavarian Forest,

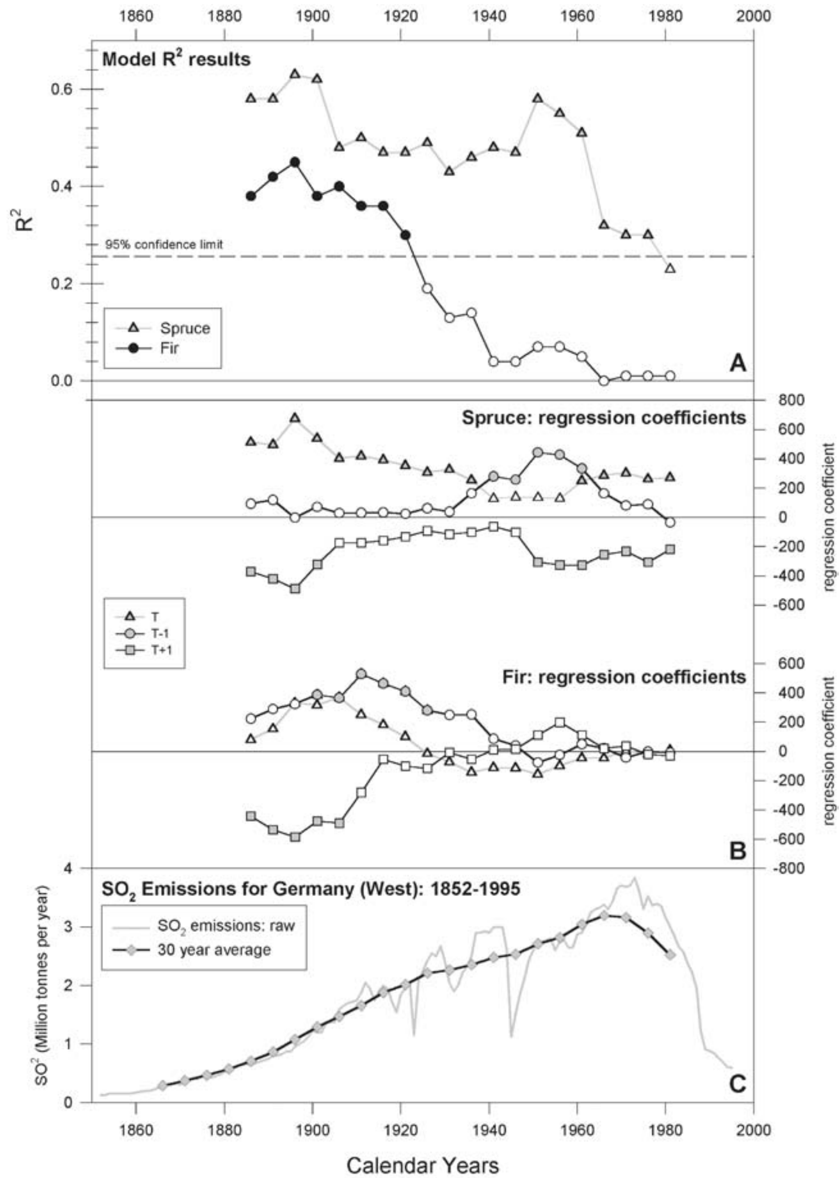


Fig. 7A–C Thirty year running regression analysis obtained by regressing lagged variables for both spruce and fir against March–August precipitation**. A** Moving regression R^2 results. *Filled symbols* denote significant (95%) regression models using the regression ANOVA *F* ratio; **B** Running regression coefficients for each independent variable. *Filled symbols* denote coefficients that are significantly different (95%) from a zero slope using the *T* -test; **C** SO_2 Emissions for the former West Germany from 1852 to 1995

Greve et al. (1986) noted a slight reduction in productivity since the 1940s in low elevation (<700 m) spruce trees in north-east Bavaria (ca. 80 km north-west of the current study). The failure to verify the predicted spruce RW after 1964 (and particularly after the mid 1970s, see Fig. 6a) suggests an increased non-climatic influence on spruce growth that, by analogy with fir, could obviously be related to local SO_2 emissions. However, there is no apparent decrease in productivity.

The changing response of the two species is illustrated by regression analyses using a moving 30 year window (Fig. 7). The spruce RW data are more highly correlated with precipitation than the fir but the explained variance for both species varies over time (Fig. 7a). In the late nineteenth century and ca. 1950/60s, the spruce data explain ca. 60% of the March–August precipitation variance and approximately 45% in the intervening period. After the 1960s this relationship weakens and is not significant in the last 30 year period (1967–1996). The coefficients of the lagged variables (Fig. 7b) also vary through time although their signs do not change. The coefficients for the growth year (*t*) are all significant except for ca. 1940–1960 when the previous year's precipitation becomes more important suggesting it was the dominant influence upon spruce growth at that time.

The fir data model ca. 35–40% of the variance of March–August precipitation from ca. 1880–1920 but thereafter the relationship becomes non-significant and, over the last four decades, the ability to model March–August precipitation is practically zero. This change is also seen in the regression coefficients (Fig. 7b) which, after 1930, converge and become essentially zero after 1960.

The results in Fig. 7 confirm the analyses presented in Fig. 6. The fir data show no significant precipitation signal after ca. 1935 and the spruce data show a marked weakening in the signal after the mid 1970s. Local SO_2 emissions from Ingolstadt began in 1964, peak in the mid 1970s and coincide with the abrupt growth decline in fir during the 1970s (Fig. 6). However, the climate signal in the fir data deteriorates well before the inception of local SO_2 emissions from Ingolstadt and the variance of the difference between the two species chronologies (Fig. 4b) increases markedly after ca 1920. Eckstein and Sass (1989) also noted that the common signal between fir trees in the Bavarian Forest weakened noticeably after 1925 and Visser and Molenaar (1992a, 1992b) also indicated that the relationship between fir RW and climate in the region could not be modelled after 1945. Obviously growth in these fir trees was being affected by some additional non-climatic forcing between ca 1920 and 1960.

As there is no decrease in growth productivity in fir trees between 1930 and 1960, it is difficult to quantify what environmental factors could be affecting the response of the trees to climate. However, as with the post 1960s period, the main factor is likely to be SO_2 atmospheric pollutants. Emissions from the power station at Schwandorf (north of Regensburg, see inset map Fig. 1), which started operation around 1930 and hit peak output in the mid 1970s, had a quantifiable effect on fir growth in the lower Bavarian Forest (Riffeser and Ambros 2001). Ambient background levels of SO_2 emissions cannot also be discounted. In the former West Germany there was a steady increase in large scale SO_2 emissions from the mid nineteenth century with peak output in 1973 (Fig. 7c). It is hypothesised, therefore, that the observed decreased response of fir RW to precipitation after ca. 1930 is related to these background levels of SO_2 which were high enough to change the response of the tree-growth to climate but insufficient to cause a decrease in tree productivity. This hypothesis agrees with the analyses of Visser and Molenaar (1992a, 1992b). Severe winter/spring frost events have also been documented to have a significant effect upon fir productivity for individual years (e.g. 1929, 1940 and 1956; Elling 1993, Ellenberg 1996). The low index values in the fir data for these years, which are not related to dry spring/summer conditions, will undoubtedly also affect the results of the regression analyses in Figs. 6b and 7.

Conclusion

A time stable relationship between tree-growth and climate is an essential prerequisite for dendroclimatic reconstruction. The results presented in this paper show that the growth/climate relationships of both spruce and fir in the Lower Bavarian Forest have changed, particularly during recent decades, probably as a result of human activity. These results were anticipated for fir as earlier studies have shown disturbance after the 1960s in the region (Eckstein and Sass 1989; Visser and Molenaar 1992a; Elling 1993; Kandler 1993). Our results suggest that the main cause of the change in the growth/climate response in fir and the post 1960s decrease in productivity is due to SO_2 emissions from local sources. These observations agree with earlier work in the region (Eckstein and Sass 1989; Visser and Molenaar 1992a; Elling 1993, 2001; Ellenberg 1996). This change in growth/climate response of silver fir in the lower Bavarian Forest region during the last century, invalidates the use of these data for traditional dendroclimatic calibration.

The post mid 1970s growth/climate response change of spruce growing at low elevations has not been noted before in the Bavarian Forest. It is hypothesised that this response change is also related to the effects of SO_2 emissions in the region. The effect, however, is less marked and a reasonably time stable growth/precipitation relationship is observed from the late nineteenth century to the mid 1970s. After the late 1970s, this relationship weakens and the data are unsuitable for calibration. Calibration trials show that a restricted calibration period of 1871–1978 ($_{a}r^{2n}$=39%) is optimal to avoid possible anthropogenic effects during the last few decades and that therefore, spruce RW data may be used for traditional dendroclimatic reconstruction.

Finally, Kandler (1993) suggested that the disturbance pulse observed in fir trees over the last few decades in the Bavarian Forest is simply the most recent episode of a natural cycle in 'decline' events for this species. The strong common signal between spruce and fir over the 400 years prior to the twentieth century (Fig. 4c) and the close similarity between their decadal trends (Fig. 5) suggests that there have been no similar 'decline' events prior to the twentieth century in the Bavarian Forest region. The close similarity between decadal trends of spruce and fir prior to the twentieth century (Fig. 5), and the greater availability of historical TR data from fir, suggest that, in the future, TR data from historical firs could provide the main source of proxy precipitation information for the region over the last millennium.

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