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Original article

Utilising historical tree-ring data for dendroclimatology: A case study from the Bavarian Forest, Germany

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Summary

Although there are abundant historical tree-ring (TR) data available in Europe, these data have rarely been used for dendroclimatic reconstruction. Dendro-historical dating is possible because of a strong common signal in the TR data, which, if consistent over large areas, must represent a common climatic forcing upon growth. The most commonly cited limitations to the use of historical TR data for climate reconstructions are (1) mixed climate signals within the living TR data used to crossdate the historical TR data (e. g. European Oak) and (2) the unknown provenance and/or site ecology of the historical wood. In addition, as historical timbers were often taken from relatively young trees, they may have a different climate response from the mature living trees used for calibration studies. The short mean segment length of the historical timbers may also limit the potential to recover low frequency growth trends from these series.

In this study, we address these issues using a well-replicated TR data-set comprised of 678 living and historical TR width series of Norway spruce (*Picea abies* (L.) Karst) sampled in the Lower Bavarian Forest region in south-east Germany. The historical TR series were collected from 40 buildings in towns along the Danube River. Local knowledge suggests that almost all wood used for construction prior to the 20th century had a local origin. The historical spruce TR series correlate with living spruce chronologies from sites located below 700 m, but do not correlate with spruce chronologies from above 1050 m. Comparison of the statistical characteristics of chronologies from historical timbers (e. g. ring-width, mean sensitivity and correlation with high elevation spruce chronologies) with those from living trees at low elevation sites indicated that the timbers were derived from ecologically similar, low elevation sites. As RW series of these living-tree sites contain a strong spring/summer precipitation signal, it is suggested that the historical TR data are similarly climate-sensitive.

Differences in age-related response to climate were addressed by comparing the response of TR chronologies composed of trees < 100 years and > 110 years with spring/summer precipitation. Results from a moving window regression procedure indicate no significant difference in the climate response of these two chronologies. The segment length problem was examined by dividing the 678 TR series into

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3 age groups and applying regional curve standardisation. We demonstrate that multi-centennial trends can be captured from these data even when sample lengths of < 50 years are used. This result runs counter to the traditional approach of using only longer series in order to minimise the effects of the "segment length curse".

This case study demonstrates that, in situations where it can be shown that historical timbers are locally derived from climate-sensitive stands, these records may have considerable potential use in developing and extending dendroclimatic reconstructions. These findings suggest that many well-dated regional dendro-historical chronologies from Europe may have similar properties and that such records should be explored more carefully with a view to exploiting their palaeoclimate potential.

Keywords: Historical tree-ring data, climate reconstruction, precipitation, segment length curse, Bavarian Forest, Germany

Introduction

In many regions of the world, it is standard practice to extend living tree-ring (TR) chronologies back in time using sub-fossil wood (e. g. Briffa et al. 1995; Luckman et al. 1997; Cook et al. 2000). As the living and sub-fossil TR material often come from the same or adjacent localities, they are assumed to contain similar environmental signals, allowing the development of long dendroclimatic reconstructions from these chronologies. In regions where sub-fossil material is not preserved, historical material (e. g. from beams) may provide a source for TR data. However, despite the abundance of historical TR series in Europe (Briffa et al. 1999) and elsewhere (Kuniholm et al. 1996; Dean 1996) such data have rarely been used to extend dendroclimatic reconstructions (Richter, Eckstein 1990; D'Arrigo, Jacoby 1991; Brázdil et al. 2002; St. George, Nielsen 2002; Wilson, Topham *in press*). This is surprising because successful crossdating of historical TR series requires a strong common signal between the data-sets and, if crossdating is possible over large areas, this signal must represent a common climatic forcing upon tree growth. In central Europe where most trees reach maximum ages of ca. 200–300 years (Eckstein 1982), the successful utilisation of historical TR material in dendroclimatic studies could improve the number, density and length of dendroclimatic reconstructions for the region. This paper presents a case study that demonstrates the use of historical TR material for the development of a 500 year-long precipitation reconstruction for the Bavarian Forest region of south-east Germany (Wilson et al. *submitted*).

Potential limitations to the use of historical tree-ring series

Several possible limitations have been identified that restrict the use of historical TR series in dendroclimatology. Apart from the obvious fact that the data are collected and archived by different research communities, four primary obstacles may be recognised:

(1) **The relationship between tree-ring data and climate is complex:** In Europe, growth/climate analyses of many living-tree chronologies used to crossdate historical series have shown that the relationship between tree-growth and climate is not strictly linear and that more than one climatic factor can limit growth (Huber 1970; Pilcher, Gray 1982; Spain, Pilcher 1994). This has led to the viewpoint that "traditional" calibration of a single climate parameter is not possible with this material and that only extreme years can be studied (Becker B. et al. 1995; Vogel et al. 1996; Kelly et al. 2002). This problem is partially related to the types of sites and species sampled for historical dating studies (i. e. the living data are often not sampled from "climatically stressed" sites that dendroclimatologists would select). However, several studies suggest that dendroclimate calibration is possible in some regions of Europe with certain species that are traditionally used for dendro-historical dating (Jazewitsch 1961; Becker 1978; Kelly et al. 1989; Dittmar, Elling 1999; Wilson, Hopfmueller 2001; Brázdil *et al.* 2002; Wilson, Elling 2004; Wilson, Topham *in press*).

(2) **Unknown provenance of the historical tree-ring material:** Frequently, it is impossible to deter-

mine the original growth site of the timbers used in historical buildings. Therefore, although long, continuous chronologies can be developed, it is not known whether the earlier portions represent trees growing at similar ecological (or altitudinal) sites as the later (living) portions of the chronology (Pilcher 1982). Site selection is a critical factor in the sampling of living trees for dendroclimatic purposes. Sampling is often undertaken at the elevational or latitudinal limits of a species where growth is limited by a single climatic factor (e. g. the precipitation control upon tree-growth at lower tree-line, Fritts 1976). This strategic approach to sampling is not possible for most historical TR material and it is not known *a priori* whether the trees came from sites that share the growth response to climate shown by the living trees in the chronology. This is critical because dendroclimatic research can only be successful if all the trees sampled share a common climatic signal (Fritts 1976).

(3) **Differences in the growth/climate response with tree age:** Generally, historical timbers such as beams are cut from relatively young trees compared with the "old growth" forest usually sampled for living-tree chronologies. In such cases, dendroclimatic calibration undertaken on series from the older living trees is applied to historical TR series from much younger trees. This situation is common to many dendroclimatic reconstructions and is not unique to the utilisation of historical TR material. However, it is critical to establish that the older and younger trees have a similar climate response, thereby allowing transfer functions developed from older trees to be utilised for the reconstruction of climate from younger trees of the same species.

(4) **The "segment length curse":** In recent years there has been considerable attention to the problem of capturing low frequency variation on centennial or longer timescales in dendroclimatological research (Mann et al. 1999; Cook et al. 2000; Briffa et al. 2001; Esper et al. 2002, Esper et al. 2003). The ability to capture low frequency climate information from tree-rings is directly related to the mean length of the sample series used in developing a chronology (Cook et al. 1995). As historical TR series are generally shorter than their living counterparts, this "segment length curse" (Cook et al. 1995) poses a serious problem in the extraction of low frequency trends from composite living/historic chronologies.

Approach used in the Bavarian Forest Study

This paper addresses these issues using a highly replicated data-set from the Lower Bavarian Forest region in Germany (Fig. 1). Sub-fossil wood is rarely preserved in this region due to the relatively moist climate and the only way to extend living TR series is to use historical TR material. Wilson, Hopfmueller (2001) demonstrated that interannual variability in ring-width (RW) series from low elevation spruce trees (< ca. 700 m) in the Bavarian Forest is predominantly controlled by moisture availability and that these series crossdate with historical TR data sampled from towns in this region. Therefore the mixed signal problem (defined above) does not apply in this case as the variability in RW series from low elevation sites in this region is essentially controlled by a single climate parameter. The issues raised in points 2–4 above are addressed by a series of separate analyses using the Bavarian Forest data. Firstly, a comparison of statistical properties between the historical and living TR data is used to determine the provenance of the historical material. Secondly, the climate response of two age-classed chronologies is used to assess possible differences in the responses of trees to climate with increasing age. Finally, regional curve standardisation (Mitchell 1967; Becker M. et al. 1995; Cook et al. 1995; Briffa et al. 1996; Esper et al. 2003) is used to improve the ability to capture lower frequency trends from the historical TR series.

Data sources

Ring-width data

Between 1996 and 2001, TR samples were taken from 40 buildings in towns of the lower Bavarian Forest Region along the Danube River (Fig. 1). These samples were specifically collected to assess their utility for dendroclimatic reconstruction with, where possible, high replication from timbers in the same building. TR series were developed from historical timbers of Norway spruce (*Picea abies* (L.) Karst) and combined with RW series from trees of the same species growing at low elevations (< 700 m; Fig. 1) to develop a regional chronology that spans the interval from 1456 to 2001 (Wilson 2003). The strong common signal within the historic TR chronologies and the high dating success

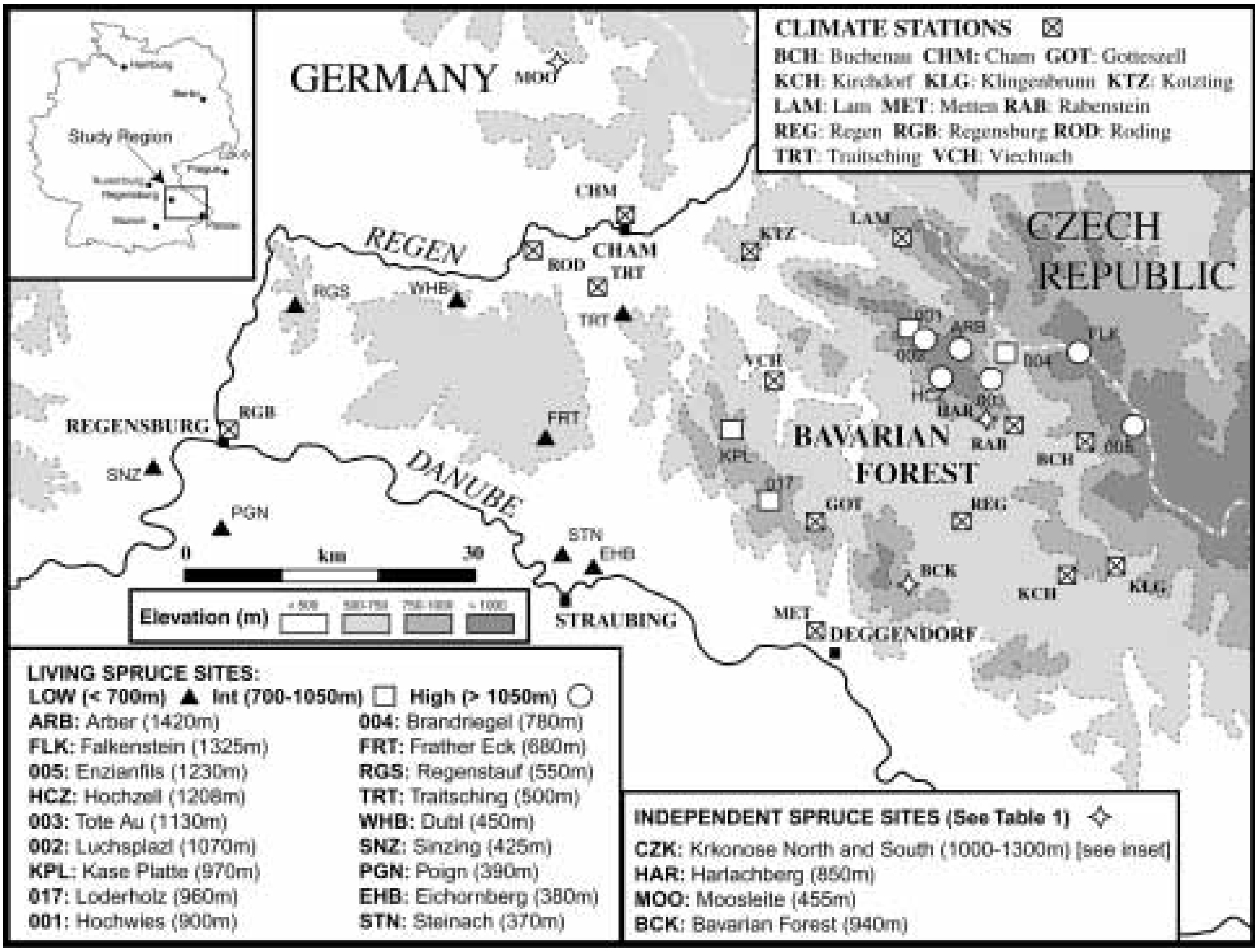

Figure 1. Location map of Tree Ring (TR) sites and climate stations. The historical TR samples were taken from buildings in or around the towns Regensburg and Straubing. The low elevation spruce sites were specifically targeted to broadly represent the likely source region from which construction material was obtained.

rate (Wilson 2000a, 2001a) imply a strong regional control upon tree-growth, which is assumed to be climate-related.

The Lower Bavarian Forest region is part of the largest area of woodland in central Europe (Priehaeusser 1965) and the abundant local materials suggest it is unlikely that significant amounts of wood would be imported for normal construction projects. Most local transport of construction wood was made using the River Regen (Fig. 1). Artificial dams were constructed to create temporary pools along the river in which the felled logs were collected. Subsequently, these dams were destroyed and the resulting flood 'flushed' the logs down river (Feldmeier *pers comm*, 2001). This technique is unlikely to have been used on the Danube due to its greater size.

Sample and chronology replication, mean segment length (MSL) and mean biological age statistics for the 500 year chronology are summarised in Fig. 2. MSL is significantly higher for series from the living trees ($MSL_{living} = 104$ years from 225 series; $MSL_{historical} = 70$ years from 453 series) and the age differences between the historic and living series are clearly seen in Fig. 2d. The mean biological age in the post-1950 period is greater than at any other period. Even in the overlap period between living and historical series the mean series length of the combined data does not exceed 60 years. MSL and tree ages for trees growing in the 20th century are clearly different from most of the trees used in construction in the preceding 400 years.

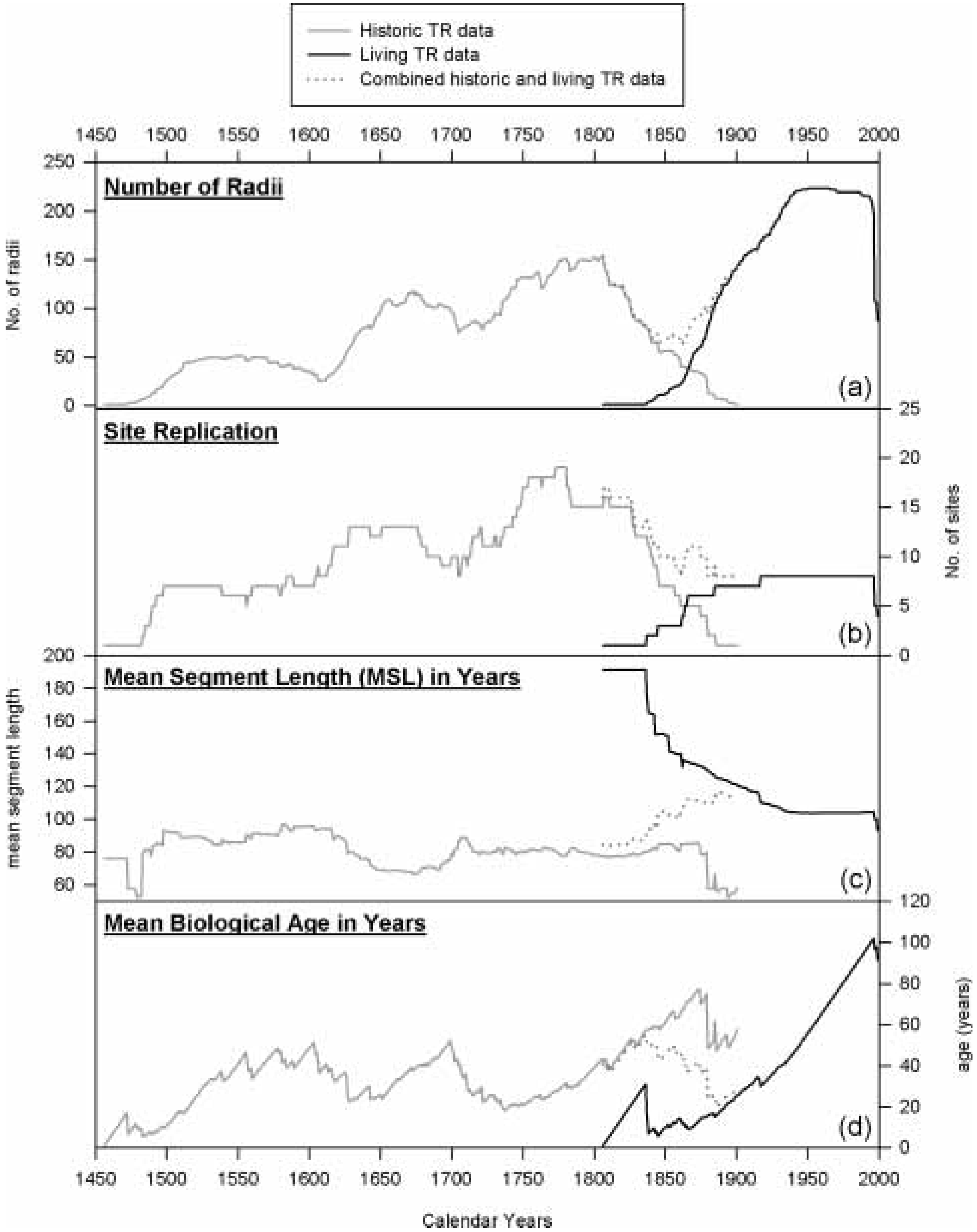

Figure 2. Summary characteristics of the spruce tree-ring data set: **(a)** Number of radii; **(b)** Number of sites; **(c)** Mean segment length; **(d)** Mean biological age. A site is defined as either a living tree site or a construction phase within a building. Replication in the building chronologies ranges from 3 (3) to 62 (37) series (beams) with a mean sample depth of 11 (8) cores (beams) per site. Replication in the living chronologies ranges from 8 (6) to 45 (23) series (trees) with a mean sample depth of 28 (15) cores (trees) per site (Wilson 2003).

Climate data

Precipitation data from 14 meteorological stations from the Bavarian Forest region (Fig. 1) were selected to develop a regional precipitation series. The data were provided by the German Weather Service and have been corrected and verified for homogeneity problems (Herzog, Müller-Westermeier 1998; Wilson 2003).

Principal component analysis (Richman 1986; Baeriswyl, Rebetez 1997) was used to assess the signal homogeneity between the 14 precipitation records over the 1913–1995 common period. Only one significant eigenvector was identified using both a correlation and covariance matrix for each of the four seasons (Wilson 2003). This indicates that the pattern of year-to-year variability in these records is homogenous and therefore data from the 14 stations were averaged, using techniques outlined in Jones, Hulme (1996), to develop a regionally representative precipitation series. The full length of this Bavarian Forest regional precipitation record is 1871–2001.

Identifying the original growth location of the historical tree-ring material

Methods

The identification of the original source location of construction wood is extremely difficult without historical "meta" data that documents where wood was actually felled for a particular building. However, the strong common signal between the historical and living TR chronologies from the Bavarian Forest Region, plus the high success rate in dating historical structures (Wilson 2000a, 2001a), strongly suggest that construction timbers in the study region do have a local origin. Moreover, recent studies (Dittmar, Elling 1999; Wilson, Hopfmueller 2001; Wilson, Elling 2004), have established that spruce RW series from low elevation sites in this region contain a strong precipitation signal. Therefore, although the construction timbers may be assumed to be local in origin, the source elevation of the original trees needs to be established to develop an optimal reconstruction of precipitation.

Wilson, Hopfmueller (2001) studied 14 living spruce RW chronologies from an elevational transect in the Bavarian Forest and identified three elevational zones (< ca. 700 m; ca. 700–1050 m; and > ca. 1050 m) that could be distinguished by the statistical properties of the TR series. For example, RW data from lower elevation living spruce generally show relatively high RW values and high mean sensitivity (MS), while low RW and MS values prevail at high elevations (Wilson, Hopfmueller 2001, see Fig. 3). Assuming that similar differences also occurred in the past, it should be possible to use the properties of the ring series to identify the approximate elevation from which construction timbers were obtained.

Wilson, Hopfmueller (2001) also demonstrated that low elevation (< ca. 700 m) spruce chronologies do not correlate with the high elevation (> ca. 1050 m) spruce chronologies from this region. Wilson, Topham (*in press*) confirmed that this lack of relationship has existed for the last five centuries. They developed a high elevation living/historic composite series for the Bavarian Forest region consisting of six high elevation living spruce chronologies (Wilson, Hopfmueller 2001, Fig. 1) and 30 historical RW series taken from string instruments (e. g. violins and cellos, Wilson, Topham *in press*). There is a strong linear relationship ($r^2 = 0.90$, Fig. 4) between the elevation of the living tree sites and their correlation with this composite high elevation chronology. The strength of this relationship allows the correlation between the high level composite spruce chronology and historical TR series to be used to estimate the elevation of the site from which those historical timbers were derived.

This hypothesis was tested using independent data. The elevation of five living tree chronology sites (Fig. 1), excluded from the analysis shown in Fig. 4, was estimated from the linear relationship presented in that figure. In each case the model predicts the elevation well within the 95 % predictive confidence limits (Tab. 1) indicating that the source elevations of historical spruce timbers can be estimated from the statistical properties of their TR series.

Results

Comparison of the basic statistical properties of the historic RW series and the living spruce chronologies from the three elevational zones in the Bavarian Forest indicates there is no significant difference in RW or mean sensitivity between the historic data and the low elevation sites (Fig. 3). However, RW and MS data from the living chronologies at inter-

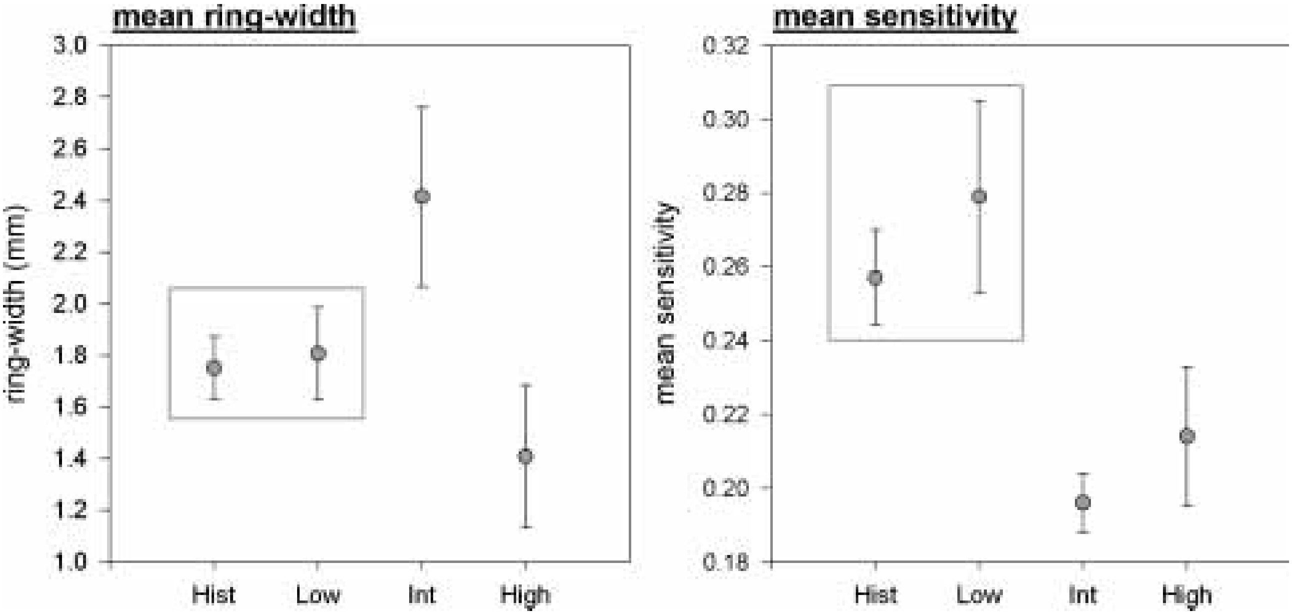

Figure 3. Comparison of the mean values for RW and mean sensitivity for the historic (Hist) spruce tree-ring series and the living tree-ring series from each elevational zone (Int = Intermediate). The mean values shown are the average of site (chronology) means not individual radii in order to remove the effects of differing sample numbers in each chronology. The 95 % confidence range for each mean function is shown.

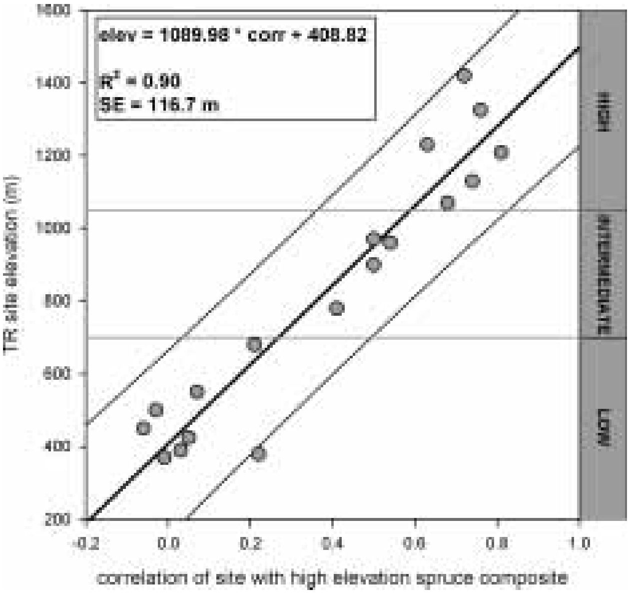

Figure 4. The linear relationship between site elevation and the correlation of the site chronology with a high elevation living/historic composite spruce chronology over the 1896–1984 period (for details see text). The 95 % predictive confidence limits (+/– two standard errors: 233m) are shown. In calculations involving each of the six 'defined' high elevation living tree chronologies (Wilson, Hopfmueller 2001), the composite chronology was adjusted by removing the data from the chronology being examined. The location of each living chronology is shown in Fig. 1.

mediate and high elevation sites are significantly different from those of the historic data. These results indicate that the historic TR data have similar RW and MS characteristics to chronologies from contemporary low elevation living-tree sites.

Prediction of the source elevation of the trees comprising the historic TR series, using the regression equation shown in Fig. 4, indicates that all of these sites come from low elevations. This result is shown and independently verified by plotting these pre-

Table 1. Elevational modelling results for 5 spruce chronologies excluded from the analysis in Figure 4. The predicted elevations of these additional sites is based on the regression equation shown in Figure 4 (the relationship with high elevation data). The location of the sites is shown in Figure 1. Corr[H] = correlation of the site chronology with the high elevation living/historic spruce composite series. Corr[L] = correlation of the chronology with the low elevation living/historic spruce composite series.

Site Code	Actual Elevation	Corr[H]	predicted Elevation	Corr[L]
CZK [N]	1000–1300	0.58	1036	–0.06
CZK [S]	1000–1300	0.62	1079	–0.14
HAR	850	0.52	980	0.50
MOO	455	0.02	431	0.78
BCK	940	0.58	1041	0.16

dicted elevations against the correlation of the chronology for each site with the low elevation composite master chronology comprising all the historic series (less the one being tested) plus the eight low elevation spruce chronologies (Fig. 5). Almost all the historical TR series plot within the confidence limits defined by the relationship with the low elevation composite chronology. The only significant anomaly is the Geiss 2 chronology which is the oldest site chronology in the historic spruce data-set (1456–1538). This site was independently crossdated using fir samples at the same site. However, Wilson (2001b) noted that the crossdating result (and, by extension, the climate signal) using the spruce chronology was much weaker than that based on the fir chronologies.

The foregoing analyses support two significant conclusions. Firstly, for this region, the source elevation for historical timbers can be estimated +/– ca. 200 m by the strength of the correlation of that individual site chronology with either the high or low elevation spruce chronology masters. Secondly, these analyses indicate that the sampled historic TR series came from trees that were cut from low elevation sites in the Bavarian Forest.

Age modelling of tree-response to spring/summer precipitation

Methods

The Bavarian Forest is predominantly a cultivated forest landscape (Priehaeusser 1965) and the sampled living TR sites were generally even aged. It was difficult, therefore, to obtain well-replicated samples of two different age classes at each of the living-tree chronology sites to test for differences in the growth/climate response with varying tree age. Therefore, the low elevation living tree data were combined into a single data-set (8 sites, 225 radii, MSL range from 44–191 years) and subdivided into young (< 100 years, n = 65 series) and old (> 110 years, n = 104 series) populations. Samples in the 100–110 year range were excluded to provide two discrete age groupings.

The number of radii available in each age group differ considerably between sites (Tab. 2) and using the "grand mean" of all radii in each age group would bias the resultant mean series to particular well replicated sites (e. g. the "young" group would be biased to TRT). Therefore, the "young" and "old" composite chronologies were developed by averaging the site chronologies, weighting each chronology

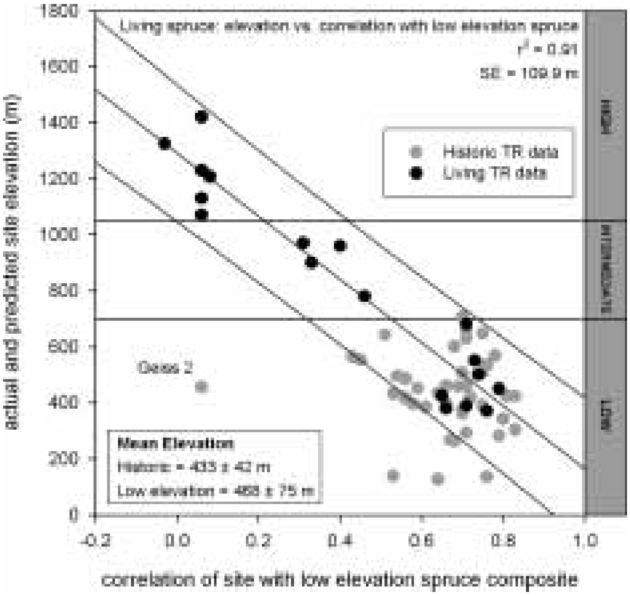

Figure 5. Scatter plot showing the relationship between the elevation of living spruce chronologies and their correlation with the low elevation composite chronology (for details see text). The 95 % predictive confidence limits generated from the living data are shown. The predicted elevations of the historic sites (based on the linear relationship in Fig. 4) are also shown. The mean predicted elevation for the historical sites and the low elevation living sites are shown with their 2× standard error confidence limits.

Table 2. Replication (n) for each living spruce chronology site by age group. Old trees = samples > 110 years; Young trees = samples < 100 years. r = the correlation of each site standard chronology with the mean chronology of the remaining six chronologies in that age group over their common age range. RW data from the EHB site were not used in this analysis as all radii were < 100 years.

	Old		**Young**	
Living site	**n**	**r**	**n**	**r**
FRE	17	0.64	12	0.65
PGN	10	0.62	2	0.54
RGS	4	0.68	4	0.47
SIN	15	0.58	8	0.56
STN	34	0.61	5	0.75
TRT	1	0.36	29	0.71
WHB	23	0.77	5	0.69
Total	104		65	

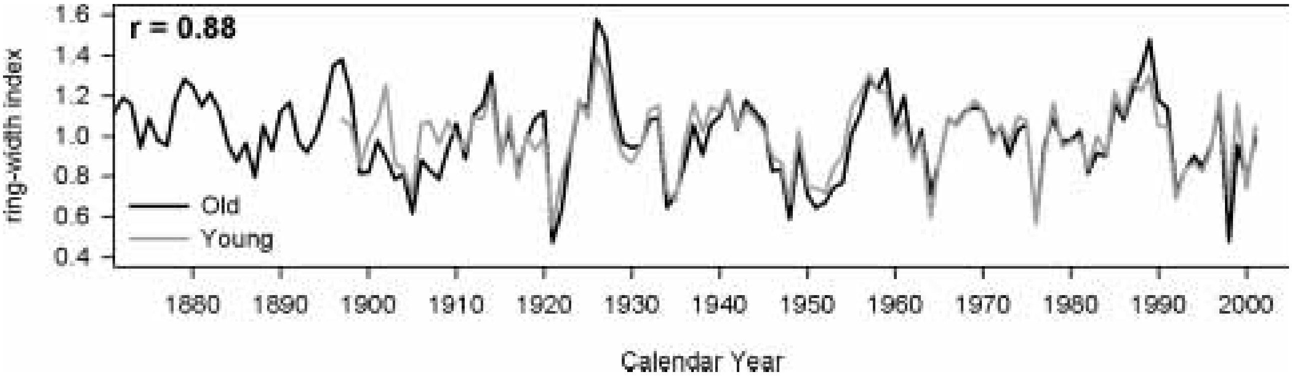

Figure 6. Comparison of mean standardised spruce chronologies from old (> 110 years) and young (< 100 years) trees.

equally to reduce bias. For each site, the variance in the raw RW data was stabilised using an adaptive power transformation (Cook, Peters 1997) and individual series detrended by subtracting a best fit 80 year spline (Cook, Peters 1981). The detrended individual series were then averaged to formulate a site chronology. Correlations between each site chronology and the mean of the other six chronologies in that age group are generally quite high (Tab. 2), implying that the low replication of some sites is unlikely to have a major effect upon the final mean regional series. Finally, the individual site chronologies were averaged together to develop an overall regional mean series that is weighted equally for each site regardless of the replication of that site. It should be noted that the "old" chronology for the TRT site represents only one tree that is poorly correlated with other older chronologies (Tab. 2), but it is included in the analysis because it is the most highly replicated site in the "young" group.

The MSL of the two age defined chronologies is 128.1 and 76.9 years, i. e. roughly equivalent to the MSL range in the living/historic composite series (Fig. 2c). Differences in the growth/climate relationship between the "old" and "young" chronologies and climate were assessed by:

(i) a simple correlation with March-August precipitation over the 1897–2001 period.

(ii) a shifting window regression procedure to assess possible changes in the climate signal over time in both chronologies. Each chronology (lagged at t – 1, t, and t + 1) was regressed iteratively against March-August precipitation over a 15-year window shifted forward five years in each iteration to asses the combined signal inherent in lagged variables through time. The relatively short 15-year window was used because it would be more sensitive to outliers than longer intervals and would therefore increase the chance of identifying subtle differences between the response of the 'old' and 'young' data. A similar moving window regression approach was used by Wilson, Elling (2004) to assess the time stability of spruce and fir to March-August precipitation.

Results

The two age-grouped spruce chronologies are strongly correlated (r = 0.88) over their common interval (Fig. 6) indicating that these younger and older trees carry a very similar common signal, implying a common climatic forcing. Correlations of the "old" and "young" regional chronologies against March-August precipitation (1897–2001) are statistically indistinguishable (r = 0.40 and 0.42, respectively). The moving regression procedure provides a more robust assessment of the changing growth/climate response through time (Fig. 7) and the results for both chronologies are remarkably similar. From ca. 1900–1940, both chronologies model ca. 40–50 % of the precipitation variance and maximise the explained variance around ca. 1950. After ca. 1950, the explained variance ranges between 40 % and 60 % with both chronologies showing a marked reduction in their ability to model March-August precipitation after 1980. This recent decline in predictive power is probably related to SO_2 pollution effects upon spruce growth in the region (Wilson, Elling 2004).

Overall, no significant difference in growth/climate response is observed between the "older" and

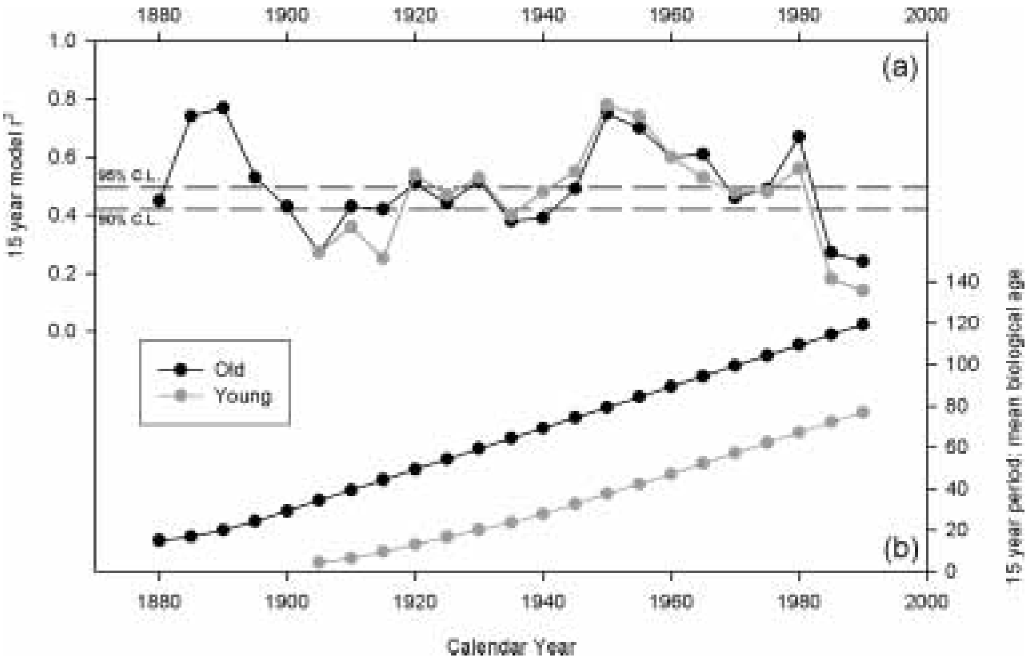

Figure 7. Changes in the response of the "old" and "young" chronologies over time. Calculations are based on 15 year periods incremented at 5 year intervals; **(a)** Change in the explained variance (r^2) of March-August precipitation accounted for by lagged variables of the RW chronologies. The 90 % and 95 % confidence limits of the regression models where calculated using the ANOVA F ratio **(b)** Increase in mean biological age of trees in the chronologies.

"younger" chronologies developed from the living TR data-set and no obvious systematic change in response is apparent due to the increasing biological age in both chronologies (Fig. 7b). It is therefore concluded that the relatively young historic TR series can be combined with the older living TR data to develop a robust spruce composite chronology for dendroclimatic reconstructions.

The "segment length curse" and potential standardisation strategies

Methods

Fig. 2c demonstrates that the MSL of the spruce data-set is very low. If traditional negative exponential functions or flexible digital filters were used to standardise these RW series, little low frequency information would be captured. In these series most frequencies > ca. 30–50 years (MSL/3, Cook et al., 1995) would be lost. This is apparent when these data are detrended using either the Hugershoff function (Wilson 2000b), a fixed 80-year spline (Wilson, Elling 2004) or more standard negative exponential/straight line functions (analysis not shown).

Regional curve standardisation (RCS) is a detrending technique that aims to emphasise the potential low frequency signal in TR data with low MSL (Mitchell 1967; Becker M. et al. 1995; Cook et al. 1995; Briffa et al. 1996; Esper et al. 2003). RCS attempts to capture low-frequency information greater than the mean length of the samples. In its most basic form, RCS aligns all available TR series by cambial age to develop a mean series of "average behaviour" that is typical for the species and region. Deviations of individual series from this regional curve are interpreted as ecological or climatological signals that result in higher or lower growth rates.

The RCS method was utilised to detrend the spruce data and assess whether low frequency trends can be recovered from the present data-set. These analyses may also establish whether samples of < 50 years in length can usefully be included in the data-set without prejudicing the potential recovery of low frequency information from these data.

The 678 measured spruce series in the Bavarian Forest data-set have a mean length of 81.2 years. These series were subdivided into three groups based on sample length, namely; SHORT

Table 3. Replication and mean sample length (MSL) of the three age groups used to assess the effects of MSL on the chronologies developed by Regional Curve Standardization. The separation between the MEDIUM and LONG sub-sets is based on the MSL of their combined data-set (86 years).

Age Group	Age range	No. of radii	MSL
SHORT	<= 50	90	42.9
MID	<= 86 and > 50	338	68.0
LONG	> 86	250	112.2

(< = 50 years); MEDIUM: (50–86 years) and LONG (> 86 years; Tab. 3). Fig. 8a shows the replication of each age group through time. Most samples in the LONG data-set are from living trees and the MEDIUM data-set is predominantly from trees growing in the 17th and 18th centuries. If the climate and ecological forcing upon the growth of the trees was constant over space and time the cambial age-aligned curves (Fig. 8b) for these three data-sets should be almost identical over the common cambial interval. This is clearly not the case. Growth rates in the youthful portion of the SHORT and MEDIUM data-sets are markedly higher than those of the LONG data-set. The lower mean growth rates of the first 40 years in the LONG data-set could be related to real differences in the growth rate of young trees during the 19th and early 20th centuries compared with other periods in the record. Alternatively, this difference may be an artefact due to the increased probability of missing the pith when sampling older, larger trees than younger, smaller ones. Unfortunately, no pith off-set data are available to address this issue in this data-set.

The age-aligned curves for each group (Fig. 8b) were smoothed with a cubic smoothing spline of 10 % their series length (Esper et al. 2003). These three smoothed curves were subsequently used to detrend the individual RW series in each age group and the indexed series were averaged to produce three age-grouped RCS chronologies.

Composite chronologies were developed from this spruce data-set to illustrate the relative merits of spline (SPL) and regional curve (RCS) standardisation. The SPL chronology developed by Wilson, Elling (2004) used a fixed 80-year cubic smoothing spline that retains only decadal or higher frequency information. The RCS chronology uses the age-grouped RCS approach described above. In both cases, each historical and living site chronology was weighted equally in the final composite chronology to avoid bias due to differences in series replication at each site.

Results

The three age-grouped RCS chronologies (Fig. 9) show a significant low frequency signal, although there are differences between the series that are mainly related to sample replication (Fig. 8a) and ultimately weak signal strength (Fig. 9b). These three series generally show above average index values, ca. 1700–1775 and in the 20th century; and low index values, ca. 1520–1640 and ca. 1800–1875. How-

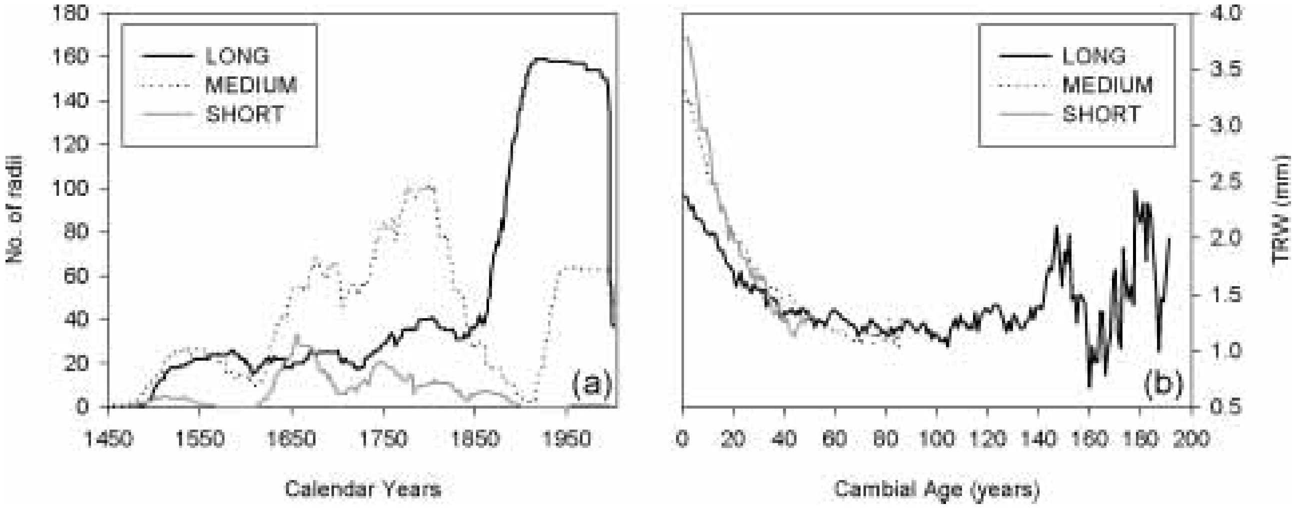

Figure 8. Characteristics of the age grouped tree-ring data-sets; **(a)** Sample depth over time; **(b)** Cambial age-aligned mean curves.

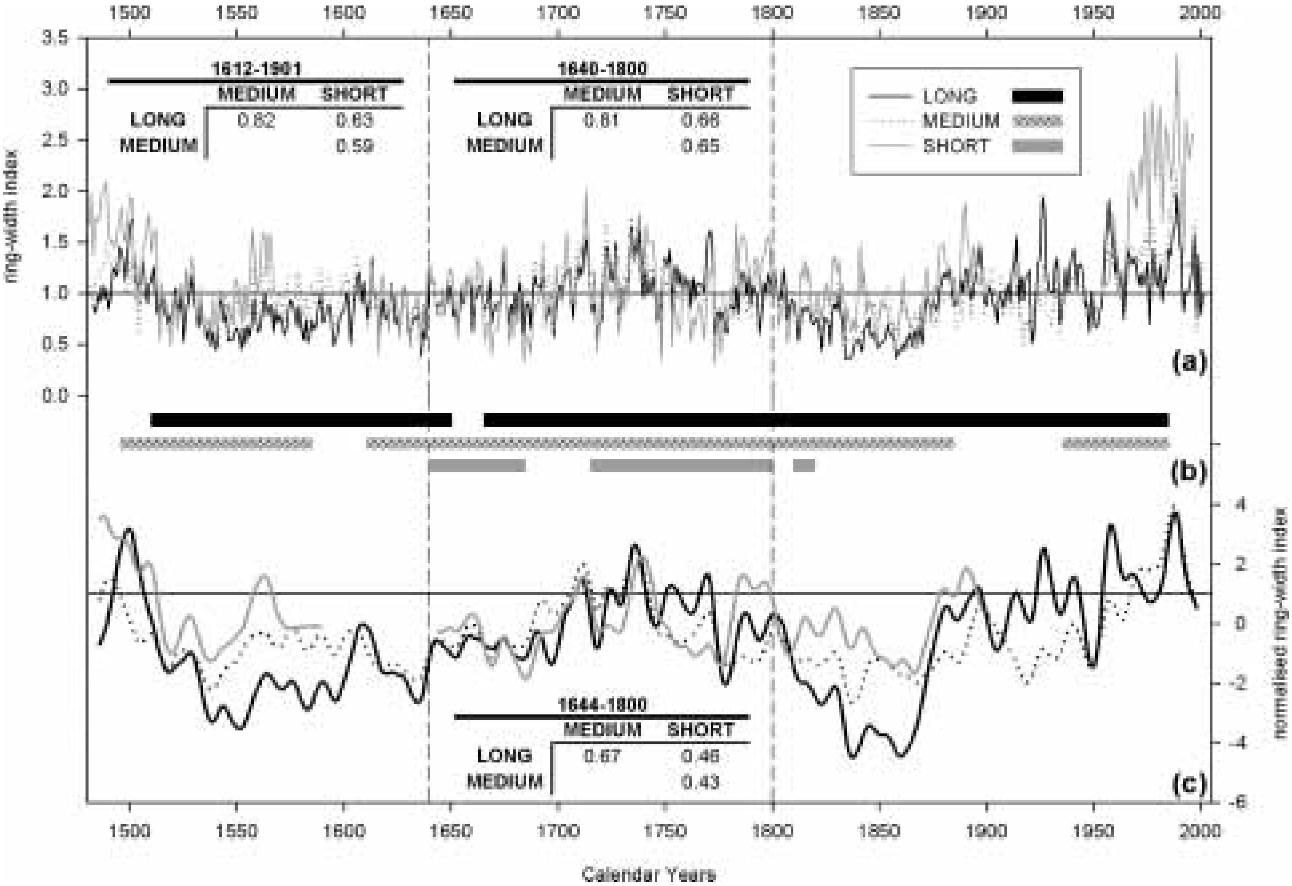

Figure 9. Comparison of the age grouped RCS chronologies. **(a)** Comparison of the non-filtered RCS chronologies. Correlation matrices are shown for the well replicated 1640–1800 period (EPS roughly > 0.85, Fig. 9b) and the full common period (1612–1901), which excludes the gaps in the SHORT data-set at 1568–1611 and 1902–1953. All correlations are significant at the 95 % confidence limit; **(b)** Bar plots showing the periods in each RCS chronology where EPS > 0.85 (Wigley et al. 1984); **(c)** Comparison of smoothed (15 year spline) age-grouped RCS chronologies normalised to the 1644–1800 period. As replication is substantially lower in the SHORT data-set, the smoothed series were normalised to ensure that the variance of the series was similar. The scale has been set to highlight differences between the smoothed series. Standard methods for quantifying the significance of the correlation values are not appropriate for these low pass filtered series (Fritts 1976, p. 324). The correlations merely provide a guide to the common low frequency variability between two series.

ever, the low index values of the mid 16th and 19th centuries are more pronounced in the LONG chronology (Fig. 9c).

The SHORT chronology agrees reasonably well with the other chronologies over the most highly replicated period for all age groups (1640–1800, Fig. 8a), where the EPS (Wigley et al. 1984) for each series is roughly > 0.85 (Fig. 9b). As all three chronologies appear to capture similar decadal and multi-decadal trends over this period, there seems to be no justification for deleting samples < 50 years in length from the final chronology. Their inclusion is also important because a good distribution of age classes is required for the successful utilisation of the RCS method (Briffa et al. 1996). The comparison between the three series (Fig. 9) also indicates that the RCS method appears to be robust in capturing low frequency information in TR series, even where pith off-set data are not available, provided that replication is high and samples are generally evenly distributed over time (see Esper et al. 2003).

Fig. 10 clearly demonstrates that the RCS chronology contains considerably more low frequency variance than the SPL chronology. However, examination of the EPS values indicate that the RCS technique is a "noisier" method than SPL standardi-

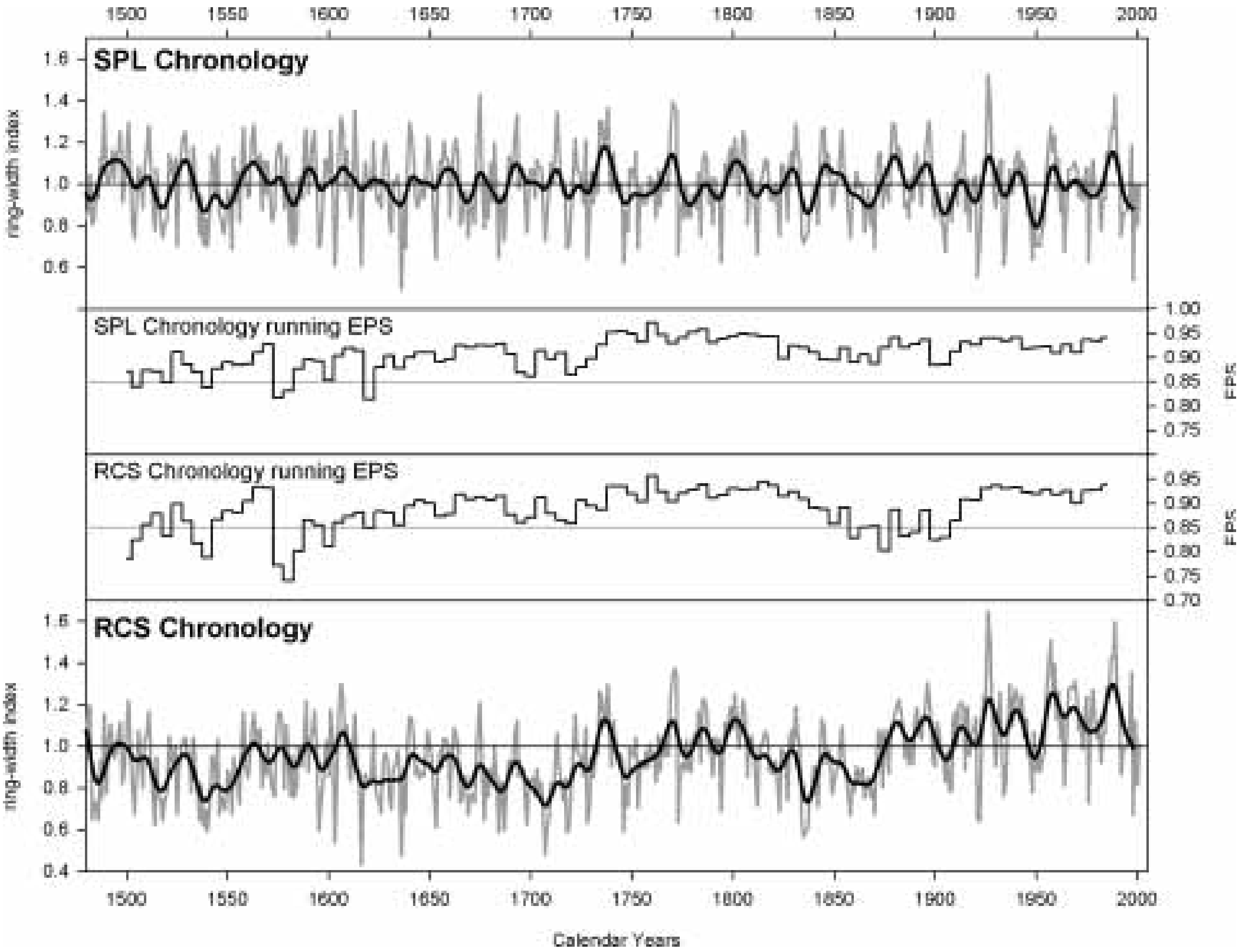

Figure 10. Comparison of living/historic regional composite chronologies developed from the same ring-width series detrended using a fixed 80 year cubic smoothing spline (SPL) and age grouped RCS (Fig. 9). The heavy lines are a 15 year smoothing spline. Running 30 year (lagged by 5 years) EPS plots are shown for each chronology. These final chronologies were developed by weighting each historic/living site chronology equally to avoid introducing bias due to differences in replication; (13 of the historical chronologies have 3–4 timbers while other sites range up to 37; Wilson 2003). The chronologies in Fig. 9 weighted all radii equally. Differences in the low frequency trend over the 1700–1750 interval between Fig. 9 and this site weighted RCS chronology are related to the high replication (37 trees and 62 radii) at one historic site. Such differences highlight the importance of weighting each chronology equally in developing composite chronologies.

sation (see Briffa et al. 1992; Cook et al. 1995). Employing RCS essentially reduces common interannual variance in order to capture the common low frequency signal (see Briffa et al. 1992; Cook et al. 1995). High replication is therefore required to develop a robust mean function from the data. EPS plots for the RCS historic/living composite chronology (Fig. 10) remain >0.80 during the period of overlap (1806–1901) between the living and historical series (see Fig. 2) but are weaker than the equivalent period in the SPL chronology. The weaker common variance and signal strength in the period of overlap are exacerbated by the low replication in the living data during this period and the clustering of start dates of the living samples.

Overall, our results demonstrate that regional curve standardisation is able to capture low frequency trends in the living/historic spruce data-set, even when samples < 50 years in length are utilised. Although no pith off-set information was available, comparison of the three age grouped sub-set derived RCS chronologies (Fig. 9) indicates that lack of pith adjustment has not introduced obvious bias in these chronologies.

Conclusions

Evaluation of the statistical properties of living TR series in the Bavarian Forest indicates that such data can be used to evaluate the probable source elevation of the historical timbers in this region. These data indicate that most of the spruce used for construction between ca. 1450 and 1900 A.D. came from local, low elevation sites. This confirms the assumptions that these timbers had a proximal source based on the abundant availability of wood in nearby forests and the available transport technology prior to the 20th century. As RW series from low elevation living trees in this region are precipitation-sensitive, it follows that these historical timbers have considerable potential use in developing long precipitation-sensitive TR chronologies from this region.

Examination of the growth response to precipitation from chronologies of living trees > 110 years and < 100 years indicates that there is no significant difference in growth/climate response between young and old trees. Therefore, TR series from historical timbers in this region (which are generally from younger trees) have a similar response to precipitation as contemporary (usually older) living trees and may be used to extend the living-tree, low elevation spruce chronologies and develop dendroclimatic reconstructions of past precipitation.

Low frequency variation may be recovered from these TR series using regional curve standardisation techniques, even though the mean segment length of these chronologies is low (< 50 years in some cases). This is a surprising result as, traditionally, dendroclimatologists utilise only the longer series to try and minimise the effects of the "segment length curse" (Cook et al. 1995).

This paper has demonstrated that many of the obstacles to the use of historical timbers in dendroclimatic reconstruction can be overcome with careful site selection and sampling. Three key factors may be identified. Firstly, the living trees of the region must be shown to be climate-sensitive; secondly, most of the timbers used probably have a local source and thirdly, that it can be demonstrated (either by known provenance of the timbers or matching dendrochronological quality) that the historical TR series contain a strong common signal that is climate sensitive. As this strong common signal is a major prerequisite for successful crossdating of historical material, these conditions should be met more frequently than previous utilisation of historical TR material suggests. The large number of specific regional historical/archaeological chronologies for many areas in Europe (Briffa et al. 1999) indicates such data-sets are readily available. Although it is unrealistic to assume that all historic TR material will be useful for dendroclimatology, more explorative work is needed to assess the dendroclimatic potential of these historical TR data-sets. In regions where climate is relatively homogenous over large areas, these large historical TR data-sets potentially represent a significant archival resource for future palaeoclimate studies.

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