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Dendrochronological investigations of Norway spruce along an elevational transect in the Bavarian Forest, Germany

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Abstract

Dendrochronological dating of historical buildings in the Bavarian Forest is notoriously difficult. These difficulties are often attributed to differences in tree response to climate with elevation. To investigate this possibility, an elevational transect of 14 Norway spruce chronologies (370 m to 1420 m) was developed from the Bavarian Forest. Correlation matrices, principal component analysis and hierarchical cluster analysis identified three elevation zones for spruce in the region (Low: ≤ ca. 680 m; Intermediate: ca. 780-970 m; High: ≥ ca. 1070 m). These analyses also showed an apparent "natural" orthogonality between high and low elevation chronologies. Intermediate elevation chronologies exhibit more year-to-year variability in common with the high elevation chronologies. Correlation analysis using monthly climate data indicates that moisture availability is the dominant factor affecting growth at low elevations. At intermediate elevations no significant correlations with climate parameters were discerned. Although similar elevational studies have demonstrated that temperature is the dominant factor limiting growth at upper tree-line sites, no clear relationship was found in this study.

The elevational differences in the response of spruce to climate has profound implications for sampling and historical dating strategies in the region. Low elevation chronologies cannot be used to date higher elevation sites. A new strategy for dating has therefore been outlined, with future sampling targeting buildings above 700 m in the region. Initial dating, at these higher elevations, will use a combined composite of intermediate and high elevation tree-ring data. It is assumed that in the future, it will be possible to derive separate intermediate and high elevation master chronologies.

Keywords: Bavarian forest, historical dating, Norway spruce, elevational transect, promax PCA, cluster analysis

Introduction

The dendrochronological dating of construction timbers from the Bavarian Forest is notoriously difficult which suggests that the common signal within the tree-ring series is either heterogeneous or weak. Lamarche (1974) stated that such dating problems could result from: (1) non-climatic environmental factors influencing ring-growth differently between sites, (2) ring growth corresponding to different climatic factors, or (3) trees at the upper or lower forest margins responding to the same climatic factors but in different ways. A fourth point which is also relevant when trying to date historical timber, is the possible importation of wood. To test which of these points is prevalent in the Bavarian Forest region, a transect of Norway spruce (*Picea abies* (L.) Karst) chronologies was sampled along an altitudinal gradient from low (ca. 350 m) to high elevation (ca. 1400 m) to investigate possible changes in tree growth/climate response with increasing elevation.

The Bavarian Forest

The Bavarian Forest, with an area of 4600 km^2, is the largest area of woodland in central Europe (Fig. 1). It is bordered by the German/Czech border on the north-east, the River Danube on the south-west, the German/Austrian border in the south-east (Passau) and a line through the towns Cham and Regensburg being the north-western boundary. Elevations through the region vary from 350-1050 m in the Lower Bavarian Forest in the west, to a range of

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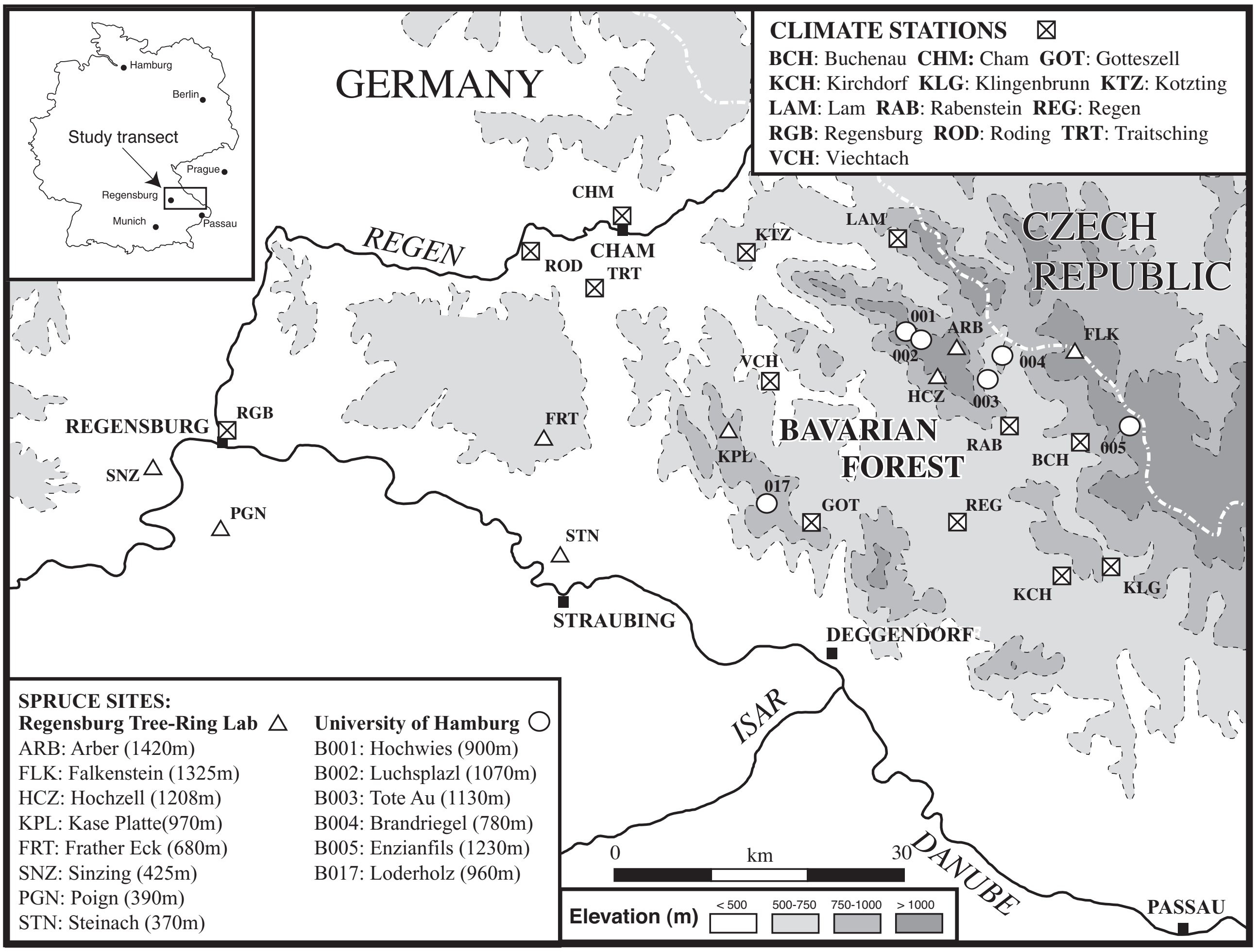

Fig. 1 - Location map showing tree-ring sites and meteorological stations.

1100-1450 m for the Upper Bavarian Forest along the German/Czech border (Priehaeusser 1965).

The Bavarian Forest lies in the border zone between the maritime climate of western Europe and the continental climate of eastern Europe (Elling et al. 1987). The area of the Danube Valley between Regensburg and Passau is one of the most continentally influenced and therefore driest regions in Germany (Noack 1979). Annual mean total precipitation values at lower elevations vary from 600-700 mm, while at higher elevations and summit sites within the Upper Bavarian Forest, precipitation values range from 1400-1800 mm. Mean annual temperature varies from 8-9 °C for the lower elevations and 4-5 °C at high elevations (Noack 1979). Annual precipitation maxima occur during the summer throughout the region with a second precipitation maximum in the winter caused by westerly and south-westerly air streams, resulting in thick winter snow cover (Noack 1979; Elling et al. 1987).

The "natural" vegetation within the region changes with elevation. Below 500 m, mixed oak forests (predominantly oak and beech) are found, while from 500-1100 m mixed forests of beech, fir and spruce are prevalent. Above 1100 m, beech and fir give way to pure spruce forest. The region has been extensively influenced by human activity. The use of wood in the 14th century as fuel for the glass industry and subsequent settlement in the area through the 15th and 16th centuries has meant that most of the area is now predominantly a cultivated forest landscape (Priehaeusser 1965). Mainly due to forestry practises, 65% of the Bavarian Forest is now spruce forest. However, natural or near natural woodland can still be found throughout the whole region as either privately owned land or land belonging to the Bavarian Forest National Park (Anonymous 1981).

Elevational transects in dendrochronology

The idea of investigating tree-growth along ecological or altitudinal transects is not new. Cieslar's (1907) pioneering work studied the relationship between ring-width and climate for the years 1902-1906 using several species at different elevations in the Austrian Alps. Although this study was essentially qualitative and involved simple comparison of annual increment to monthly and annual climate data, he showed that higher elevation sites responded positively to warm summer temperatures, while lower elevation sites produced a narrow ring during drought years.

Fritts et al. (1965) and LaMarche (1974) investigated tree-growth along ecological gradients in the American Southwest and emphasised the influence of different site conditions on tree-growth using several chronology statistics. Both projects found that the strongest ring-width response to climate occurred at both the upper and lower forest limits. Lingg (1986), using ring-width and density measurements, studied growth and response patterns of Norway spruce and Silver fir along an elevational gradient in Switzerland. His findings also showed strong relationships with climate at the lower and upper forest borders and concluded that at intervening sites, growth was mainly influenced by local factors. Kienast et al. (1987) analysed gradational changes along several altitudinal transects in Switzerland, Cyprus and the United States. As with Fritts et al. (1965) and LaMarche (1974), they used statistical tools to identify the strongest relationships between tree-ring chronologies and climate. All these studies generally agree with the principles of limiting factors and ecological amplitude (Fritts 1971, 1976). When combined, these principles describe how a tree species is more sensitive to environmental factors at the latitudinal or altitudinal limits of its range. At the forest borders, the main controls upon growth are temperature (high elevation) and precipitation (low elevation), although snow cover, soil temperatures, soil moisture, nutrient availability and nutrient uptake need to be taken into account when interpreting tree-growth/climate relationships (Tranquillini 1979; Rochefort et al. 1994).

Dittmar and Elling (1999) studied the growth/climate response of Norway spruce and European beech from several sites throughout Bavaria. Their results show, that below 700 m, spruce growth responds positively to precipitation during the growing season, while warm temperatures in the spring and summer which increase dehydration of the tree, result in a negative relationship between ring-width and temperature. At high elevations, spruce chronologies (>800-900 m) are more influenced by temperature rather than precipitation and at intermediate elevations, they found the response of growth to climate weak and indistinct (Dittmar, Elling 1999).

Dittmar and Elling (1999) stressed that verification of their work was needed, and that a multi-methodological approach was required to test their results. This paper therefore not only attempts to address the historical dating problems in the Bavarian Forest, but to also verify the results presented by Dittmar and Elling (1999).

Materials: Tree-ring and Climate data

The elevational transect

Fig. 1 presents the region of the Bavarian Forest that was targeted for sampling. Eight Norway spruce sites were sampled between 1995 and 1999. The chronology replication along the transect was improved by a further six spruce chronologies donated by the Institute of Wood Biology, University of Hamburg. These chronologies were originally sampled in 1984 (Sass 1988) for a study of forest decline, and although the sample depth of these chronologies is rather low, they still proved very useful in the present study. Tab. 1 summarises information for each site along the transect. Ecological differences are mentioned where appropriate.

Dominant or co-dominant trees were sampled from sites that were selected to minimise both between site ecological differences and the effect of human disturbance. Targeted stands were sampled from well drained local summit sites to allow for

Site Name	Elev. (m)	No. of radii	Mean sample length (years)	Chron. Length (>5 radii)	Site Description
Arber	1420	31	120.3	1832-1997	Steep, shallow soil, Southwest facing slope. Only spruce.
Falkenstein	1325	53	167.7	1750-1995	Summit site with some trees sampled on western side. Only spruce. Relatively damp site. Lightening damage on some trees.
Enzianfils	1230	16	125.5	1847-1984	Northwest facing slope. Spruce only.
Hochzell	1208	31	125.6	1836-1996	Summit site. Spruce only.
Tote Au	1130	16	143.7	1807-1984	South facing slope. Spruce only.
Luchsplazl	1070	16	98.6	1886-1984	West facing slope. Spruce only.
Käse Platte	970	34	85.3	1896-1996	Summit site. Mixed forest: spruce and fir.
Loderholz	960	18	86.9	1892-1984	Steep west facing slope. Mixed forest: spruce and fir.
Hochwies	900	13	79.6	1899-1984	Steep west facing slope. Spruce only.
Brandriegel	780	16	119.8	1856-1984	West facing slope. Mixed forest: spruce, fir and beech.
Frather Eck	680	41	101.6	1869-1996	Summit site. Mixed forest: spruce, fir and beech.
Sinzing	425	28	114.9	1843-1996	Summit site (logged area). Predominantly spruce, with periodic single fir trees.
Poign	390	21	113.4	1861-1996	Summit site. Mixed forest: spruce, pine and beech.
Steinach	370	45	121.4	1844-1998	Summit site. Mixed forest: spruce, pine and beech.

Tab. 1 - Chronology information and site characteristics. See Fig. 1 for site codes.

uniformity between sites. The highest elevation site (ARB) was not sampled from a local summit, but was selected to optimise the climate signal from the "local" upper tree-line. The chronologies obtained from the Institute of Wood Biology, Hamburg, which make up the bulk of the intermediate elevation sites, were also not sampled from local summit sites and in general cluster at the eastern end of the transect (Fig. 1 and Tab. 1). It should be noted that it was not always possible to find perfectly undisturbed sites and there was widespread evidence of forestry practise at the SNZ and FLK sites.

Chronology development

The samples were prepared using standard procedures (Stokes, Smiley 1968). Visual crossdating was verified after measurement using the computer program COFECHA (Grissino-Mayer et al. 1997). Sass (1988) and Eckstein and Sass (1989) made some tentative observations that at high elevations in the Bavarian Forest, spruce growth shows a slight post 1960s decrease in increment that might not be climate related. As such potentially non-climatic trends could affect the interpretation of the results in the present study, all analyses used pre-whitened residual chronologies. Individual series were detrended with either a negative exponential curve or a regression function of any slope using Turbo Arstan 1.0 (Cook pers comm). The residual chronology was calculated by averaging the series that result from the autoregressive modelling of the detrended measurement series.

Climate data

Precipitation data from 13 meteorological stations within the Bavarian Forest region were chosen for use in the study (Fig. 1). Tab. 2 presents some basic information for each of the 13 precipitation data sets. The common period of all the stations is 1913-1986. The data were provided by the Institute of Wood Biology, University of Hamburg and three of the stations (Roding, Regensburg, Cham) were updated with data from the Deutsche Wetter Dienst. The homogeneity of these records was tested by creating double mass plots of cumulative precipitation between pairs of stations for each of the seasons (Kohler 1949). No serious homogeneity problems were detected using this method.

Principal component analysis was used to assess the signal homogeneity between the 13 annual precipitation records over their common period. Using both a correlation and covariance matrix, only one significant eigenvector was identified explaining 78.2% and 79.5% respectively of the common variance. As these results suggest that the year-to-year variability is homogenous, the data from the 13 stations were averaged together, using techniques outlined in Jones and Hulme (1996), to develop a regionally representative precipitation series.

Temperature data were available from Munich, Passau, Regensburg and Cham (Fig. 1). The common period between the four series is from 1948-1986. The homogeneity of these data was visually tested using difference plots of candidate series minus neighbouring station series (Jones et al. 1985). Some between station discontinuities were identified using this method. It was therefore thought prudent to use the relevant 5°x 5° grid square of the Jones anomaly temperature series (Jones 1994; Parker et al. 1995; Nicholls et al. 1995) in the analyses. Although these data express the temperature signal of a much larger area compared to the study area, analysis presented by Balling (1995) shows that there is a strong common temperature signal across southern Germany (including the Alpine region) and therefore the use of the Jones data is presumed to be adequate for the present project.

Methods

Inter-site comparison was assessed using three different statistical techniques; a correlation matrix, principal component analysis (PCA) and hierarchical cluster analysis (HCA). A non-standard approach was utilised for PCA. A promax rotation (k = 3) was used to achieve a simple structure solution while allowing intercorrelation between the identified components (Richman 1986). For the HCA, Ward's method was employed, using the Pearson's correlation coefficient as the similarity measure. Ward's method maximises the between group variance while

Meteorological Station	Elev. (m)	Record length	MATP
Klingenbrunn	823	1911-1986	1163
Buchenau	740	1891-1986	1324
Kirchdorf	693	1899-1986	1015
Rabenstein	690	1881-1986	1277
Gotteszell	576	1913-1986	1123
Regen	572	1899-1986	945
Lam	541	1901-1986	1024
Viechtach	455	1901-1986	858
Traitsching	435	1900-1986	761
Kotzing	408	1901-1986	834
Cham	396	1879-1996	698
Regensburg	366	1871-1996	634
Roding	363	1895-1996	704

MATP = Mean annual total precipitation (mm) over period 1913-1986

Tab. 2 - Precipitation records used from the Bavarian Forest Region.

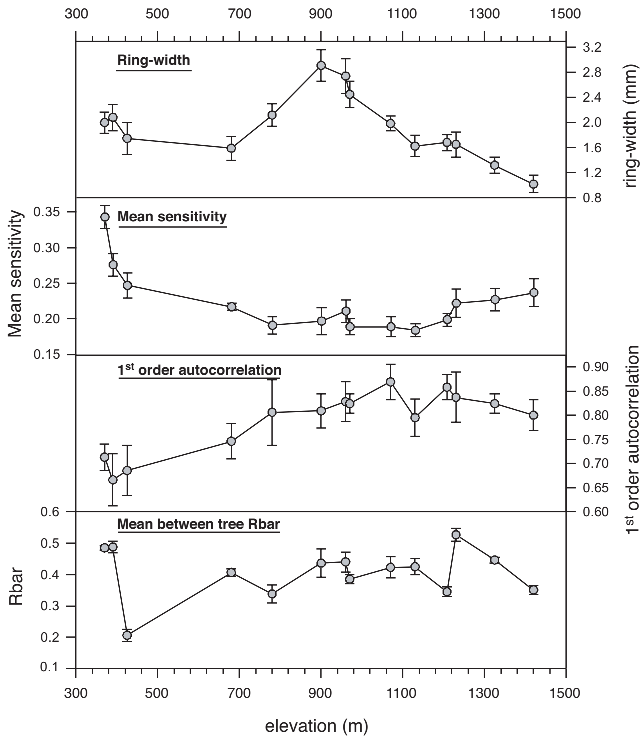

Fig. 2 - Plots showing the change in mean site values of ring-width, mean sensitivity, 1st order autocorrelation and mean between tree correlation (Rbar) with elevation (95% confidence limits are shown). The Rbar values were calculated using the pre-whitened tree-ring data, while the other statistics were calculated using the raw measurements.

minimising the within group variance and should therefore identify similar groups to the PCA.

The relationship between tree-growth and monthly climate data was examined using correlation analysis over a 17 month period from May of the previous year to September of the current year of growth. Correlations were made between the individual chronologies and the PC scores identified in the PCA, against monthly series of both the Jones anomaly temperatures data and the regional precipitation series for the region. Although the tree-ring data had been pre-whitened, the climate data did not need to be autoregressively modelled to remove persistence as they show no significant 1st order autocorrelation.

Results and discussion

Chronology characteristics

Fig. 2 plots the change in ring-width, mean sensitivity, 1st order autocorrelation and mean between tree correlation (Rbar) with elevation. In general, lower ring-width values are found towards each forest border with the narrowest rings at the upper tree-line sites. The higher ring-width values are found at intermediate elevations between ca. 850 and 1000 m which coincides with the zone of low mean sensitivity values between ca. 800 and 1200 m. Mean sensitivity values increase towards each forest border, although the values for the lower elevation sites are distinctly higher than for the high elevation sites. The high ring-width values at intermediate elevation is not a surprising observation as the trees at these elevations are generally younger than the trees towards the forest borders (see Tab. 1). 1st order autocorrelation is relatively high for all of the chronologies, but is distinctly lower (< 0.75) for the three lower elevation sites. No obvious zones can be identified when the between tree Rbar is assessed along the transect. In general, the between tree Rbar of the residual chronologies fall between 0.30 and 0.55. Only Sinzing falls outside this range with a between tree correlation of 0.21 which possibly reflects the disturbance effects of forest practises at this location.

Inter-site comparison

The correlation matrix of all 14 residual chronologies (Fig. 3) shows that the low and high elevation chronologies do not correlate between each other and that a “natural orthogonality” exists between the chronologies from these elevations. The correlation matrix also highlights (thick black lines) possible groupings of the chronologies. The elevational boundaries that appear to divide the low, intermediate and high elevation sites are 680-780 m and 970-1070 m. The intermediate chronologies (B004, B001, B017 and KPL) correlate with both the low and high elevation chronologies suggesting a gradational change of spruce’s response to climate along the transect.

PCA of the residual chronologies identified three

Elevation (m)		370	390	425	680	780	900	960	970	1070	1130	1208	1230	1325	1420
		STN	PGN	SNZ	FRT	B004	B001	B017	KPL	B002	B003	HCH	B005	FLK	ARB
370	STN														
390	PGN	0.78													
425	SNZ	0.54	0.71												
680	FRT	0.60	0.57	0.65											
780	B004	0.34	0.39	0.47	0.53										
900	B001	0.07	0.08	0.13	0.37	0.57									
960	B017	0.24	0.26	0.34	0.48	0.61	0.66								
970	KPT	0.30	0.25	0.34	0.58	0.55	0.58	0.71							
1070	B002	-0.02	0.02	0.16	0.24	0.51	0.58	0.53	0.40						
1130	B003	0.05	0.10	0.17	0.25	0.57	0.57	0.59	0.53	0.80					
1208	HCH	0.03	0.04	0.13	0.17	0.42	0.39	0.33	0.39	0.65	0.72				
1230	B005	-0.03	0.02	-0.01	-0.10	0.21	0.24	0.10	-0.06	0.42	0.34	0.35			
1325	FLK	-0.05	-0.02	0.09	0.09	0.36	0.44	0.42	0.40	0.68	0.75	0.64	0.33		
1420	ARB	0.05	0.01	0.02	0.23	0.41	0.56	0.46	0.51	0.63	0.72	0.59	0.29	0.67	

CORRELATION MATRIX

BAVARIAN FOREST SPRUCE

RESIDUAL CHRONOLOGIES

1896-1984

> 0.7
0.6 - 0.69
0.5 - 0.59
0.4 - 0.49
0.3 - 0.39
0.2 - 0.29
0.1 - 0.19
< 0.09

Fig. 3 - Correlation matrix of the residual chronologies for the period 1896-1984. Site codes are listed in Figure 1. Correlation values not significant at the 95% confidence limit (r = 0.21) are printed in grey.

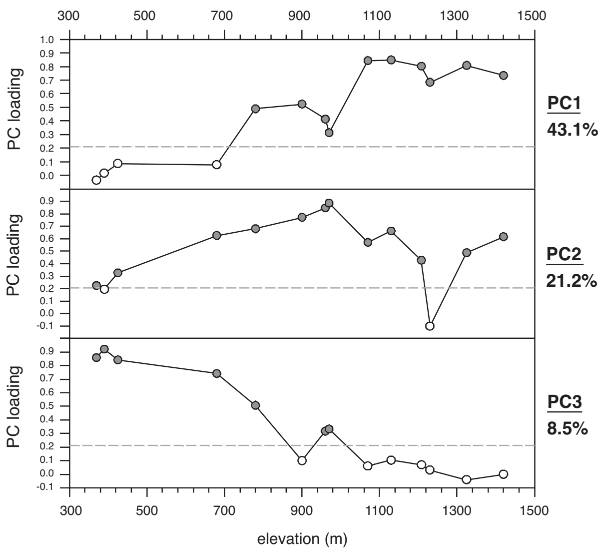

Fig. 4 - Plots of the loadings of each chronology upon each of the three significant principal components. Significant loadings at the 95% confidence limit are highlighted as grey circles.

principal components with eigenvalues greater than 1.0. Fig. 4 plots the loadings of each of the chronologies upon each of the three significant principal components. The first component, explaining 43.1% of the common variance, is most strongly related to the high elevation sites (> ca. 1070 m). The second component (21.2%) is dominated by the intermediate tree-ring sites while the low elevation sites (< ca. 680 m) load strongly upon the third component which explains 8.5% of the common variance. Fig. 4 clearly demonstrates that there is a gradual change in the chronology signals along the transect. It is interesting to note, however, that many of the chronologies load significantly on the second (intermediate elevation) component. This is especially true for those sites above ca. > 680 m. Tab. 3 presents a correlation matrix between the three principal components and again highlights the natural orthogonality between PC1 (high elevation) and PC3 (low elevation). PC2 correlates significantly with the other two component scores, but

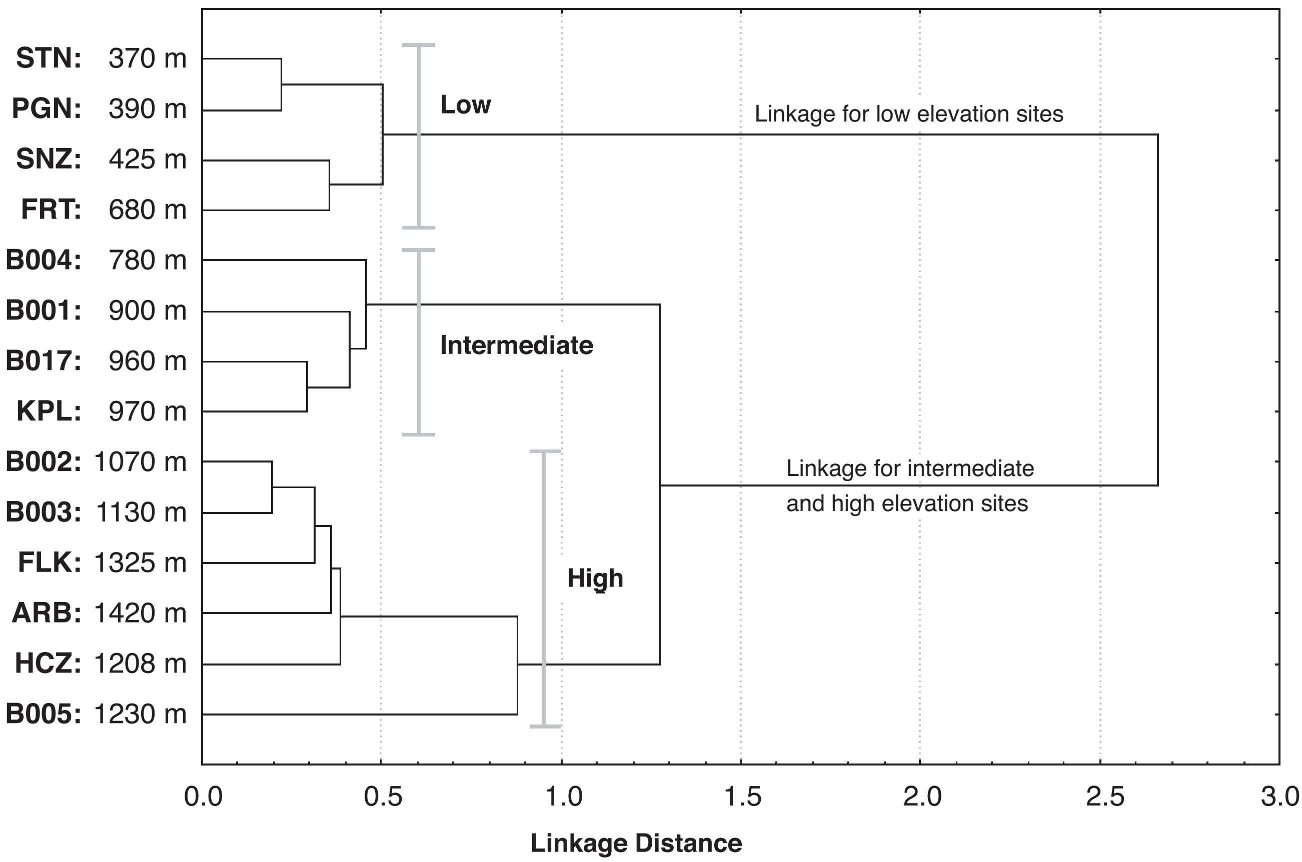

Fig. 5 - Dendrogram presenting the results from the hierarchical cluster analysis.

is more highly correlated with the high elevation related principal component. This is an important observation as it suggests that although there is a gradual change in signal along the transect, the chronologies from the intermediate elevations have more year to year variance in common with the high elevation chronologies.

Fig. 5 presents the HCA dendrogram. As with PCA, three distinct elevational groups were identified (Low = 370-680 m; Intermediate = 780-970 m; High = 1070-1420 m). The dendrogram clearly shows the initial split between the low elevation and the intermediate/high elevation chronologies. This result agrees with the natural orthogonal relationship between the high and low elevation chronologies noted in the correlation matrix (Fig. 3) and PCA (Tab. 3). Both the intermediate and high elevation chronology groups split from the same branch in the hierarchical tree, indicating that the chronologies from these two elevational zones have more year to year variability in common than with the low elevation sites.

An important observation to note from the cluster analysis is that the signal change between the chronologies is related to elevation and not distance between sites. For example, the STN and FRT sites, although spatially close (Fig. 1), are ordered based on elevation rather than their close proximity to

		HIGH	INT.	LOW
	PC	**1**	**2**	**3**
HIGH	**1**	–	**0.41**	0.02
INT.	**2**		–	**0.28**
LOW	**3**			–

Tab. 3 - Correlation matrix between the principal components. 95% signifiance level = 0.21.

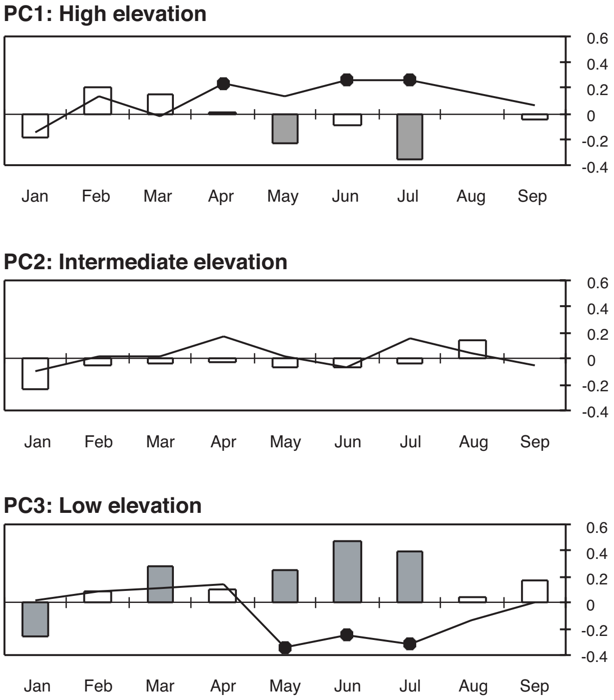

Fig. 6 - Correlation analysis of the three principal component chronologies against precipitation (bars) and temperature (lines) over the period 1913-1986. Significant (95%) correlations are highlighted.

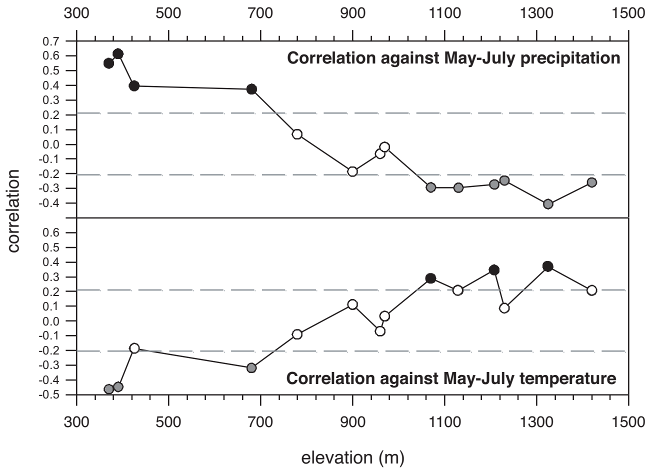

Fig. 7 - Correlation of each chronology with both May-July precipitation and temperature. Horizontal dashed lines delineate the 95% confidence limits. Points highlighted in black denote significant positive correlations, while grey points highlight significant negative correlations.

each other. The same can be said for sites B001 and B002. Only in the high elevation zone does the classification pattern related to elevation break down. The HCZ and B005 sites are out of place in the hierarchical classification. Their anomalous classification in the hierarchy may either reflect site specific effects upon growth or the effect of some external influence that is non-climatic in nature. Sass (1988) and Eckstein and Sass (1989) stated that there was some evidence at high elevations for forest decline effects and Sander et al. (1995) indicated that air pollution had had a marked effect upon spruce growth at high elevations in the Czech Republic. It is highly likely, therefore, that the break down of the "elevation" related signal in the hierarchical classification is due to a non-climatic influence that appears to affect higher elevation spruce sites.

Growth/climate relationships

As the autocorrelative nature in the ring-width chronologies was removed when they were prewhitened, no significant relationships with prior year's climatic conditions were observed and so the results presented here concentrate on the nine months of the current year (January to September). To facilitate interpretation, only the results of the relationships between the three principal component chronologies and climate are initially presented.

The results from the correlation analysis are presented in Fig. 6. PC1, which is related to the high elevation chronologies, shows significant positive correlations to April, June and July temperature, while significant negative correlations occur against May and July precipitation. The principal component related to the low elevation chronologies (PC3) correlates positively with March, May, June and July precipitation and negatively with May to July temperatures. A negative correlation to January precipitation is also observed. No significant correlations occur between PC2 and monthly precipitation or temperature data suggesting that the climatic influence upon tree growth at intermediate elevations is weak and indistinct.

To further quantify the influence of both precipitation and temperature on tree growth, each chronology along the transect was correlated with a

	P_{ct}	P_{cp}
PC1 (high)	0.16	**-0.27**
PC2 (int.)	0.00	-0.06
PC3 (low)	**-0.21**	**0.48**

P_{ct} = Partial correlation with temperature controlling for precipitation
P_{cp} = Partial correlation with precipitation controlling for temperature

Tab. 4 - Partial correlation analysis results for each principal component with May-July precipitation and temperature. Bolded values are significant at the 95% confidence limit.

seasonalised series (May-July) of both precipitation and temperature. The results from this correlation analysis are presented in Fig. 7. The positive correlations against May-July precipitation can clearly be seen for the low elevation sites, but above ca. 750 m the intermediate chronologies show no significant relationship. Above ca. 1070 m, the chronologies show negative correlations with precipitation. Correlations of the chronologies against May-July temperature show the same trend but inverse of that noted for precipitation. The chronologies below ca. 750 m show negative correlations, while above ca. 1070 m, positive correlations are generally seen. The chronologies that fall between 750 m and 1070 m show no significant correlation with May-July temperature.

In some respects, such correlation analyses can be misleading. The correlation between the seasonalised (May-July) series of precipitation and temperature is -0.51. This significant inverse relationship between precipitation and temperature may in fact bias the interpretation of the correlation analysis results. To assess this potential bias, Tab. 4 presents the results from a partial correlation analysis between the three principal component scores and May-July temperature and precipitation. This analysis shows that it is in fact precipitation that has a significant affect (inversely) upon growth at the higher elevations. At lower elevations, precipitation is the dominant control upon growth, although temperature also has a negative impact upon ring-width formation. The strong positive correlations between the low elevation sites and precipitation is not surprising as there is a strong precipitation gradient in the region (Tab. 2). Mean total annual precipitation is ca. 700 mm at low elevations while it ranges from 1400-1800 mm at high elevations (Noack 1979), suggesting that there is a relative dry climatic regime for spruce growth at low elevations, while there is an excess of precipitation for growth at high elevations.

The partial correlation analysis results indicate that temperature has little control upon tree-growth at high elevations. This result, however, does not agree with the literature where it is often observed that temperature shows a positive relationship with tree-growth at high elevations during the growing season (Fritts et al. 1965; LaMarche 1974; Kienast et al. 1987; Dittmar, Elling 1999). Interpretation of the partial correlation analysis results should, however, be approached with caution for several reasons. Firstly, the results could reflect the fact that the precipitation data express a more “local” signal while the temperature data portray a larger scale temperature signal due to the larger area covered by the 5x5 degree grid square. Secondly, the theoretical upper tree-line limit for the Bavarian Forest would be about 1500-1600m (Elling pers comm 2000). The ARB and FLK sites are at least 100-200 m below this theoretical limit and the trees may therefore not express as strong a signal with temperature as they would if they were growing at a “true” temperature controlled upper tree-line.

Conclusions

The results presented in this paper have demonstrated that three elevational zones can be identified for Norway spruce in the Bavarian Forest (Low = ≤ ca. 680 m; Intermediate = ca. 780-970 m; High = ≥ ca. 1070 m). Fig. 8 summarises the pertinent results that were important in identifying these elevational zones. The low elevation chronologies have high mean sensitivities, low autocorrelation and appear to be controlled predominantly by moisture availability. At intermediate elevations, the controls upon growth are more complex. The chronologies show the lowest mean sensitivity and no apparent relationships can be discerned with climate using correlation analysis. Principal com-

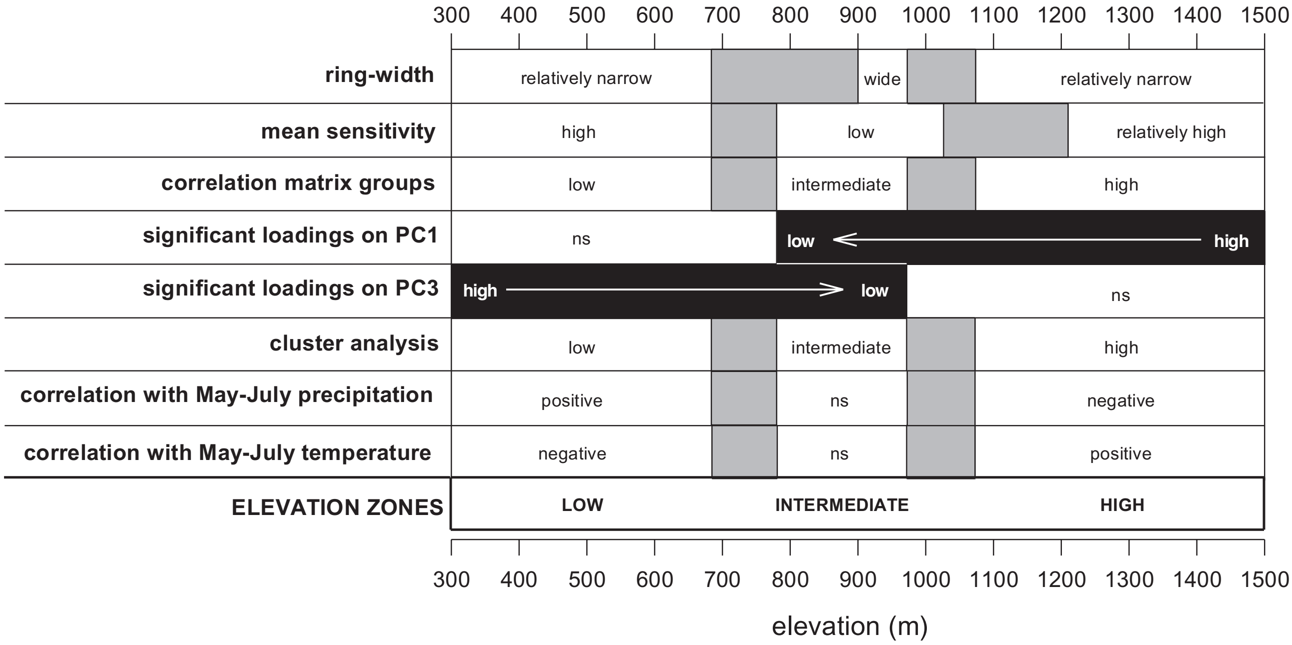

Fig. 8 - Summary diagram highlighting the consistency of each of the described analyses in identifying the same elevational zones. The grey boxes define overlap elevations between each identified zone. ns = not significant.

ponent analysis and hierarchical cluster analysis show that the intermediate elevation chronologies have more year-to-year variability in common with the high elevation chronologies than the low elevation chronologies. The high elevation chronologies express relatively high mean sensitivity values (though not as high as low elevations) and high 1st order autocorrelation. Partial correlation analysis, however, shows that the climate signal at high elevations is relatively weak, and that temperature is not the dominant control upon growth as would normally be expected. It is hypothesised that these ambiguous results reflect; (1) inadequate representation of the large scale temperature series used, (2) the fact that upper tree-line in the Bavarian Forest is controlled by topography rather than climate, and (3) the possibility that in recent decades non-climatic factors (possibly air pollution) are effecting spruce growth at high elevations in the region (Eckstein, Sass 1989; Sander et al. 1995).

In general, these results agree with those described by Dittmar and Elling (1999). Although their spruce data came from a larger region, they identified the same lower elevational zone (< 680 m). Their high elevation zone, however, was identified to start at ca. 800-900 m which is lower than that of the present study (ca. 1070 m). This difference in limits of the high elevation zones could reflect a local signal in the Bavarian Forest compared to a larger scale signal in Bavaria as a whole.

How can the results presented in this paper help the dendroarchaeologist develop a strategy for historical dating in the Bavarian Forest? The between site correlation of the chronologies within each elevational zone is high (ca. 0.60, Fig. 3). Therefore, theoretically one could assume that it will be possible to construct three different master series for each elevational zone. This has already been successfully undertaken at low elevations (Wilson 2000b). Analysis by Wilson (2000a) shows that the overlap between the low elevation living chronologies and the historical data collected from Regensburg and its surrounding area compare very well at both high and low frequencies. This homogeneity in between site signal is also observed between all the historical data for the last 500 years (Wilson 2000b). These results suggest that timber used for construction at lower elevations around the Danube River (Fig. 1) were most likely taken from living stands below ca. 680 m rather than higher elevations.

The extension of the intermediate and high elevation chronologies is potentially more problematic. There are few settlements above 1070 m, and so extension of the higher elevation chronologies using construction material appears to be almost impossible. As both the promax PCA (Tab. 3) and the HCA (Fig. 5) quantified that the intermediate elevation chronologies have more variance in common with the high elevation chronologies, a possible initial strategy would be to "pool" the intermediate and high elevation data together to construct a mean series for dating purposes. Several towns exist over 680 m and it is hypothesised that historical dating of the timbers from these towns will be facilitated by using an intermediate/high elevation composite master chronology. Theoretically it may be possible, in the future, to split the data and construct separate intermediate and high elevation living/historical master composite chronologies.

In conclusion, the results in this paper broadly confirm those described by Dittmar and Elling (1999), although more work is needed to benchmark both climatic and non-climatic controls upon growth at high elevations. The work in this paper has also resulted in the development of a new strategy for historical sampling in the region. Future historical sampling will target towns that are situated above 680 m in the hope of deriving a robust mean composite series that is representative for the higher elevations in the Bavarian Forest.

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References

Anonymous, 1981. Der Wald in Bayern. Bayerisches Staatsministerium für Ernaehrung, Landwirtschaft und Forsten, 152 pp.

Balling RC, 1995. Analysis of German climatic variations during the period of instrumental record. Geophysical Research Letters, 22(3): 223-226.

Cieslar A, 1907. Einige Beziehungen zwischen Holzzuwachs und Witterung. Centralblatt fuer das Gesamte Forstwesen, 33: 289-311.

Dittmar C, Elling W, 1999. Jahrringbreite von Fichte und Buche in Abhaengigkeit von Witterung und Hoehenlage. Forstwissenschaftliches Centralblatt, 118: 251-270.

Eckstein D, Sass U, 1989. Dendroecological assessment of decline and recovery of fir and spruce in the Bavarian Forest. In Air pollution and Forest Decline. In Bucher JB, Bucher-Wallin I (Eds), Proceedings of the 14th International Meeting for specialists in Air Pollution Effects on Forest Ecosystems, IUFRO P2.05, Interlaken, Switzerland, Oct. 2-8: 255-260.

Elling W, Bauer E, Klemm G, Kock H, 1987. Klima und Boeden. Waldstandorte - Nationalpark Bayrischer Wald, 1, 254 pp.

Fritts HC, Smith DG, Cardis JW, Budelsky CA, 1965. Tree-ring characteristics along a vegetation gradient in northern Arizona. Ecology, 46: 393-401.

Fritts HC, 1971. Dendroclimatology and Dendroecology. Quaternary Research, 1: 419-449.

Fritts HC, 1976. Tree Rings and Climate. London: Academic Press, New York, 567 pp.

Grissino-Mayer HD, Holmes RL, Fritts HC, 1997. The International Tree-Ring Data Bank Program Library, Version 2.1, Users Manual. Tucson, Arizona.

Jones PD, Raper SCB, Santer BD, Cherry BSG, Goodess CM, Kelly PM, Wigley TML, Bradley RS, Diaz HF, 1985. A Grid Point Surface Air Temperature Data Set for the Northern Hemisphere. Technical Report TRO22, U.S. Dept. of Energy, Carbon Dioxide Research Division, 251 pp.

Jones PD, 1994. Hemispheric surface air temperature variations: a reanalysis and an update to 1993. Journal of Climate, 7:1794-1802.

Jones PD, Hulme M, 1996. Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. International Journal of Climatology, 16: 361-377.

Kienast F, Schweingruber FH, Bräker OU, Schär E, 1987. Tree-ring studies on conifers along ecological gradients and the potential of single-year analyses. Canadian Journal of Forest Research, 17: 683-696.

Kohler MA, 1949. Double-mass analysis for testing the consistency of records and for making adjustments. Bulletin of the American Meteorological Scociety, 30: 188-189.

LaMarche VC Jr, 1974. Frequency-dependant relationships between tree-ring series along an ecological gradient and some dendroclimatic implications. Tree-Ring Bulletin, 34: 1-20.

Lingg W, 1986. Dendrooekologische Studien an Nadelbäumen im alpinen Trockental Wallis (Schweiz). Berichte der Eidgenoessischen Anstalt fuer das forstliche Versuchswesen, 287: 3-81.

Noack EM 1979. Witterung und Klima im Nationalpark Bayrischer Wald - Nationalpark Bayrischer Wald, 5, 132 pp.

Nicholls N, Gruza GV, Jouzel J, Karl TR, Ogallo LA, Parker DE, 1995. Observed climate variability and change. In Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (Eds), Climate Change 1995: The science of climate change. Contribution of Working Group 1 to the second assessment report of the IPCC. Cambridge University Press.

Parker DE, Folland CK, Jackson M, 1995. Marine surface temperature: observed variations and data requirements. Climate Change, 31: 559-600.

Priehaeusser G, 1965. Bayrischer und Oberpfaelzer Wald - Land an der Grenze 320 pp.

Richman MB, 1986. Rotation of principal components. Journal of Climatology, 6: 293-335.

Rochefort RM, Little RL, Woodward A, Peterson DL, 1994. Changes in subalpine tree distribution in western North America: Effects of climate and other environmental factors. The Holocene, 4: 89-100.

Sander C, Eckstein D, Kyncl J, Dobry J, 1995. The growth of spruce (*Picea abies* (L.) Karst.) in the Krkonose-(Giant) Mountain as indicated by ring width and wood density. Annales des Sciences forestiéres, 52: 401-410

Sass U, 1988. Dendrooekologische Untersuchungen an Fichten und Tannen im Bayrischen Wald. Unpublished Diplomarbeit, University of Hamburg.

Stokes MA, Smiley TL, 1968. An Introduction to Tree-Ring Dating. University of Chicago Press, Chicago, IL, USA.

Tranquillini W, 1979. Physiological Ecology of the Alpine Timberline. Springer-Verlag, Berlin, Germany, 137 pp.

Ward JH, 1963. Hierarchical grouping to optimise an objective function. Journal of the American Statistical Association, 58: 236-244.

Wilson RJS, 2000a. A Preliminary Reconstruction of March-August Precipitation for the last 500-years in the Lower Bavarian Forest Region, Germany. (Poster presentation at the International Conference on Dendrochronology for the Third Millennium, 2-7 April, 2000 Mendoza, Argentina).

Wilson RJS, 2000b. Dendro-Historische Datierung in Regensburg und Umgebung. Erarbeiteter Forschungbericht für die Regensburger Denkmalpflege, Deutschland, 15 pp.