Detrending ability of several regression equations in tree-ring research: a case study based on tree-ring data of Norway spruce (*Picea abies* [L.])

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ABSTRACT: The aim of this study was to investigate tree-ring width variability and to distinguish groups of trees with similar growth trends in order to study tree growth responses to various stand and site conditions. The methods of cluster analysis were employed for this purpose. Four distinct groups of trees were identified. For each group, the mean tree-ring curve was calculated in order to look for the main signals that distinguish the groups from one another. The idea behind this was to divide the samples into homogeneous groups with similar growth trends, representing typical examples of variability of the studied Norway spruce population. In the next step, several regression functions were studied and compared for their ability to fit the ring-width-age data applied to the mean ring-width curve of each group. Fischer's *F*-test was used to test the differences in goodness of fit between the equations in each group. From all examined/applied equations, smoothing spline, polynomial of degree 5, and Šmelko-Burgan functions were found to be the most universal and suitable for detrending of all examined ring width curves. Hugershoff function was found to be suitable for curves with one local maximum only. Exponential and Korf's functions were unsatisfactory for the purposes of tree ring curves detrending.

Keywords: radial increment; growth functions; empirical fitting; tree-ring indices; dendroclimatology

Tree-ring widths largely reflect environmental conditions. The effect of different factors is visible in the variation of ring size and structure, which systematically vary throughout the life of the tree. The information contained in annual tree rings is a valuable source for studying environmental changes by methods of dendrochronology (Fritts 1976; Schweingruber 1996). Recently, dendroclimatological methods based on these principles have been widely used for the growth prognosis of tree species under the conditions of climate warming (Andalo et al. 2005; Ricker et al. 2007; Su et al. 2007). In addition to climatic factors, more complex dendroecological approaches study also site factors as variables influencing the tree ring width (Adams, Kolb 2005; Bolli et al. 2007).

Although the use of tree rings for studying environmental changes is widespread, the extraction of desired signal from unwanted noise can be difficult and uncertain. The conceptual model for ring widths according to Cook and Briffa (1992) indicates that the variance of a ring width series may be decomposed into a pure age trend component (A), two common stochastic signal components: climatic (C) and exogenous disturbance (D1), and two unique stochastic signal components: endogenous disturbance (D2) and unexplained variability (E). In dendroclimatic studies, the common climatic signal C is of interest, while other signals are collectively considered as non-climatic variance or noise. The removal of non-climatic trend components from ring-width series is known as standar-diza-

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tion (Fritts 1976). Standardization transforms the non-stationary ring widths into a new series of stationary, relative tree ring indices that have a defined mean of 1.0 and stabilized variance. Many deterministic (few stochastic) models are known and applied to growth trend estimation and to removing non-climatic variance from ring series. The models belong to the family of linear, exponential, polynomial, or more complex growth functions, as comprehensively summarized for example by Vyskot et al. (1971), Šmelko et al. (1992), and most recently by Pretzsch (2009).

The aim of the present study is to perform analyses of tree-ring series obtained during extensive research of declining unnatural Norway spruce (*Picea abies* [L.] Karst.) forests in northern Slovakia in order to:

– contribute to the knowledge of variability of tree diameter growth in different site and stand conditions,
– compare the suitability of commonly used equations to fit and to standardize various observed tree-ring series.

MATERIAL AND METHODS

Study region and sampling scheme

The data for the analysis originate from the Orava region in northern Slovakia, belonging to the West Beskids flysch built of sandstones, slates and claystones. Moderately cold and very wet hilly climate is typical of the region. The altitude ranges from about 500 to 1,700 m a.s.l. Unnatural spruce forests predominate in the region. Recently, the forests have been extensively affected by forest decline driven by bark beetles (*Scolytidae*) and honey fungus (*Armillaria* sp.) accompanied by destructive harmful factors, mainly wind and snow. Climatic factors have been examined as possible reasons for the observed forest decline.

Pairs of dominant and co-dominant spruce trees, one healthy and one declining, were selected in each sample plot. The plots were arranged in three linear transects situated across the region in the directions of the highest variability of site conditions. In such a way, the whole range of variability of site and stand conditions was covered. From each selected tree, one increment core was taken with a standard increment borer at breast height (1.3 m) in May 2008. To avoid reaction wood, the cores were strictly sampled in up-and-down slope directions. Site and stand parameters were assessed for each sample plot, and for each sample tree quantitative and qualitative parameters were measured or visually assessed.

Dendrochronological analyses

From the whole data set, 104 tree ring series were extracted for the analysis, each containing more than 90 radial rings at breast height (i.e. from adult trees older than 100 years). Tree-ring width was measured to the nearest 0.01 mm with the positional measuring system TIME TABLE. A local ring-width curve was derived, and the obtained ring-width series were cross-dated, checked, and corrected for missing and false rings using dendrochronological software PAST 32 (Holmes 1994).

Detection of representative incremental patterns

For each ring series, linear increment trend (LIT) was computed for cambial age classes 21–40, 41–60, 61–80 and 81–100 years as the slope of the fractional straight line for each class. If on average the incremental curve shows an upward trend in the range of the age class, LIT is > 0, if the trend is downward, LIT is < 0. Cluster analysis was used to group similar ring series according to LIT values for age classes that represent input variables. Hierarchical clustering by Ward's method and Euclidean distances was used for the estimation of the number of clusters. For the final grouping of ring series, K-means clustering for the predefined number of clusters by the method of maximum starting distance between clusters was applied. Software STATISTICA 7.0 (StatSoft, Inc., 2009) was used. Consequently, selected site-related (altitude and soil quality), stand-related (stand density, vertical structure, stand damage) and tree-related parameters (tree age, crown length, health status) of clusters were compared between the clusters.

Standardization of mean incremental curves

For each cluster, the mean incremental curve was computed and detrended (standardized) using six various functions with the aim to remove non-climatic signals. Two commonly used incremental functions (Hugershoff and Korf), two simple empirical functions (exponential and polynomial), and one so far unpublished incremental function combining both exponential and polynomial elements

Table 1. List of the functions used for standardisation of example incremental curves

1.	$y(t) = a \times t^b \times \exp(-ct) + d$	Hugershoff (1936)
2.	$y(t) = a \exp\left(\frac{b}{1-c} t^{1-c}\right) \frac{b}{t^c}$	Korf (1939)
3.	$y(t) = a_0(1 + \exp(a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4))$	Šmelko-Burgan (Burgan 1983)
4.	$y(t) = a + \exp(-bt) + c$	Exponential (Fritts 1976)
5.	$y(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$	Polynomial
6.	$\sum_{i=1}^{n} (y_1 - \hat{f}(x_i))^2 + \lambda^3 \int \hat{f}(x)^2\, dx$	Spline (Ruppert et al. 2003)

y – radial increment; t – cambial age; a, b, c, d – parameters of the function; x_i – variable used for increment prediction (e.g. age); λ – smoothing parameter

designed by Šmelko and Burgan in Slovakia, were applied (Table 1). Furthermore, we also applied a cubic smoothing spline method (Reinsch 1967 cited in Cook, Peters 1981; Ruppert et al. 2003), which belongs to nonparametric or semiparametric statistical methods. The spar value of 0.9 was used for the calculation of the smoothing parameter. R software was used for the computation of all detrending functions.

F-test was employed to compare the goodness of fit between the particular models expressed by the mean square of their residual errors (MS_i):

$$F = \frac{MS_1}{MS_2}$$

$$MS_1 = \frac{\sum_{i=1}^{n_1} (y_1 - \hat{y}_1)^2}{n_1 - k_1} \qquad MS_2 = \frac{\sum_{i=1}^{n_2} (y_2 - \hat{y}_2)^2}{n_2 - k_2}$$

where:
n – sample size,
k – degrees of freedom of regression parameters.

For each cluster, the minimum mean square was taken as reference for the comparison of other functions. Subsequently, *P*-value was calculated to determine the statistical significance of differences between the reference model and other models. Moreover, the differences in goodness-of-fit between all selected detrending equations were compared using AIC (Akaike information criterion), since the criterion not only rewards of fit, but also includes a penalty that is an increasing function of the number of estimated parameters.

To compare the models by AIC (Akaike 1974), we selected the model for each cluster with minimum *AIC* value. Then we used the formula:

$$\mathrm{EXP}((AIC_{\min} - AIC_i)/2)$$

in order to evaluate the relative probability that the i^{th} model minimizes the information loss.

RESULTS

Representative incremental patterns

The sample file of 104 tree-ring series was divided into four groups (clusters) on the basis of the partial trends of radial increments in the age interval of 21–100 years (Fig. 1). Main differences between clusters are in the number and in the position of radial increment culminations in time. Cluster 1 has its main local maximum at the age of around 30–40 years and a slight indication of its secondary maximum at 80 years. An early main maximum before the age of 30 years and a late secondary significant maximum after 100 years are typical of cluster 2. Cluster 3 differs from the others by a striking secondary maximum at middle age (60–90 years). Cluster 4 resembles cluster 1, but its main maximum appears much earlier, before the age 20 years.

Table 2 summarizes the differences in selected site, stand and tree-related parameters between the clusters. The revealed differences are generally unclear (Table 2). The only noteworthy difference is a significantly higher proportion of multi-storied stands in cluster 3, which is a probable reason for its distinct secondary increment maximum at middle age. In the case of cluster 1, a higher proportion of poor sites and sites at higher elevations could cause its later first maximum and in general a slower drop of the incremental curve. A higher proportion of damaged stands, sparse stands and stand rests in clusters 2 and 4 could contribute

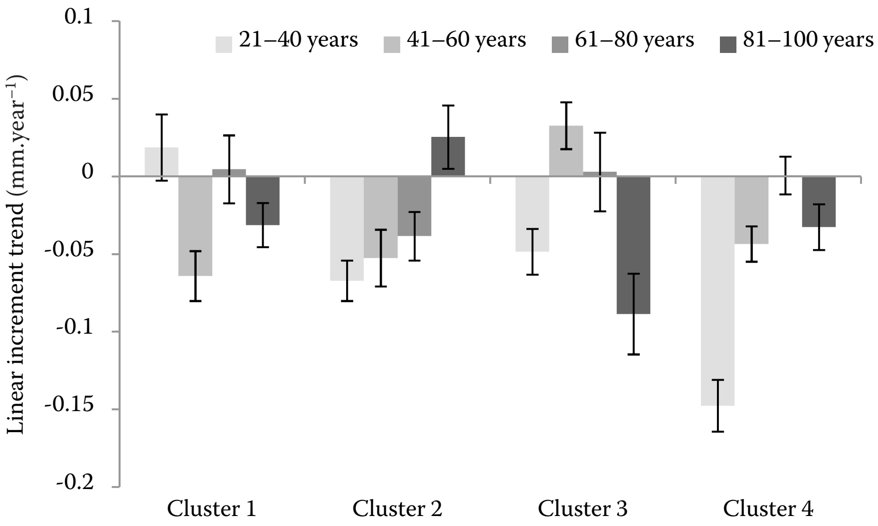

Fig. 1. Linear radial increment trends (LIT) of designed clusters according to cambial age classes (whiskers represent a 95% confidence interval)

to the late increment maximum indication due to light increment.

Standardization of incremental curves

In the text below, a graphical comparison of goodness-of-fit between particular equations for the clusters is presented.

In the case of cluster 1, exponential and Korf's equations were shown to represent the growth trend of the mean increment in the worst way, using both *MS* and *AIC* statistics. Following the *F*-test, a spline or polynomial equation tended to have the best fit, and thus they were assumed to remove the major portion of the non-climatic variance. However, using the *AIC*, the Šmelko and Burgan equation was found to be better than the spline one. Similarly, for cluster 2, Korf's and exponential function can be said to be insufficient to explain the growth trend. The best equations (according to *MS* as well as *AIC*) were Šmelko and Burgan and Hu-

Table 2. Comparison of the clusters according to selected site, stand- and tree-related parameters

Variable		Cluster 1			Cluster 2			Cluster 3			Cluster 4		
Continuous		Med.	Q10	Q90	Med.	Q10	Q90	Med.	Q10	Q90	Med.	Q10	Q90
Altitude (m a.s.l.)		1,052	730	1,175	957	785	1,114	793	760	1,125	959	775	1,117
Stand density		6	3	8	6	0	7	7	0	8	4	3	7
Tree age (years)		120	99	140	120	101	133	99	96	133	123	99	135
Relative crown length (%)		53	38	63	48	37	83	61	47	79	48	37	60
Categoric		*n*	(%)	SE	*n*	(%)	SE	*n*	(%)	SE	*n*	(%)	SE
Soil quality	Oligotrophic	11	55	± 15	5	20	± 18	8	32	± 16	13	38	± 13
	Hemioligotrophic	5	25	± 19	12	48	± 14	13	52	± 14	15	44	± 13
	Eutrophic	4	20	± 20	8	32	± 16	4	16	± 18	6	18	± 16
Vertical structure	Stand rests	1	5	± 22	4	16	± 18	3	12	± 19	0	0	–
	One-storey	15	75	± 11	21	84	± 8	10	40	± 15	32	94	± 4
	Multi-storey	4	20	± 20	0	0	–	12	48	± 14	2	6	± 17
Stand damage	Undamaged	4	20	± 20	6	24	± 17	11	44	± 15	4	12	± 16
	Moderate	10	50	± 16	12	48	± 14	9	36	± 16	11	32	± 14
	Strong	6	30	± 19	7	28	± 17	5	20	± 18	19	56	± 11
Tree status	Healthy	11	55	± 15	14	56	± 13	11	44	± 15	15	44	± 13
	Declining	9	45	± 17	11	44	± 15	14	56	± 13	19	56	± 11

Med. – median; Q10, Q90 – quantiles; *n* – sample size, % – ratio, SE – standard error

Table 3. Comparison of goodness of fit of the models inside cluster 1, 2, 3 and 4

Function	df	MS	AIC	F	p
Cluster 1					
Spline	100	215.2	930	Reference	
Polynomial	100	264.1	900	1.2272	0.1496
Šmelko-Burgan	101	289.2	908	1.3438	0.0668
Hugershoff	102	304.6	913	1.4154	0.0387
Korf	103	410.6	944	1.9080	0.0005
Exponential	103	524.9	970	2.4391	0.0000
Cluster 2					
Šmelko-Burgan	101	252.6	911	Reference	
Polynomial	100	257.0	914	1.0174	0.4655
Hugershoff	102	260.5	913	1.0313	0.4383
Spline	100	322.9	993	1.2785	0.1061
Korf	103	736.5	1,024	2.9157	0.0000
Exponential	103	1,125.0	1,070	4.4537	0.0000
Cluster 3					
Spline	100	357	984	Reference	
Polynomial	100	374.9	954	1.0506	0.4006
Šmelko-Burgan	101	489.6	982	1.3720	0.0543
Hugershoff	102	1,314.9	1,088	3.6848	0.0000
Korf	103	failed to converge			
Exponential	103	1,226.6	982	3.4374	0.0000
Cluster 4					
Hugershoff	102	1,783.3	1,121	Reference	
Polynomial	100	1,783.7	1,123	1.0002	0.4993
Šmelko-Burgan	101	2,059.7	1,137	1.1550	0.2345
Spline	100	2,235.0	1,182	1.2533	0.1253
Korf	103	2,646.8	1,163	1.4842	0.0234
Exponential	103	3,741.4	1,200	2.0980	0.0001

df – degrees of freedom; MS – mean square of residuals; AIC – value of the Akaike information criterion

gershoff equations along with the polynomial one. The growth trend in cluster 3, as represented by the mean curve, belongs to the most complicated and the functions such as exponential and Korf's ones tend to have an almost linear shape, thus supposed not to be sufficient. Cluster 4 has a similar trend like cluster 2, but with the more complicated trend at mature age, with increased increment width at the age of around 120.

As seen in Table 3, in cluster 1 the spline was chosen as a reference model with the best goodness of fit (the mean root square is 215). It is clear from the comparison of other models with the reference model based on F-test that the models including the polynomial of degree 5 and Šmelko-Burgan could be used instead of the reference model. Moreover, the comparison by means of *AIC* showed the polynomial of degree 5 as the best model fitting to cluster 1. The Hugershoff and Korf growth functions and the exponential model were not satisfactory to be used for cluster 1.

In the case of cluster 2, the model developed by Šmelko and Burgan was taken as a reference model as it provided the best fit according to both *MS* and

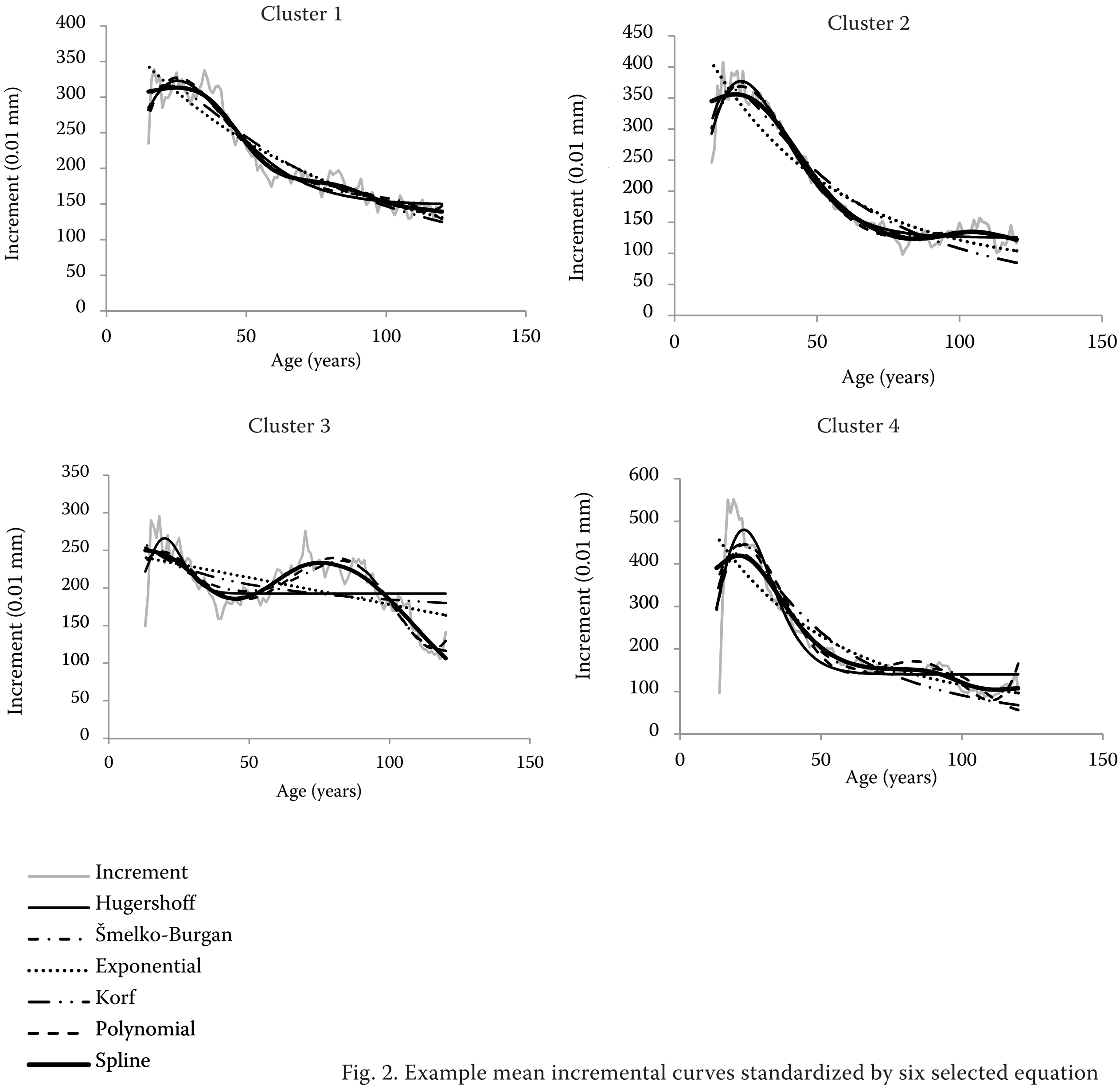

Fig. 2. Example mean incremental curves standardized by six selected equation

AIC (Table 3). The other models, which could be used instead of the reference model, are polynomial of degrees 5, Hugershoff, and spline. In contrast, unsatisfactory models are Korf's and exponential ones.

In cluster 3, similarly like in cluster 1, the spline was found to have the best goodness of fit comparing the mean square of the residuals, as it can be seen from Table 3. On the contrary, when the AIC method was used, one can see that the polynomial function provided the best fit. The spline function was shown as the third best. Among the other models, the polynomial model and that developed by Šmelko and Burgan were the only two models that could potentially be used instead. However, when compared with *AIC*, Šmelko and Burgan and exponential functions provided the second best fit. This cluster is characterized by very complex forest structures, and hence the theoretical models such as Korf and Hugershoff, and those with only two or even three regression parameters appear to fit the data very weakly. For such forests, stochastic methods seem to be better to use for detrending, because the complicated diameter growth is supposed to be the result of tree competition, and employing the known growth function is not apparently enough to maintain the low-frequency climatic signals.

The Hugershoff function was chosen as reference for cluster 4 on the basis of both *MS* and *AIC*. The models that can also be efficiently utilized for growth modelling are the polynomial of degrees 5, spline, and the function of Šmelko and Burgan.

DISCUSSION

The first objective of the paper was to describe the variability of tree-ring width patterns and to verify their expected relations mainly to various stand conditions. Considering this objective, a multifactorial statistical method, namely cluster analysis, was employed. Each tree-ring series was divided into four groups according to age. The linear increment trends within the four groups represented input variables. Similarly, Koprowski and Zielski (2006) used a hierarchical cluster analysis to distinguish regions with similar increment patterns. This method was successfully employed also by Wilson and Hopfmueller (2001 as cited in Koprowski, Zielski 2006) to distinguish groups of trees at various altitudes.

In contrast to our expectations, stand and tree related parameters did not differ substantially between the specified clusters of trees. It means that it is not possible to estimate radial increment patterns on the basis of tree and stand parameters satisfactorily. According to the results of our study, almost 50% of the markedly abnormal tree ring series having more than one local maximum (cluster 3), which are expected in multi-storied uneven-aged stand structures, belong to the trees growing in single-storied even-aged stands. Therefore, detrending functions that are able to fit abnormal and complicated incremental curves should be universally applied to ring series standardization.

Another aim of the study was to compare the ability of various increment functions to fit the different growth trends of pre-defined clusters using the least-square method. For the analysis, the following six equations were selected: Korf, Šmelko-Burgan, exponential, polynomial of degree 5, Hugershoff and cubic spline. For each cluster, the best function was determined by Fischer's *F*-test and Akaike information criterion. There exist many studies dealing with dendrochronology and the equations to be potentially used for such analyses. However, many studies focusing on tree-ring research do not analyze the particular equations and do not compare them with one another. In most methodologies, only one equation is chosen for ring-width studies without its previous evaluation. However, after a review of recently published articles dealing with tree-ring research, we can conclude that the smoothing spline method prevails. A spline provides more natural fit to the data because it operates effectively as a centrally weighted moving average of the data (Cook, Peters 1981) and in the recent tree-ring research it has been widely used as the best method (Fritts et al. 1991; Gray et al. 2004; Pérez et al. 2005; Büntgen et al. 2007; and others). As stated by Cook and Peters (1980 in Brienen and Zuidema 2005) a flexible cubic spline is the most appropriate detrending method for trees from closed-canopy stands. This could result from the fact that trees from closed-canopy stands are affected by many different factors (not only by climate), and thus to analyze only the climate influence one would need to remove signals caused by such factors from tree-ring width. For instance, Brienen Zuidema (2005) fitted cubic splines of different flexibility to remove long-term growth trends and to filter out the low-frequency variation that might be caused e.g. by canopy-dynamics. Bouriaud and Popa (2008) employed a stiff spline fit to the individual series to remove the low-frequency signal variation caused by aging. Even though the stochastic functions, such as smoothing spline or Friedman smoother, are widely used to model biological trends in tree-ring series, these curves may remove much of the climate signal at the same time, because they do not have a biological meaning (Cook, Peters 1981; Cook, Kai-riukstis 1990). As indicated by Fang et al. (2010), these stochastic approaches are more applicable to trees that experienced strong disturbance or that suffered from competition. As seen in our study, the trees that are investigated come from forests with different structure that results in different growth dynamics, thus employing the stochastic functions seems to be the most appropriate. On the contrary, Carrer and Urbinati (2006) used an exponential curve to remove the tree-ring trend in the particular series resulting from the tree circumference increasing with time. Wilson and Hopfmueller (2001) also detrended particular series with either exponential curve or regression function of any slope. Büntgen et al. (2007) used residuals from a cubic smoothing spline to remove non-climatic biological age trends. Other authors employed polynomial equations. For example, Podlaski (2002) fitted increment series of fir, beech, and pine with the fifth order polynomial regression. There are also authors who used multiphased detrending. For instance, Bijak (2010) employed two-staged detrending using the exponential curve and the linear regression function for each tree-ring width series to pronounce the climate-related high-frequency signal and to minimize the long-term age-dependent trend. However, deterministic equations such as negative exponential, linear or Hugershoff are the most appropriate for individual tree-ring series in open-canopy forests (Fritts 1976; Bräker 1981 as cited in Fang et al. 2010). From among deterministic functions, a linear or negative exponential function is less suitable for tree-ring research, since they cannot imitate the accelerated growth of tree rings close to the pith (Fang et al. 2010), thus for instance Hugers-hoff function could be used instead (Waren 1980; Bräker 1981). Fang et al. (2010) also pointed out the end-fitting problem of Hugershoff equation suggesting that the disturbances for a certain period could bias the global fitted function (also stated by Melvin 2004). In our study, the Hugershoff function showed one of the best fittings except for cluster 3, where trees experienced two maximums of growth increment, one at the growth beginning and second at the age of about 80 years. Here, the best function was shown to be a smoothing spline.

CONCLUSION

To summarize the results from our analysis, simple equations such as exponential function, which is widely used for detrending all over the world, along with Korf's function were shown to be the weakest in fitting the tree-ring series of all clusters. There are many cases when tree-ring series have more than one maximum, which is caused in many cases by thinning or other management measures and they should be removed to study low-frequency climatic signals. For such cases, the common equations such as exponential, linear, Hugershoff, Korf are not able to satisfactorily remove significant non-climatic variability. Moreover, the end-fitting problem is present when using such equations. As resulted from our study, the most appropriate deterministic function was Hugershoff function, which optimally fit the data at the pith. However, it was found inappropriate when employed for close-canopy trees that were stressed by competition or other disturbances and had more than one maximum of growth increment caused by other than climatic factors. For such tree-ring series, more flexible functions such as smoothing spline, polynomial of higher degree and that proposed by Šmelko and Burgan should be preferred to preserve the low-frequency variance caused by climate dynamics.

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