Dendrochronologia 29 (2011) 99–107

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.de/dendro

Original article

Statistical modelling and RCS detrending methods provide similar estimates of long-term trend in radial growth of common beech in north-eastern France

Jean-Daniel Bontemps [a,b,*], Jan Esper [c]

[a] AgroParisTech, ENGREF, UMR 1092 Inra/AgroParisTech Laboratoire d'Etude des Ressources Forêt-Bois (LERFoB), 14 rue Girardet, 54000 Nancy, France
[b] INRA, Centre de Nancy, UMR 1092 Inra/AgroParisTech Laboratoire d'Etude des Ressources Forêt-Bois (LERFoB), 54280 Champenoux, France
[c] Department of Geography, Johannes Gutenberg University, Becherweg 21, 55099 Mainz, Germany

ARTICLE INFO

Article history:
Received 7 April 2010
Accepted 30 September 2010

Keywords:
Growth trends
Dendrochronology
Standardisation
Statistical modelling
Fagus sylvatica

ABSTRACT

Dendrochronological methods have greatly contributed to the documentation of past long-term trends in forest growth. As these methods primarily focus on the high-frequency signals of tree ring chronologies, they require the removal of the ageing trend in tree growth, known as 'standardisation' or 'detrending', as a prerequisite to the estimation of such trends. Because the approach is sequential, it may however absorb part of the low-frequency historical signal.

In this study, we investigate the effect of a sequential and a simultaneous estimation of the ageing trend on the chronology of growth. We formerly developed a method to estimate historical changes in growth, including a careful control of site fertility in the sampling design and a simultaneous separation of the site fertility, developmental stage, and calendar year effects on growth, using a statistical modelling (SM) approach. The method has been applied to the radial growth of dominant trees in even-aged stands of common beech in north-eastern France. We compare the SM method to the regional curve standardisation (RCS) method, which is widely used in dendrochronology, and has been proven to retain more long-term signals than other detrending techniques. We also test a variant of the RCS in which the developmental stage is measured by size rather than age, as is the case in the SM approach.

The SM and RCS methods produce similar long-term chronologies, showing an increase of approximately 50% in radial growth over the 20th century and a recent decline of around 18% in magnitude. The negative bias induced by the sequential estimation of ageing and date effects on growth in the RCS is identified, but remains minor. The chronology estimated using the RCS variant (regional size curve) is lower in magnitude than that estimated using the RCS, but the difference is moderate (5%). These results highlight the conservative properties of the RCS with regard to the low-frequency historical signals in growth. They also suggest that singularly high estimates of growth trends reported in the dendrochronology literature are not method-dependent. We hypothesize that they may be caused by a negative site-age linkage in sampling designs. The decline reported for common beech in this temperate area of France is lower in magnitude than that evidenced in Mediterranean contexts.

Introduction

Since the discovery of long-term trends in forest growth (Lamarche et al., 1984), the dendrochronological approach has been a main contributor to research on this topic in temperate/boreal ecosystems (Spiecker et al., 1996; Jacoby and D'Arrigo, 1997; Esper et al., 2002; Boisvenue and Running, 2006). However, the nature of the signal extraction procedures used (Briffa et al., 1996) has questioned the reliability of radial growth chronologies.

The traditional aim of dendrochronological methods is to build annual tree-ring chronologies, either for climate reconstruction purposes in dendroclimatology or for dating and analysing disturbances and variations in the local environment in dendroecology (Fritts, 1971; Fritts and Swetnam, 1989). Because high-frequency fluctuations are of primary interest, ring chronologies must be filtered out from the negative effect of ageing (Fritts, 1976). With increasing concern about the impact of global change on forest ecosystems, growing attention has been paid to low-frequency historical trends arising in chronologies (Jacoby and D'Arrigo, 1997;

* Corresponding author at: AgroParisTech, ENGREF, UMR 1092 Inra/AgroParisTech Laboratoire d'Etude des Ressources Forêt-Bois (LERFoB), 14 rue Girardet, 54000 Nancy, France.
E-mail addresses: jean-daniel.bontemps@engref.agroparistech.fr (J.-D. Bontemps), J.Esper@geo.uni-mainz.de (J. Esper).

1125-7865/$ – see front matter © 2011 Istituto Italiano di Dendrocronologia. Published by Elsevier GmbH. All rights reserved.
doi:10.1016/j.dendro.2010.09.002

Table 1
Location, age and site conditions of the sampled common beech stands.

Stand pair	Forest	Location[a]	Stand age[b]		Site conditions				
			Oldest (years)	Youngest (years)	Elevation (m)	P[c] (mm)	T[d] (°C)	SWC[e] (mm)	pH[f]
1	Haye	6°05′E, 48°39′N	136	72	400	903	9.1	52	6.8
2	Haye	6°05′E, 48°40′N	137	66	370	893	9.1	46	6.0
3	Haye	6°07′E, 48°39′N	143	58	395	903	9.1	69	5.5
4	Sarrebourg	7°00′E, 48°44′N	109	53	325	929	8.9	141	6.4
5	Hesse	7°04′E, 48°40′N	157	63	325	998	9.1	147	4.9
6	Lemberg	7°17′E, 49°00′N	142	84	295	891	9.0	126	4.7
7	Mouterhouse	7°24′E, 49°01′N	132	53	370	921	8.8	107	4.0
8	Goendersberg	7°26′E, 49°07′N	184	47	360	853	9.2	108	4.7
9	Morimond	5°42′E, 48°03′N	124	56	440	894	9.0	140	5.0
10	La Petite Pierre	7°18′E, 48°51′N	122	39	330	885	8.8	109	4.2
11	Fislis	7°24′E, 47°31′N	169	90	480	942	9.2	141	4.7
12	Ban d'Uxegney	6°25′E, 48°10′N	122	75	405	1105	8.9	121	4.3
13	Sainte Hélène	6°39′E, 48°19′N	131	65	340	933	9.2	121	4.6
14	Fraize	6°24′E, 48°21′N	153	84	365	951	9.0	117	4.2
Mean			140.1	64.6	370	928	9.0	110	5.0
Standard deviation			20.2	15.0	50	62	0.1	33	0.9

[a] Mean coordinates of the paired plots (European datum 50 system).
[b] At 0.30 m height in 1998.
[c] Mean annual precipitation (1961–1990).
[d] Mean annual temperature.
[e] Soil water capacity at 1-m depth.
[f] pH of the first mineral soil horizon.

Boisvenue and Running, 2006). The dendrochronological approach has thus been applied as a method to separate ageing and historical trends in tree growth (Becker et al., 1995; Spiecker et al., 1996; Jacoby and D'Arrigo, 1997). While statistical methods are relevant for addressing confounding of factors, dendrochronological methods sequentially estimate the effects of age and date on growth. The effect of age is first estimated and then removed from ring size in a 'detrending' or 'standardisation' phase (Cook and Kairiukstis, 1990). In such a sequential procedure, the estimation of the age effect can absorb part of the low-frequency historical trend recorded in tree rings, and reduce its magnitude in the final chronologies. When these trends are positive (as most often encountered to date; Boisvenue and Running, 2006) the negative ageing trend will be estimated at a magnitude lower than it is in reality, and will result in a potential negative bias in these historical trends (Fritts, 1976; Briffa et al., 1996; Briffa and Melvin, 2008). Among other methods, the regional curve standardisation (RCS) method (Becker, 1989; Briffa et al., 1992) is known to retain more long-term trends than tree-level standardisation techniques (Fritts, 1976) and has been intensively used to detect growth changes (Boisvenue and Running, 2006). The implementation of simultaneous signal separation methods such as the analysis of variance has been suggested (Dupouey et al., 1992), but this method applies at a low resolution (age and date classes are required) and has been scarcely used (Bergès et al., 2000). The magnitude of the potential bias due to sequential estimation of age and historical trends in dendrochronological methods thus remains unknown.

We previously addressed the issue of changes in forest growth through a modelling case study on even-aged stands of common beech (*Fagus sylvatica* L.) in north-eastern France (Bontemps et al., 2009, 2010). Measuring historical growth variations in that species is of particular interest because common beech has been shown to experience recent climate-driven decline in both Mediterranean (Jump et al., 2006; Piovesan et al., 2008) and temperate (Charru et al., 2010) contexts, following decades of increases (Badeau et al., 1995; Bontemps et al., 2009). How severe is this decline, relative to previous periods, and to what extend is the decline method-dependent are crucial issues. In our study, we applied the paired-plots sampling method (Untheim, 1996) to accurately separate the effects of date and ageing on growth and control site fertility. It is based on the comparison of growth in pairs of young/old stands located at the same sites. The effects of site, developmental stage and calendar year were simultaneously estimated using a statistical modelling (SM) approach. For the dynamic interpretation of trends, the developmental stage was represented by size (Bontemps et al., 2009). The radial growth of dominant trees at breast height revealed a 50% increase in growth rate over the 20th century (Bontemps et al., 2010). Because the sampling was specifically designed to separate ageing and historical trends and the estimation method minimizes confounding problems, this chronology was considered to be a reliable baseline.

The first objective of the analysis was to study the impact of a sequential extraction of the effects of ageing and date on the final tree-ring chronology and on the magnitude of its variations, by applying the RCS detrending method. Because the SM and RCS methods also differ in the proxy used for the developmental stage – size or age – a second objective was to assess the impact of the age/size substitution in the standardisation phase of the RCS. We thus applied a variant of the method where the developmental stage is represented by size.

Materials

We sampled pure and even-aged stands of common beech (*F. sylvatica* L.) in north-eastern France (semi-continental range). These stands are attested to have been managed as high forests since their origin (Hüffel, 1926). They were sampled in State forests to grant management continuity through time. Thinning operations in these forests are acknowledged to have been traditionally moderate (Polge, 1981).

The sampling relied on 14 pairs of young/old neighbouring stands (Untheim, 1996) chosen for granting comparable site fertility conditions across generations. The procedure included control of topography, parent rock, soil texture and stoniness, and humus forms. The site conditions were further assessed from the measurement of environmental indicators, based on belowground vegetation and soil analyses (pH, cation exchange capacity, C:N ratio, phosphorus content, and soil water capacity or SWC). The average within-pair distance was 160 m. The older stand generation was on average 140.1 years old (SD: 20.2 years). The younger one was on average 64.6 years old (SD: 15.0 years). Systematic between-generation differences in environmental indicators were screened using paired *t*-tests. They confirmed the accuracy of the sample (Bontemps et al., 2009). Details regarding the location, age, and site conditions of the sampled stands are listed in Table 1. Stands were located at elevations of between 295 and 480 m. The precipitation (period: 1961–1990) was 928 mm on average, and the mean annual temperature was 9.0 °C. Both showed restricted variations over the sample. Soil types encompassed in the sample included brown soils of moderate depth on calcareous rock in pairs 1–4 (pH > 5.5, low SWC), thick acidic sandy soils on sandstones in pairs 6, 7 and 10 (pH < 4.7, moderate SWC), and thick brown soils in the other pairs (pH between 4.2 and 5.0, SWC moderate to high).

Dominant trees were defined as the 100 largest-diameter trees at a height of 1.30 m per hectare. Accordingly, three dominant trees per stand were sampled in 0.06-ha circular plots, following the Duplat and Tran-Ha (1997) protocol. Tree-ring measurements were taken on stem disks sampled at a height of 1.30 m. On each disk, measurements of ring widths were performed to the nearest 1/100 mm using a digital positiometer and were repeated along four orthogonal radii distributed from a random primer direction. Ring series were cross-dated after the identification of pointer years. The mean of the four ring width series available for each tree was first computed. As the purpose was the analysis of the radial growth of dominant trees, a raw mean growth chronology was computed for each stand, providing an estimate of the annual growth rate in dominant radius (corresponding to the dominant ring width, or RW_0). In total, 2379 annual increments arising from the 28 stands were available. The tree-ring series are shown against cambial age, size, and calendar year in Fig. 1.

Methods

Statistical modelling approach (SM)

The model was elaborated and fitted in Bontemps et al. (2010).

Model structure and functional expression

The dominant radius and ring width were denoted by R_0 and RW_0, respectively. The radial growth rate of the dominant trees was written as a multiplicative composition of the developmental stage, site and date effects. It was basically modelled by a growth equation (f_1) accounting for the effect of developmental stage represented by size R_0, and the effect of site represented by a single parameter S. This parameter was identified with the multiplicative scale parameter of the equation. The effect of calendar year was expressed as a function f_2 of time measured from a base date (t_b) and introduced in the model as a multiplier of the site parameter (a particular value S_b of S is observed at date t_b). The radial growth rate was approximated as the annual ring width. The model is expressed as follows:

$$RW_0(t) = f_2(t - t_b) S_b f_1(R_0(t-1)) \quad (1)$$

where $f_2(t_b) = 1$.

Because the radial growth series exhibited a maximum followed by a decreasing but non-asymptotic pattern (Fig. 1), we represented the effect of developmental stage by a non-asymptotic sigmoid growth curve. The corresponding growth equation was parameterised to identify the vertical scale parameter as the maximum growth rate (S_b) and the horizontal scale parameter as the radius of the maximum growth rate (K). Its expression is as follows:

$$RW_0 = S_b f_1(R_0) = \frac{S_b (R_0/K)^m}{(1 - m + m(R_0/K))} \quad \text{with } m < 1 \quad (2)$$

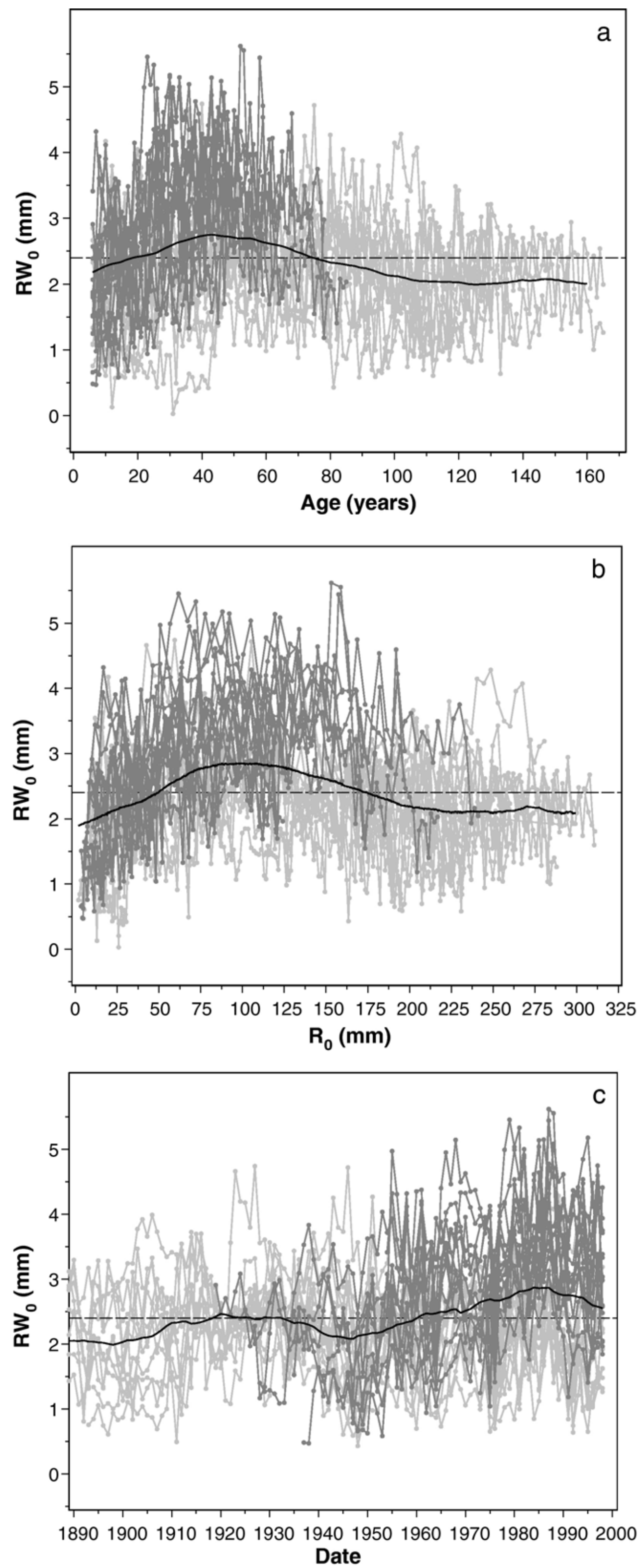

Fig. 1. Raw tree-ring width (RW_0) chronologies at breast height from dominant trees of pure and even-aged stands of *Fagus sylvatica* L. in north-eastern France against: (a) cambial age, (b) size (dominant radius R_0), (c) calendar year. Light grey: old stand generation, dark grey: young stand generation. Data were smoothed (black line) by moving averages over a 20-year or 50-mm range. The reference line indicates the mean tree ring width over the dataset (2.4 mm).

where S_b is the maximal growth rate (mm/year), K is the radius (mm) at which S_b is observed, and m is a shape parameter (dimensionless).

The effect of calendar year (f_2) was represented by a cubic spline function with equally spaced nodes using a 15-year internode and with t_b = 1900. The vector of the spline parameters was denoted by θ.

Statistical methodology

The data are longitudinal and are organized according to two nested levels corresponding to stand pairs and stands within pairs (hereafter denoted by levels 1 and 2). Accordingly, the models were fitted using hierarchical non-linear mixed-effects models (Lindström and Bates, 1990) fitted by maximum likelihood. S_b was found to vary between stand pairs (level 1). K was found to vary at level 2, with a systematically lower value for the younger generation. The residual variance was modelled as a power function of the expected increment. The statistical expression of the model is given in Eq. (3):

$$RW_0(t) = f_2(t - t_b, \theta) S_b f_1(R_0(t-1), K, m) + \varepsilon_t \quad (3)$$

with

$$S_b \sim N(S_{b0}, \sigma_{S_b,1}),\ K \sim N(K_0, \sigma_{K,2}),\ \varepsilon_t \sim N(0, V(\varepsilon_t)),\ V(\varepsilon_t) = \sigma^2 RW_0(t)^{2\lambda}$$

where λ is the power for the residual variance function, S_b and K are considered random parameters with Gaussian distribution, and $\sigma_{S_b,1}$ and $\sigma_{K,2}$ are their standard deviations, at levels 1 and 2, respectively. $S_{b0}, K_0, m, \theta, \sigma_{S_b,1}, \sigma_{K,2}, \sigma$, and λ are fixed parameters. The model parameter estimates are listed in Table 2 of Bontemps et al. (2010).

Regional curve standardisation approach (RCS)

Principle

The RCS technique (Erlandsson, 1936) is described in Becker (1989) and has been named as RCS since Briffa et al. (1992). The basic principle of standardisation techniques is to remove age-related signals in growth series to obtain a bias-free chronology (Cook and Kairiukstis, 1990). Standardisation is achieved by dividing the size of each available ring by the value expected from its cambial age in a reference curve. Such a curve can be estimated either by fitting smoother functions to individual growth series against cambial age or – as is the case in the RCS – by averaging all individual series of a sample according to cambial age and smoothing this mean curve. This curve is typically deemed the 'regional curve' (RC). Because rings averaged at each cambial age refer to different dates, the RC usually shows strong regularity (Becker, 1989; Esper et al., 2002). The RCS method has been reported to retain more low-frequency signals than methods based on individual-tree detrending (Becker, 1989; Briffa et al., 1992; Esper et al., 2002; Melvin and Briffa, 2008).

Computations and chronology estimation

The RCS methodology was applied to the dominant radial growth series. For each ring, the cambial age i is denoted by a_i with $a_i \in [1, a_{\max}]$, where $a_{\max}$ is the maximum cambial age over the dataset. The calendar year j is denoted by t_j with $t_j \in [t_{\min}, t_{\max}]$, the year range of the dataset. The number of rings available at age a_i and date t_j is denoted by n_{ij}. Ring widths at age a_i and year t_j are denoted by $RW_0\ (a_i, t_j)$ and are further indexed by $k \in [1, n_{ij}]$ when $n_{ij} > 1$.

The RC was calculated for all a_i as:

$$\overline{RW}_0(a_i) = \frac{\sum_{j=t_{\min}}^{t_{\max}} \sum_{k=1}^{n_{ij}} RW_{0,k}(a_i, t_j)}{\sum_{j=t_{\min}}^{t_{\max}} n_{ij}} \quad (5)$$

The RC was smoothed (denoted by $\overline{\overline{RW}}_0$) using a polynomial function fitted by ordinary least squares. A polynomial of degree 4 was selected from successive F-tests for nested model comparison (Seber and Lee, 2003). Each ring $RW_0\ (a_i, t_j)$ was then standardised to a growth index $I_0\ (a_i, t_j)$ using Eq. (6):

$$I_0(a_i, t_j) = \frac{RW_0(a_i, t_j)}{\overline{\overline{RW}}_0(a_i)} \quad (6)$$

The RCS chronology was finally obtained by averaging growth indexes at each calendar year t_j:

$$\overline{I_0}(t_j)_{age} = \frac{\sum_{i=1}^{a_{\max}} \sum_{k=1}^{n_{ij}} I_{0,k}(a_i, t_j)}{\sum_{i=1}^{a_{\max}} n_{ij}} \quad (7)$$

Variant based on regional size curve

All the notations are the same except for R_0, which varies in $[R_{0\,\min}, R_{0\,\max}]$ (minimum and maximum dominant radius over the sample). Because the dominant radius is a continuous variable, the RC was directly estimated from a polynomial fit of ring widths against dominant radii ($\overline{\overline{RW}}_0(R_0)$). Based on the same nested model comparison procedure, a polynomial of degree 4 was selected and ring widths were detrended using:

$$I_0(R_0, t_j) = \frac{RW_0(R_0, t_j)}{\overline{\overline{RW}}_0(R_0)} \quad (8)$$

The regional chronology was calculated as the average of growth indexes at each calendar year:

$$\overline{I_0}\left(t_j\right)_{size} = \frac{\sum_{i=R_{0\min}}^{R_0} \sum_{k=1}^{n_{ij}} I_{0,k}(R_0, t_j)}{\sum_{i=R_{0\min}}^{R_0} n_{ij}} \quad (9)$$

To facilitate the comparison between the different methods, the annually resolved RCS chronologies were smoothed using a non-parametric local cubic spline. Finally, to express the evolution in growth relative to the same reference year (taken as 1900) as in the modelling approach, the RCS chronologies were adjusted to the 1900 level of the applied cubic-spline smoothers.

In the following section, all reported trends and their differences are thus measured on a relative scale with the value 1 in 1900 and can be equivalently expressed in percentages of variation since that date.

Results

RCS chronology estimate

The RCS chronology estimate is shown in Fig. 2. A progressive increase in radial growth rate is evident. The first peak is observed in the 1920s at a level of +25%. The maximum level of increase was a rise of 49% in the mid 1980s, relative to 1900. The period 1950–1990 is reported to be very favourable to radial growth. The average increase over the 20th century is 26.0%. The long-term trend reveals medium-term variations including reductions in the 1940s and 1990s, where it reduces to a level of +13% and +32%, respectively. These periods include singular successions of years showing low levels of growth. The RCS chronology also confirms the large amplitude of inter-annual growth variations. Some years reveal especially strong negative deviations (the most severe being 1921, 1947–1949, 1964, and 1976).

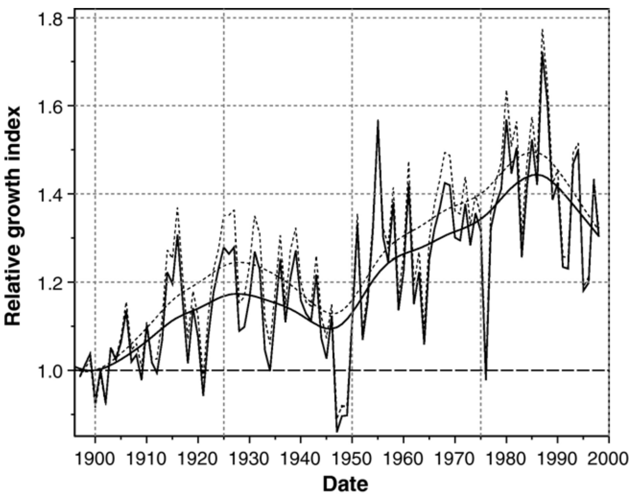

Fig. 2. Comparison of radial growth chronologies estimated by the RCS method and the RCS variant (based on a regional size curve). Both chronologies were smoothed using a cubic spline smoother. Full lines: RCS chronology based on the regional size curve, dotted lines: RCS chronology based on the regional age curve.

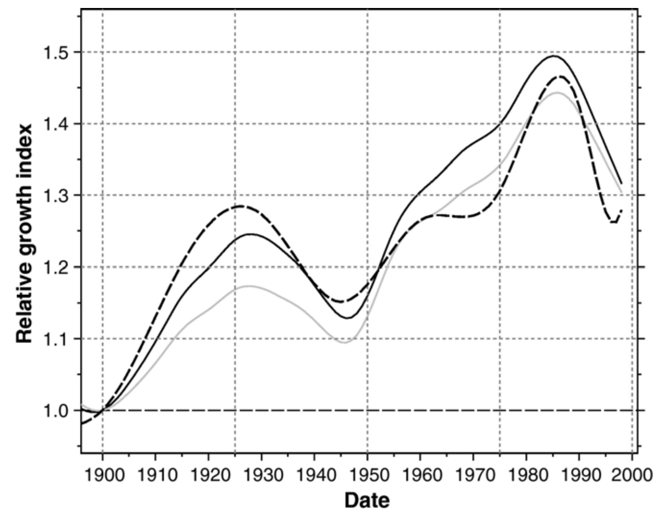

Fig. 3. Comparison of radial growth chronologies estimated by the RCS (regional curve standardisation) and SM (statistical modelling) methods. Full black line: RCS chronology based on the regional age curve. Dotted black line: SM chronology. Full grey line: RCS variant chronology based on the regional size curve. The RCS chronologies were standardised according to the smoother estimates of 1900, for comparison with the SM chronology.

RCS variant based on regional size curve and comparison with the RCS chronology

The RCS variant chronology is shown in Fig. 2. The annual and medium-term variations depicted in this chronology are identical to those of the standard RCS. The maximum level of growth is again recorded in the mid 1980s at a level of 44%, close to that depicted in the standard RCS. However, the RCS variant is found to produce a systematically lower estimate of the long-term trend across calendar years. The difference is greatest around the peaks of the increases in the 1920s (−7%) and in the 1960–1980s (−6%) and reaches a minimum −2.8% in the 1950s. Over the 20th century, the average increase is 4.4% below the standard RCS estimate (+21.6%).

Comparison of SM and RCS chronology estimates

The comparison of SM and standard RCS chronologies is shown in Fig. 3. The SM and RCS chronologies were very similar, in both the course and amplitude of past variations. The difference in the 20th century average trend is below 2% (+24.7% for the SM chronology). At their maximum level in the 1980s, the difference is only 3% (SM: +47%, RCS: +49%). The greatest difference is observed in the 1970s when the standard RCS trend denotes a less marked growth reduction during that decade. Noticeably, the order relationship between the two chronologies swaps between the first and second halves of the century (level of +25% for the peak in the 1920s in the SM approach), indicating a slightly higher mean trend in the RCS chronology.

The comparison between the RCS variant and SM chronologies (Fig. 3) reveals similar patterns, with a closer fit than between the standard RCS and SM records. However, the RCS variant chronology falls noticeably below the SM record in the first half of the century, with values up to −12% in the 1920s. The average growth trend over the 20th century is 3% below that of the SM chronology.

Discussion

RCS detrending has been applied for the analysis of long-term trends in forest growth. The estimation of trend magnitude leans on specific working assumptions of the method: (i) the estimation of the developmental stage and calendar year effects on growth is sequential, and not simultaneous as in a statistical approach. (ii) The developmental stage is measured by the cambial age of the rings and not by tree size. When growth is affected by a long-term trend, trees of a given age show different sizes in time. Tree size may therefore be more accurate than age for measuring the developmental stage. We tested the following hypotheses related to these assumptions: (i) the prior removal of developmental stage may absorb part of the long-term trend. This hypothesis was tested by a comparison with a statistical model applied to the same sample, where ageing and historical effects are estimated simultaneously. (ii) The trend is influenced by the proxy used for measuring the tree developmental stage (age or size). This hypothesis was tested by implementing a variant of the RCS method where the developmental stage is substituted by size. This variant was also required to compare the RCS and SM approaches on the basis of a unique proxy for the ageing trend.

Effect of developmental stage proxy: comparison of standard RCS and RCS variant

The standard RCS and RCS variant chronologies displayed very similar variations through the 20th century. The RCS variant also produced a systematically lower trend (Fig. 2). The magnitude of the difference varied between 3 and 7% (mean for RCS trend: +26.0%, for RCS variant: +21.6%).

Our interpretation of the difference is as follows. An increase in growth implies that larger tree sizes are attained within a given period of time. When growth increments are expressed as a function of size, growth-size curves of the young trees are thus expanded to the right, relative to those of the older trees. This expansion effect does not occur when increments are expressed as a function of age (see Fig. 1a and b). Because the increments increase with developmental stage in the younger tree generation (Fig. 1), the expansion effect brings the growth-size curves of the two tree generations closer than in a comparison at a constant age. The growth trend estimate is thus of lower magnitude when standardisation is based on the size – rather than the age – curve. A mathematical interpretation of this age/size substitution effect is provided in Appendix A.

In our view, there are two reasons why the use of size instead of age for measuring developmental stage should be preferred. First, a number of papers have demonstrated a direct size-dependence of metabolic processes associated with tree growth (Shinozaki et al., 1964; Valentine, 1985; Ryan et al., 1997; West et al., 2001), whereas there is poor evidence of true ageing processes in tree species (Thomas, 2002). Second, the growth trend can be interpreted as a contraction of the time period required to reach a given dimension when growth is compared at constant size (Bontemps et al., 2009), which is crucial for forest planning. This is not true for a comparison at a constant age, associated with sizes that differ in time, with no direct interpretation.

Effect of sequential estimation: comparison of RCS variant and SM methods

Because the size-for-age substitution impacts the trend retained in the RCS approaches, we discuss the comparison of the RCS variant and the SM chronologies. The prior removal of developmental stage was hypothesized to capture some of the long-term trend (Fritts, 1976). Our results (Fig. 3) suggest that this hypothesis is only partially true for this current sampling. The RCS variant chronology falls below the SM chronology over the first half of the study period, but the records become closer over the following period and culminate at a similar level. Over the century, the mean trend of the RCS variant is 3.1% below the SM mean trend (+21.6%/+24.7%). The present study shows that the sequential extraction of the effects negatively impacts the magnitude of trend, but the effect remains moderate. Very similar decennial variations in growth rate are also depicted in the two methods.

The first interpretation of this finding is related to the structure of retrospective sampling designs. The regional curve is calculated as an average over all trees, both young and old individuals. Therefore, when a positive trend affects tree-rings, the regional curve is overestimated in the older trees and underestimated in the younger ones. In retrospective sampling designs, the proportion of old tree rings increases when moving back in time. In contrast, the recent period is equally covered by young and old tree rings. While growth indexes might be underestimated for remote periods, biases in the estimate of the size effect may somehow compensate over generations for a recent period. The definition of this ‘recent period’ depends on the age range covered by the younger available trees. The second interpretation lies in the uniqueness of the standardisation curve in the RCS. The RC estimation requires a matching of all tree-ring series by age (or size), resulting in a chronological misalignment of rings (Cook and Kairiukstis, 1990). As soon as the sampled trees offer a significant range of ages (or sizes), decennial variations in the growth rate (Fig. 2) cannot be captured by the RC average. This conservative property of the RCS method with regard to the historical signal does not hold true in tree-based standardisation methods (Fritts, 1976). However, it requires that a wide range of tree ages be sampled.

Statistical modelling or RCS method: which method to use?

The RCS method is a filtering method used to estimate growth chronologies (Fritts, 1971) and it is not intended for the study of ageing processes in growth. The statistical modelling (SM) method is aimed at describing and quantifying growth patterns (Pretzsch et al., 2008) and it has been extended to perform the estimation of long-term trends (Elfving and Tegnhammar, 1996). Because both methods are used for such estimations, the question arises as to which one to choose.

First, the RCS methodology is a heuristic method of estimation, not a method based on a fitting criterion. It consists of a sequential non-parametric estimate of the effects of age and calendar year. To avoid possible biases in the chronologies due to this sequential procedure, a ‘signal-free’ RCS methodology has recently been proposed (Melvin and Briffa, 2008). This relies on an iterative estimation of the age curve and the growth index chronology. However, the simultaneous separation of factors, based on a fitting criterion, is precisely the aim of statistical methods (the maximum likelihood or least squares criteria require the solving of a system of simultaneous equations in the model parameters). It allows an estimation of the trend conditional on other effects, *i.e.* “other things being equal”. Second, the statistical approach requires the formulation of a model. Assumptions relative to the expression and articulation of the different effects are explicit. The interpretation of the trend can thus be discussed with respect to the model expression, which is more ambiguous in the RCS approach. As an illustration, the effects of size and date in the SM approach (Eq. (1)) are clearly assumed to be multiplicative. Eqs. (8) and (9) in the RCS method suggest that the combination of these effects is not far from being multiplicative, but how far remains unknown. Finally, no inference in a statistical sense is made possible when applying the RCS. In our modelling approach (Bontemps et al., 2010), statistical inference made it possible in particular, to decide which growth equation best described the ageing effect, to identify a significant divergence between young and old trees at a recent period, and to derive a confidence interval for the long-term trend, based on the properties of parameter estimators. However, the SM approach implementation is less straightforward, and is of limited interest for fast exploratory analyses.

We sampled stands of restricted ages, managed as even-aged high forests since their origin, with moderate interventions (Polge, 1981). Accordingly, the observed ageing trends in growth chronologies were found to be regular and fairly homogenous over the sample (Fig. 1). They did not challenge the estimation of the regional age curve (RCS) and required reasonable assumptions in the modelling approach (Bontemps et al., 2010). In more natural old-growth forest ecosystems, disturbances and episodes of stand closure result in release/suppression phases in rings of surviving trees (Devall et al., 1998; di Filippo et al., 2007). The RCS originally foresees the combining of data from a larger number of trees in which presumed disturbance events do not occur synchronously. Here again, the averaging process greatly attenuates the impact of isolated disturbances (Cook and Kairiukstis, 1990). The regional curve may, however, remain uncertain in the late-growth domain, as replication of very old trees is often low (Briffa and Melvin, 2008). The modelling approach can be extended to any set of growth chronologies as long as some common ageing pattern can be identified and can be accurately described by a mathematical function (f_1 in Eq. (1) can be replaced by any appropriate function). The minimum assumption of a decreasing ageing trend remains plausible even in old-growth forest trees facing disturbances (Fritts, 1976, chapter 6; Devall et al., 1998). Other general models that capture successions of suppression-release phases in tree-ring chronologies have also been formulated (Warren, 1980).

Role of sampling designs in growth trend studies

Our results show that there is no major impact of the signal extraction method used (RCS or SM) on the magnitude of the trend. In addition, the reported trend shows an increase of around 50%, which is half as much as reported in Badeau et al. (1995) applying the RCS to data from the same species, forest structure and area (increase >100% over 1900–1990). In the dendroecology literature, recurrent high (and sometimes seemingly excessive) estimates for long-term trends have been reported. For example, a 100% increase over the 20th century was found in Lamarche et al. (1984), Schadauer (1996), Rathgeber et al. (1999), and Vejpustkova et al. (2004), while increases up to 200–300% have also been reported (Becker et al., 1995). Our comparison suggests that no bias in the RCS is likely to amplify the reported trend. Our estimate was obtained from a sampling design intended to carefully balance site and age dimensions. In addition, studies on permanent plot designs (Eriksson and Johansson, 1993; Elfving and Tegnhammar, 1996; Dhôte and Hervé, 2000) and dendrochronology studies including a careful control of site conditions (Szeicz, 1997; Bergès et al., 2000; Podlaski, 2002) have reported trends that are around 40–50% in magnitude. We therefore hypothesize that some of the reported estimates may result from imbalances in sampling designs.

Sampling campaigns oriented towards growth trend analysis require that a wide range of tree ages be considered and that age and site fertility be balanced (Spiecker, 1999). However, the control of site conditions is explicit in only a few of the aforementioned studies (prior age/site balance in the sampling in Szeicz, 1997; Podlaski, 2002; or posterior control of designs in Bergès et al., 2000). Rather, a recurrent and pragmatic approach relies on building wide samples over a regional or national forest resource (Hornbeck et al., 1988; Schadauer, 1996; Becker et al., 1995), in which age classes and site conditions are assumed to balance. In managed forests, however, the older stands are often located in less fertile conditions, where harvesting is postponed (Badeau et al., 1995; Becker et al., 1995; Piovesan et al., 2008), resulting in a possibly positive artifact in the magnitude of growth trends. This site-age linkage may even be valid in natural forests, as evidence for a growth rate-longevity trade-off has also been reported (Peñuelas, 2005). The *sampling design* hypothesis has been poorly addressed. Using a dendrochronological approach, Bert and Becker (1990) sampled several hundred trees to cover the regional variability in site conditions of silver fir in the Jura Mountains. Interestingly, they showed that 50% of the initial trend was removed when a posterior stratification of site fertility was applied (Becker et al., 1995).

Prior control of age-site balance in sampling designs remains crucial when the purpose is to diagnose growth trends, in the field of dendroecology. The paired-plots sampling, as applied here, offers a way to control the balance of these factors. When plots are sampled without a specific control of site conditions, the collection of environmental information related to these plots is fundamental for posterior resampling.

Conclusion

It was shown that: (i) the sequential estimate of the regional curve (RC) and the historical chronology in the RCS method has a negative impact on the long-term trend retained in detrended chronologies; (ii) the use of age instead of size as a proxy for developmental stage in the RC computation increases the magnitude of the retained trend. Because these effects are opposed, the similarity between the standard RCS and the statistical modelling (SM) chronologies was partially inflated. Nevertheless, these effects are quantitatively moderate, and the chronologies developed with the RCS or the SM methods are found to be in good agreement over this site-age balanced design. Our results point towards the conservative nature of the RCS with respect to low-frequency historical signals in growth. Also, while the RCS method is easier to implement, the SM approach provides a more interpretable signal and should be preferred in the specific context of the assessment of growth trends. Regional curves based on cambial age or tree size were equally easy to implement, and size constitutes a better proxy for developmental stage when tree growth is affected by a long-term trend.

As an outcome of this comparative study, we hypothesize that high trend estimates from some previous dendrochronological studies are related to negative age-site biases in sampling designs. Therefore, the careful control and presentation of these sampling designs remains a crucial need in such studies. The decline in the growth of common beech has been observed since 1985, and it reaches a magnitude of – 35% (RCS) and – 40% (SM) relative to that date. The end-20th century level of growth is close to that of the 1960s. This decline is therefore less acute than that evident in Mediterranean contexts (Jump et al., 2006; Piovesan et al., 2008).

Acknowledgements

We thank the French Ministry for Forests, Agriculture and Fisheries for providing funding to the present study. We also wish to thank Jean-Christophe Hervé and Laurent Bergès for fruitful discussions on the RCS approach in the years 2001–2002, and the two anonymous reviewers for their appropriate comments.

Appendix A. Effect of proxy selected for tree developmental stage (size or age) on the magnitude of growth trend

The radial growth increment ΔR is considered to be dependent on the permanent site conditions (S), developmental stage, and calendar year. Stand density is omitted. The growth trend is estimated by comparing increments in trees of the same developmental stage, growing at different dates, which is achieved by removing the ageing trend in tree rings. We compare the magnitude of these trends when cambial age or size (R) is chosen as a proxy for the developmental stage.

A.1. Comparison of growth increments at a constant cambial age

When the environment is stationary, the increment is written:

$$\Delta R = f_0(S) * f_1(\text{age}) \tag{A.1}$$

where f_0 and f_1 are the effects of site and age. S is a constant indicating the site conditions. Here and in the following, "*" indicates an operation that respects the sign of the function effects on ΔR (for instance multiplicative in the formulation of Eq. (1)). We now consider a particular cambial age a_0 for the comparison:

$$\Delta R = f_0(S) * f_1(a_0) \tag{A.2}$$

When the environment is non-stationary and positive growth trends are induced, a function of calendar year f_2 is introduced in (A.2), corresponding to the modification of site conditions:

$$\Delta R = f_0(S) * f_1(a_0) * f_2(\text{date}) \tag{A.3}$$

where f_2 is an increasing function of date.

A.2. Comparison of growth increments at a constant size

We consider the size-age relationship $R = f_R$ (age) that applies in a *stationary environment*. The specific size R_0 is reached at the cambial age a_0:

$$R_0 = f_R(a_0) \tag{A.4}$$

The function f_R is a strictly increasing function of age, and we may write:

$$a_0 = f_R^{-1}(R_0) \tag{A.5}$$

In order to express growth as a function of size, Eq. (A.2) is thus rewritten as:

$$\Delta R = f_0(S) * f_1(f_R^{-1}(R_0)) \tag{A.6}$$

We introduce $F_1 = f_1 \circ f_R^{-1}$ and simplify Eq. (A.6) as:

$$\Delta R = f_0(S) * F_1(R_0) \quad (A.7)$$

When the environment is non-stationary and positive growth trends are induced, a function of calendar year f_2 is introduced in Eqs. (A.6/A.7). *As a main difference, the size–age relationship (A.4) is also affected by a positive shift ($f'_R > f_R$) or say equivalently, a higher size R'_0 is reached at the same age a_0.* Eq. (A.7) is thus rewritten as:

$$\Delta R = f_0(S) * F_1(R'_0) * f'_2(\text{date}) \quad (A.8)$$

with

$$R'_0 = f'_R(a_0) > R_0 \quad (A.9)$$

Because f_R is a strictly increasing function of age, we may find $\Delta > 0$ such that:

$$f'_R(a_0) = f_R(a_0 + \Delta) \quad (A.10)$$

From Eqs. (A.8)–(A.10), we thus have:

$$\Delta R = f_0(S) * F_1(f_R(a_0 + \Delta)) * f'_2(\text{date}) \quad (A.11)$$

And because $F_1 = f_1 \circ f_R^{-1}$:

$$\Delta R = f_0(S) * f_1(a_0 + \Delta) * f'_2(\text{date}) \quad (A.12)$$

The comparison of f_2 and f'_2 (Eq. (A.3) and (A.12)) depends on the variations of f_1 with age (ageing effect on growth).

A.3. Comparison of age- and size-related historical trends f_2 and f'_2

Usually, f_1 is a function with a maximum, increasing at early developmental stage and decreasing over the remainder of the tree lifespan. Because the decreasing phase is not observed in the younger tree generation of our sample (Fig. 1), the comparison of growth is established over stages where f_1 is predominantly an increasing function of age. Thus we have:

$$f_1(\text{age} + \Delta) > f_1(\text{age}) \quad (A.13)$$

By equating Eqs. (A.3) and (A.12) using (A.13), we deduce that:

$$f'_2 < f_2$$

A.4. Conclusion

The estimate of growth trend based on a growth comparison at constant size is lower than that based on a comparison at constant age if the growth phase compared across tree generations in the sample exhibits a positive pattern with the developmental stage (as in the case of the present study). The contrary would be true if the growth phase compared decreases across the developmental stage. No immediate conclusion could be drawn if both increasing and decreasing phases were represented in the younger generation of trees sampled.

References

Badeau, V., Dupouey, J.-L., Becker, M., Picard, J.-F., 1995. Long-term growth trends of *Fagus sylvatica* L. in north-eastern France. A comparison between high and low density stands. Acta Oecologica 16, 571–583.

Bert, G.D., Becker, M., 1990. Vitalité actuelle et passée du sapin (Abies alba Mill) dans le Jura, Etude dendroécologique. Annals of Forest Science 47, 395–412.

Becker, M., 1989. The role of climate on present and past vitality of silver fir forests in the Vosges mountains of northeastern France. Canadian Journal of Forest Research 19, 1110–1117.

Becker, M., Bert, G.D., Bouchon, J., Dupouey, J.-L., Picard, J.-F., Ulrich, E., 1995. Long-term changes in forest productivity in northeastern France: the dendrocological approach. In: Landmann, G., Bonneau, M. (Eds.), Forest Decline and Atmospheric Deposition Effects in the French Mountains. Springer, Berlin, Heidelberg, New York, pp. 143–156.

Bergès, L., Dupouey, J.-L., Franc, A., 2000. Long-term changes in wood density and radial growth of Quercus petraea Liebl. in northern France since the middle of the nineteenth century. Trees 14, 398–408.

Boisvenue, C., Running, S.W., 2006. Impacts of climate change on natural forest productivity—evidence since the middle of the 20th century. Global Change Biology 12, 862–882.

Bontemps, J.-D., Hervé, J.-C., Dhôte, J.-F., 2009. Long-term changes in forest productivity: a consistent assessment in even-aged stands. Forest Science 55, 549–564.

Bontemps, J.-D., Hervé, J.-C., Dhôte, J.-F., 2010. Dominant radial and height growth reveal comparable historical variations for common beech in north-eastern France. Forest Ecology and Management 259, 1455–1463.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlen, W., Zetterberg, P., Eronen, M., 1992. Fennoscandian summers from AD 500—temperature changes on short and long time scales. Climate Dynamics 7, 111–119.

Briffa, K.R., Jones, P.D., Schweingruber, F.H., Karlén, W., Shiyatov, S.G., 1996. Tree ring variables as proxy-climate indicators: problems with low-frequency signals. In: Jones, P.D., Bradley, R.S., Jouzel, J. (Eds.), Climate Variations and Forcing Mechanisms of the Last 2000 Years. Springer, Berlin, pp. 9–41.

Briffa, K.R., Melvin, T.M., 2008. A closer look at Regional Curve Standardization of tree-ring records: justification of the need, a warning of some pitfalls, and suggested improvements in its Application, 30 pp., http://www.cru.uea.ac.uk/cru/people/briffa/Briffa_HB_2008.pdf.

Charru, M., Seynave, I., Morneau, F., Bontemps, J.-D., 2010. Recent changes in forest productivity: an analysis of national forest inventory data for common beech (*Fagus sylvatica* L.) in north-eastern France. Forest Ecology and Management 260, 864–874.

Cook, E.R., Kairiukstis, L.A. (Eds.), 1990. Methods of Dendrochronology. Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 26–28, 98–102, 104–123, 119–120.

Devall, M.S., Parresol, B.R., Armesto, J.J., 1998. Dendroecological analysis of a Fitzroya cupressoides and a Nothofagus nitida stand in the Cordillera Pelada, Chile. Forest Ecology and Management 108, 135–145.

Dhôte, J.-F., Hervé, J.-C., 2000. Productivity changes in four sessile oak forests since 1930: a stand-level approach. Annals of Forest Science 57, 651–680 (in French).

Duplat, P., Tran-Ha, M., 1997. Modelling of dominant height growth of sessile oak (*Quercus petraea* Liebl.) in France. Regional variability and effect of the recent period (1959–1993). Annals of Forest Science 54, 611–634 (in French).

Dupouey, J.-L., Denis, J.-B., Becker, M., 1992. A new method of standardization for examining long term trends in tree-ring chronologies. Lundqua Report 34, 85–88.

Elfving, B., Tegnhammar, L., 1996. Trends of tree growth in Swedish forests 1953–1992: an analysis based on sample trees from the National Forest Inventory. Scandinavian Journal of Forest Research 11, 26–37.

Eriksson, H., Johansson, U., 1993. Yields of Norway spruce (*Picea abies* (L.) Karst.) in two consecutive rotations in southwestern Sweden. Plant and Soil 154, 239–247.

Erlandsson, S., 1936. Dendrochronological Studies. Stockholms Hogskolas Geokronol. Institute, Report 23, Uppsala, Sweden.

Esper, J., Cook, E.R., Schweingruber, F.H., 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science 295, 2250–2252.

di Filippo, A., Biondi, F., Cufar, K., de Luis, M., Grabner, M., Maugeri, M., Presutti Saba, E., Schirone, B., Piovesan, G., 2007. Bioclimatology of beech (*Fagus sylvatica* L.) in the Eastern Alps: spatial and altitudinal climatic signals identified through a tree-ring network. Journal of Biogeography 34, 1873–1892.

Fritts, H.C., 1971. Dendroclimatology and dendroecology. Quaternary Research 1, 419–449.

Fritts, H.C., 1976. Tree Rings and Climate. Caldwell, New Jersey, USA, pp. 267–268.

Fritts, H.C., Swetnam, T.W., 1989. Dendroecology: a tool for evaluating variations in past and present forest environments. In: Begon, M., Fitter, A.H., Ford, E.D., Macfadyen, A. (Eds.), Advances in Ecological Research, vol. 19. Academic Press, pp. 111–188.

Hornbeck, J.W., Smith, R.B., Federer, C.A., 1988. Growth trends in 10 species of trees in New England, 1950–1980. Canadian Journal of Forest Research 18, 1337–1340.

Hüffel, G., 1926. Methods of Forest Planning in France. Berger-Levrault, Nancy, Paris, Strasbourg, 225 pp. (in French).

Jacoby, G.C., D'Arrigo, R.D., 1997. Tree rings, carbon dioxide, and climatic change. Proceedings of the National Academy of Science 94, 8350–8353.

Jump, A.S., Hunt, J.M., Peñuelas, J., 2006. Rapid climate change-related growth decline at the southern range edge of *Fagus sylvatica*. Global Change Biology 12, 2163–2174.

Lamarche, V.C., Graybill, D.A., Fritts, H.C., Rose, M.R., 1984. Increasing atmospheric carbon dioxide: tree ring evidence for growth enhancement in natural vegetation. Science 225, 1019–1021.

Lindström, M.J., Bates, D.M., 1990. Nonlinear mixed effect models for repeated measures data. Biometrics 46, 673–687.

Melvin, T.M., Briffa, K.R., 2008. A "signal-free" approach to dendroclimatic standardisation. Dendrochronologia 26, 71–86.

Peñuelas, J., 2005. A big issue for trees. Nature 437, 965–966.

Piovesan, G., Biondi, F., di Filippo, A., Alessandrini, A., Maugeri, M., 2008. Drought-driven growth reduction in old beech (*Fagus sylvatica* L.) forests of the central Apenines, Italy. Global Change Biology 14, 1–17.

Podlaski, R., 2002. Radial growth trends of fir (*Abies alba* Mill.), beech (*Fagus sylvatica* L.), and pine (*Pinus sylvestris* L.) in the Swietokrzyski National Park (Poland). Journal of Forest Science 48, 377–387.

Polge, H., 1981. The influence of thinnings on the growth constraints of Beech. Annals of Forest Science 38, 407–423 (in French).

Pretzsch, H., Grote, R., Reineking, B., Rötzer, T., Seifert, S., 2008. Models for forest ecosystem management: a European perspective. Annals of Botany 101, 1065–1087.

Rathgeber, C., Guiot, J., Tessier, L., 1999. Productivity increase of pubescent oak in the French Mediterranean area. Annals of Forest Science 56, 211–219 (in French).

Ryan, M.G., Binkley, D., Fownes, J.H., 1997. Age-related decline in forest productivity: pattern and process. Advance in Ecological Research 27, 214–262.

Schadauer, K., 1996. Growth trends in Austria. In: Spiecker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.-P. (Eds.), Growth Trends in European Forests. EFI Research Report No. 5. Springer, Berlin, Heidelberg, pp. 275–289.

Seber, G.A.F., Lee, A.J., 2003. Linear Regression Analysis, 2nd ed. Wiley, Hoboken, NJ, USA, 653 pp.

Shinozaki, K., Yoda, K., Hozumi, K., Kira, T., 1964. A quantitative analysis of plant form—the pipe model theory. I. Basic analyses. Japanese Journal of Ecology 14, 97–105.

Spiecker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.P. (Eds.), 1996. Growth Trends in European Forests. Springer, Berlin, Heidelberg, p. 367.

Spiecker, H., 1999. Growth trends in European forests—do we have sufficient knowledge? In: Karjalainen, T., Spiecker, H., Laroussinie, O. (Eds.), Causes and Consequences of Accelerating Tree Growth in Europe, EFI Proceedings No. 27. , pp. 157–169.

Szeicz, 1997. Growth trends and climatic sensitivity of trees in the North Patagonian rain forest of Chile. Canadian Journal of Forest Research 27, 1003–1014.

Thomas, H., 2002. Ageing in plants. Mechanisms of Ageing and Development 123, 747–753.

Untheim, H., 1996. Has site productivity changed? A case study in the eastern Swabian Alb, Germany. In: Spiecker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.-P. (Eds.), Growth Trends in European Forests, EFI Research Report No. 5. Springer, Berlin, Heidelberg, pp. 133–147.

Valentine, H.T., 1985. Tree-growth models: derivations employing the pipe-model theory. Journal of Theoretical Biology 117, 579–585.

Vejpustkova, M., Zahradnik, D., Sramek, V., Fadrhonsova, V., 2004. Growth trends of spruce in the Orlické hory Mts. Journal of Forest Science 50, 67–77.

Warren, W.G., 1980. On removing the growth trend from dendrochronological data. Tree-ring Bulletin 40, 35–44.

West, G.B., Brown, J.H., Enquist, B.J., 2001. A general model for ontogenetic growth. Nature 413, 628–631.