FUNDAMENTAL RESEARCH

For. Sci. 61(5):817–828
http://dx.doi.org/10.5849/forsci.14-139

forest ecology

Expressing Tree-Ring Chronology as Age-Standardized Growth Measurements

Samuli Helama

Tree-ring data of individual trees show lifelong biological trends as a function of cambial age. The compilation of a tree-ring chronology entails standardization (detrending) of the series. Tree-ring standardization commonly derives detrended series of dimensionless tree-ring data that are devoid of the original growth measurements (millimeter, density). A new method is proposed in this study. This method derives modeled tree-ring growth variations to calculate age-standardized tree-ring chronology that allow comparisons between the absolute growth measurements of different sites, regions, or species and between the absolute growth measurements and environmental factors such as climate variables. The modeled tree-ring growth is simply obtained through ranked transformation of the tree-ring values within the user-defined reference age class (RAC) and all remaining cambial age classes. The chronology is thus presented on the scale of growth measurements of the specific tree's age, instead of dimensionless tree-ring indices. This presentation allows the accurate estimation of both the short- and long-term growth variations. The RAC method used at the timberline sites in northern Finland revealed a nonlinear age-dependent association between mid-summer (July) temperature and Scots pine growth of 0.072 mm/° C and 0.014 mm/° C for cambial age ranges of 1 to 5 to 226 to 330 years.

Keywords: dendrochronology, dendroclimatology, dendroecology, timberline, tree growth

Tree rings are commonly used indicators of forest health and decline (Dobbertin 2005); they can also be used to evaluate influences of forest management (Spiecker 2002) and climate (Fritts 1976) on tree growth. Moreover, tree rings are used for reconstructing the past climate changes in paleoclimatology studies (Briffa 2000). Tree-ring data of a particular site or region are expressed as mean chronologies to present the growth variability more reliably than by an individual series. The comparison of tree-ring values of a number of individual trees of different biological (cambial) ages is common to most of the tree-ring methods. A difficulty with carrying out both of these elementary tasks is that tree-ring series of individual trees contain an age-dependent trend. This trend partly arises from the geometric constraint of adding an annual volume of biomass to the stem of a tree that has an increasing radius (Cook 1990). It is observed as wide rings near the pith and exponentially decreasing ring widths as the tree ages, whereas negative trends of linear or convex shapes are typical for dendrodensitometric data (Schweingruber et al. 1988, Briffa et al. 1992, 1996, Helama et al. 2008). Dendroisotope data may also contain age-dependent trends, as shown for carbon and oxygen isotopes (Esper et al. 2010). The tree-ring chronologies are routinely compiled as means of tree-ring indices to deal with these age-dependent trends. This is done subsequent to tree-ring standardization, which is a process that removes the age-dependent trend (hence, detrending) from the initial, measurement, series. Thus, the standardization has become one of the generally accepted principles of dendroecology and dendroclimatology methodologies (Fritts and Swetnam 1989).

Although the detrending may appear to be an optimum solution for the age-dependent growth problem (and the standardization has actually become a basis of dendrochronological determination), this method of processing tree-ring data is subject to various pitfalls (Cook et al. 1995, Briffa et al. 1996, Cook and Peters 1997). There is no single method of tree-ring standardization. Tree-ring indices are derived from the expected growth curve that is thought to represent the aging trend, which can be either determined separately for individual trees or commonly for a population of trees. A common practice in standardization is to determine an expected growth curve individually for each series or for a population of trees (Cook et al. 1990a, 1995, Briffa et al. 1992, 1996) and derive dimensionless tree-ring indices from the curve. Such indices possess the essential benefit of having lost the type of nonstationary process arising from the aging effects on growth, and the index series are routinely reduced to a mean chronology (Fritts 1976, Cook et al. 1990b). Tree-ring standardization does, however, alter the spectral properties of the resulting tree-ring indices, and the different approaches have their specific methods to modify the data to remove the age-dependent trend (Cook and Briffa 1990, Briffa et al. 1992, Murphy and

Manuscript received August 4, 2014; accepted April 28, 2015; published online May 28, 2015.

Affiliations: *Samuli Helama (samuli.helama@metla.fi), Finnish Forest Research Institute, Northern Unit, Rovaniemi, Finland.*

Acknowledgments: *Two anonymous reviewers are thanked for their helpful comments. This study was supported by the Academy of Finland (Grant 251441).*

Palmer 1992, Helama et al. 2004). The largest differences are commonly observed for the low-frequency band of growth variations as not all of the methods preserve the long-term variations in the tree-ring data (Briffa et al. 1992, Helama et al. 2004). It is commonly accepted that the method that preserves the long-term growth variations in the chronology is the regional curve standardization (RCS) as described by Briffa et al. (1992, 1996). In the RCS method, the mean growth trend is calculated by averaging the individual series aligned by their cambial age, smoothed, and used as an "expected growth curve" for the tree-ring series (Briffa et al. 1992, 1996, Melvin et al. 2007). The dimensionless tree-ring indices are computed as ratios between the observed tree-ring value and that of the expected curve. Thereafter, the tree-ring indices are realigned according to their cross-dated calendar years, and the resulting tree-ring index time series are used to calculate the mean chronology. As a result, the use of the RCS method establishes the tree-ring indices as being dimensionless, which is common among the standardization methods.

The disadvantage to being dimensionless is that the dimensionless tree-ring indices no longer have a direct connection to the original age-dependent features of growth. The resulting tree-ring indices are no longer expressed in the original growth measurement units. The expected value of 1.0 is given when the index is computed simply as the ratio between the observed growth measurement and the growth predicted by the curve (Fritts 1976, Monserud 1986, Cook et al. 1995). Such tree-ring chronologies are not comparable in absolute terms. First, the tree-ring chronologies are unusable for comparisons between the absolute growth levels of different sites, regions, or species. Second, it is not possible to derive relationships between an environmental factor such as a climate variable and absolute growth change. For example, it is impossible to calculate how many millimeters the tree-ring growth has increased per 1° C for the growing season. Any comparison of this type is usually not possible with the initial tree-ring measurement series either. The exception is when such data contain an exhaustive number of tree-ring series from mixed-age stands that allow subsampling into separate age classes and mean chronologies built from the corresponding subset of data. The growth measurements can also be preserved in terms of the annual basal area of each ring, but the time series of basal area increments commonly come with trends attributable to increasing ring area. Moreover, the calculation of basal area increments cannot be applied for dendrodensitometric (Schweingruber et al. 1988, Helama et al. 2008) or dendroisotope data (Esper et al. 2010). Yet another method, logarithmic transformation of measurements and then taking the first differences, can still be converted back to raw values by taking antilogs. The disadvantage of differencing is that the method acts as a high-pass filter and virtually all low-frequency variance is attenuated (Cook et al. 1990a).

This study provides a new approach that retains the growth units in standardizing tree rings. It is a method that is independent of age-trend estimation and does not derive dimensionless tree-ring indices. Here, the tree-ring measurements are converted to rank data (Conover 2012). This transformation is first carried out within the user-defined reference age class (RAC), and then within all remaining cambial age classes. Ranking provides a basis for the age standardization of the remaining rings. The *n*-ranked tree-ring value within each cambial age class is replaced by the *n*-ranked absolute tree-ring value within the RAC. In this method, the growth fluctuations embody stable means and variances through all cambial ages but will also retain the externally driven fluctuations in the means and variances of the data for the calendar years. The resulting tree-ring chronology is expressed as a mean record of absolute growth variations relative to growth values observed at a certain tree age. The method preserves the original mean and variance of the reference tree rings, thus producing a chronology that expresses the tree-ring growth variations inherent for a sample set of trees at a chosen cambial age. The chronologies produced using the new method were compared with the tree-ring chronologies from conventional standardization approaches. The new method results in the estimation of short- and long-term growth fluctuations comparable to those with the methods commonly used in published tree-ring research. It is notable that no loss of low-frequency growth variations was observed when the chronologies constructed by the RCS and new RAC method were analyzed.

Materials and Methods

Tree-Ring Data

Tree-ring width data for Scots pine (*Pinus sylvestris* L.) were used to demonstrate the novel method. These data originated from a number of timberline locations in northeastern Finnish Lapland (Helama et al. 2004). Samples from both living trees and deadwood were included in the data set to construct one continuous regional tree-ring chronology (between latitudes 69°15′ N and 68°28′ N and longitudes 27°20′ E and 25°42′ E). Standing dead trees or logs on the ground preserved in subaerial conditions (snag) represented the tree generations that grew earlier in the same dry-land stands as the current living trees. This material was sampled in the unmanaged locations using an increment borer to extract cores for tree-ring analysis at breast height. In the case of most decayed wood, the samples were extracted as a cross section. The material was gathered during several past investigations, but more detailed information on the field sampling is unavailable. Moreover, the data do not provide estimates of pith offsets for each core sample. Scots pine is relatively shade-intolerant, and the height growth of seedlings may be altered by factors associated with the distance to the nearest shelter tree (Strand et al. 2006). Any variation in the height growth of seedlings may alter the breast height age of the sampled trees. On the other hand, wide intertree spacing, inherent to the timberline locations sampled, was expected to minimize these effects. However, it is possible that the lack of pith offset estimates may contribute bias in the estimation of age-dependent growth characteristics and thus increase the uncertainty when either the RCS and RAC method is applied to tree-ring data. Previously, an evaluation of the possible influences of not knowing the pith offsets when calculating RCS chronologies showed that the issue had no substantial effect on estimation of the trends in the resulting time series (Esper et al. 2009). If the variability in height growth rates and number of years to reach the missing pith is large, the effect may become more substantial, with implications for determining the appropriate width of the RACs (see below), in which case the narrow age classes are more unfavorable than the wider age classes. The sample sites include Saariselkä (139 trees), Karasjok (11 trees), Karhunpesäkivi (15 trees), and Muotkanruoktu (80 trees) (Helama et al. 2004). Tree-ring widths were measured under a light microscope to the nearest 0.01 mm and carefully cross-dated using several numerical methods, including the Pearson correlation and the *t*-value calculation (Aniol 1983, Holmes 1983, van Deusen 1990), along with visual comparison of tree-ring characteristics. Cross-dating enabled temporal synchronization of the sample series and the construction of the tree-ring chronology and was used to identify missing rings in

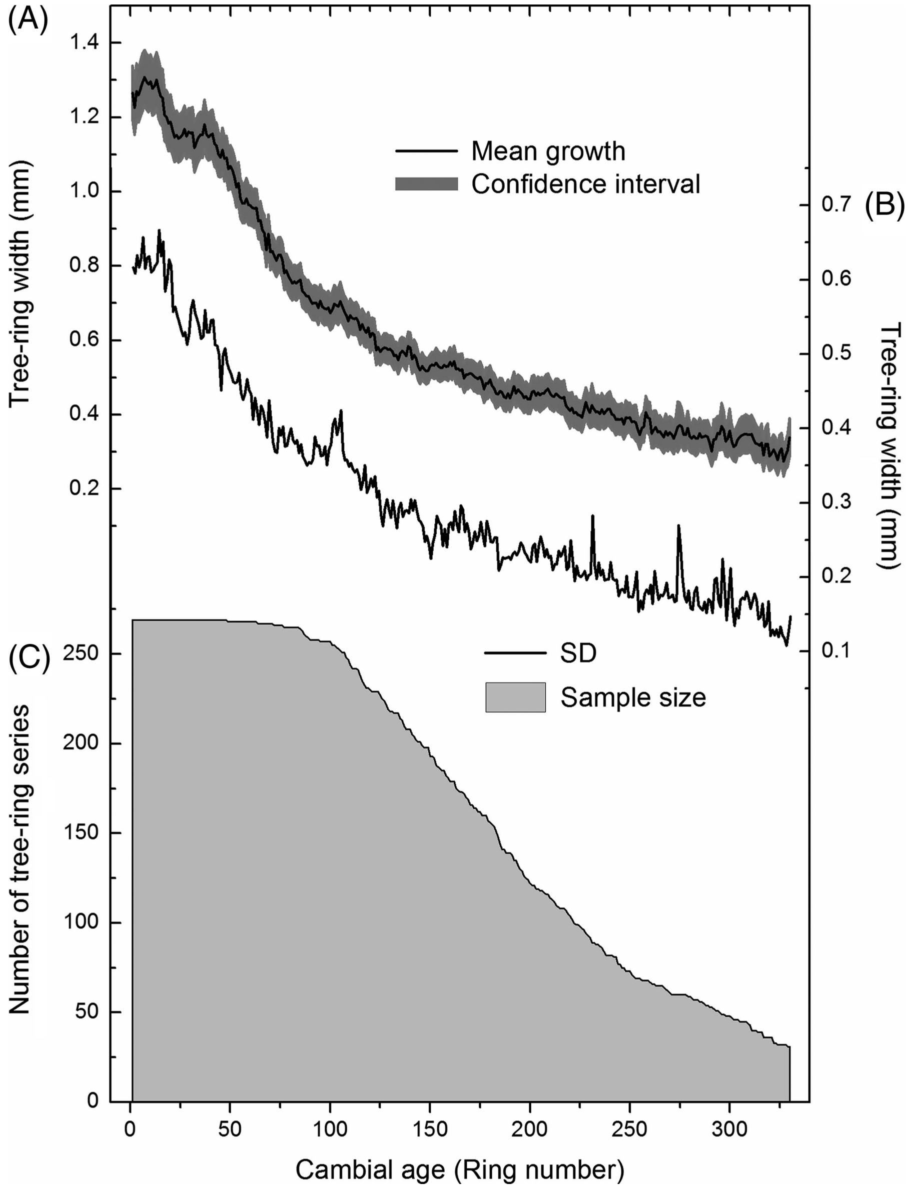


Figure 1. Age-dependent change of 1-year means for the measured ring-width series with 95% confidence intervals (A), in the SDs for the measured ring width (B), and the number of series available to calculate the age-dependent trend (C). These series are aligned according to cambial ages and thus are shown as a function of tree age.

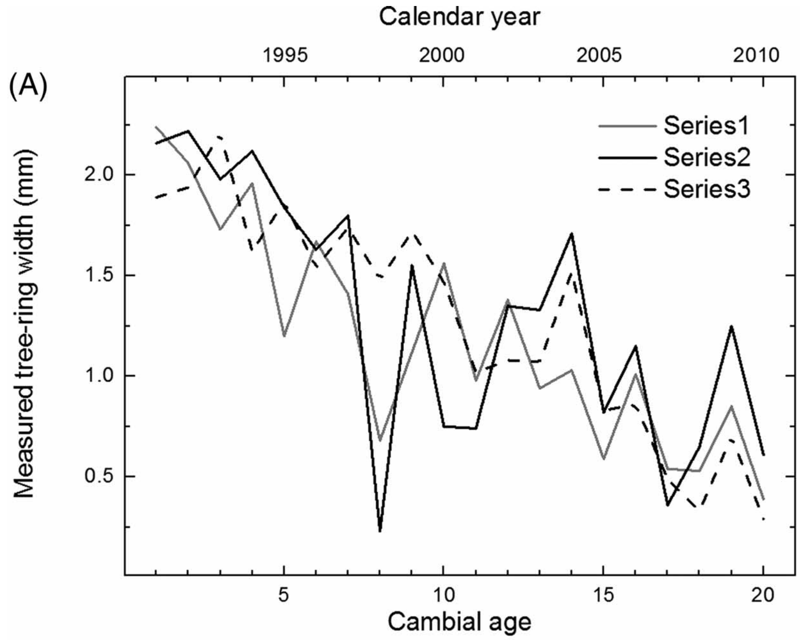
the sample series. The synchrony obtained among tree-ring series ensures the dating of each ring to an exact calendar-year scale (Fritts 1976). A marked decline in sample size occurred during the 13th century and was associated with a reduction in the reliability of chronology; thus, tree-ring data before AD 1300 were not included in the comparison of resulting chronologies of this study. The mean segment length of the series was 196 (SD, 75) years.

These tree-ring data exhibit an age-dependent trend that becomes obvious when data are aligned by their cambial ages (Figure 1). According to these figures, the widest rings are expected near the pith, with an exponential decline in tree-ring widths as the tree ages (Figure 1A). A similar trend was observed for the variance of the growth departures with relatively larger growth fluctuations that occur at younger ages (Figure 1B).

Rank Transformations

Transformations of the data were carried out in three steps. First, the tree-ring values of the selected age class (RAC) were ranked. The RAC was chosen to represent a subsample of tree-ring growth within a cambial age range of interest. Second, the tree-ring values that represented other cambial age classes were converted into ranked data on a class-by-class basis. When no other information on cambial age was available, the ring number was counted from the pith outward and that would be used to estimate the age. Third, the *n*-ranked tree-ring value within the respective cambial age classes other than RAC was replaced by the *n*-ranked absolute tree-ring value from the RAC.

The procedure was characterized by using a surrogate set of simplified data. The measurement values that showed the age-dependent trends (Figure 2A and B) were first rank transformed to carry out the process. The rank transformations were carried out using 5-year intervals for these samples. The cambial age classes were, thus, 1–5, 6–10, and 16–20 years, whereas the RAC was chosen to represent cambial ages 11–15 years (Figure 2C). Consequently, the measurement data within each cambial age class was modeled to



(B) Measurement series (C) Rank transformations (D) Modelled series

Year	Age		Series-1	Series-2	Series-3	Age	Series-1	Series-2	Series-3	Year	Series-1	Series-2	Series-3
1991	1	Cambial age class 1-5	2.24	2.16	1.89	1	15	12	6	1991	1.71	1.35	0.98
1992	2		2.06	2.22	1.94	2	10	14	7	1992	1.08	1.52	1.02
1993	3		1.73	1.98	2.21	3	3	9	13	1993	0.82	1.07	1.38
1994	4		1.96	2.12	1.62	4	8	11	2	1994	1.03	1.33	0.74
1995	5		1.20	1.84	1.87	5	1	4	5	1995	0.59	0.83	0.94
1996	6	Cambial age class 6-10	1.67	1.63	1.54	6	12	11	8	1996	1.35	1.33	1.03
1997	7		1.41	1.80	1.74	7	5	15	14	1997	0.94	1.71	1.52
1998	8		0.68	0.23	1.48	8	2	1	7	1998	0.74	0.59	1.02
1999	9		1.12	1.55	1.72	9	4	9	13	1999	0.83	1.07	1.38
2000	10		1.56	0.75	1.47	10	10	3	6	2000	1.08	0.82	0.98
2001	11	Reference age class 11-15	0.98	0.74	1.02	11	6	2	7	2001	0.98	0.74	1.02
2002	12		1.38	1.35	1.08	12	13	12	10	2002	1.38	1.35	1.08
2003	13		0.94	1.33	1.07	13	5	11	9	2003	0.94	1.33	1.07
2004	14		1.03	1.71	1.52	14	8	15	14	2004	1.03	1.71	1.52
2005	15		0.59	0.82	0.83	15	1	3	4	2005	0.59	0.82	0.83
2006	16	Cambial age class 16-20	1.01	1.15	0.86	16	13	14	12	2006	1.38	1.52	1.35
2007	17		0.54	0.36	0.49	17	7	3	5	2007	1.02	0.82	0.94
2008	18		0.53	0.65	0.33	18	6	9	2	2008	0.98	1.07	0.74
2009	19		0.85	1.25	0.70	19	11	15	10	2009	1.33	1.71	1.08
2010	20		0.39	0.61	0.29	20	4	8	1	2010	0.83	1.03	0.59

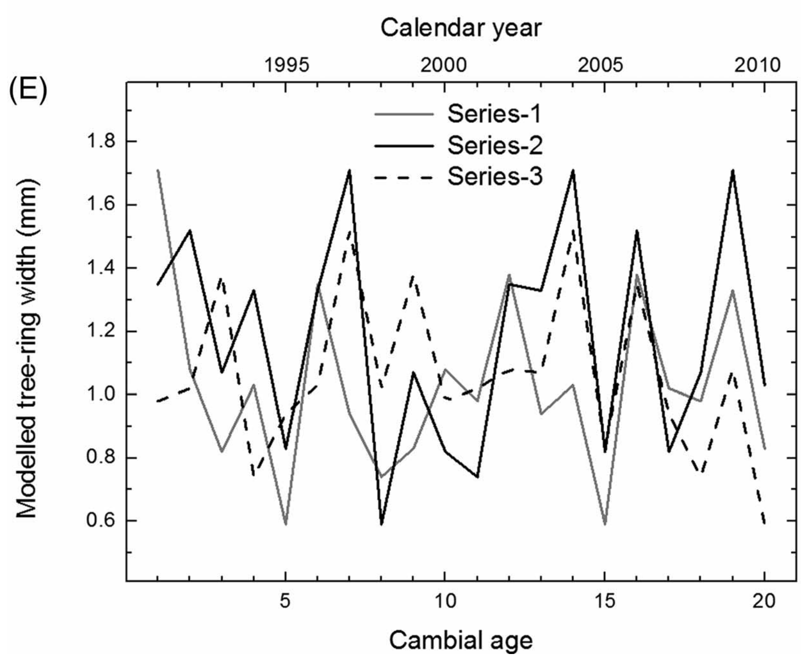


Figure 2. The compilation of age-standardized growth measurements. The measurement series (A and B) are rank transformed for each cambial age class (C), and the *n*-ranked measurement values are replaced by their correspondingly ranked values within the RAC to derive a new set of modeled series (D) that no longer exhibit cambial trends (E).

represent tree-ring growth variations within the RAC, i.e., between the cambial ages 11 and 15 years (Figure 2B and C). The *n*-ranked measurement values within each cambial age class were substituted by their *n*-ranked data values within the RAC to achieve the final conversion (Figure 2D). The modeled tree-ring widths of the resulting series did not exhibit the age-dependent trends (Figure 2E). Moreover, the mean tree-ring measurements were 1.09 mm over the RAC (Figure 2B). The resulting age-standardized growth measurements varied around this mean value (Figure 2D and E).

When the number of tree-ring values within the RAC did not equal the number of values in the cambial age class to be standardized, the rank data (*rk*) were adjusted by using the expression

$$rk'_{ij} = (rk_{ij} - (n_j/2 + 0.5)) \times (n_{\mathrm{ref}}/n_j) + n_{\mathrm{ref}}/2 + 0.5 \qquad (1)$$

where rk'_{ij} is the closest integer for the tree-ring series i and cambial age class j, rk_{ij} is the rank to be scaled, n_j is the total number of ranked tree-ring values for cambial age class j, and n_{ref} is the total number of ranked tree-ring values within the RAC.

Experimental Design

Comparing Young and Old Rings

The new method was first used to generate two tree-ring chronologies. Consequently, the first chronology was compiled using the rings between the cambial ages 1 and 100 (RAC_{1-100}) and the second chronology by using the rings between the cambial ages of 101 and 330 ($RAC_{101-330}$) as their RACs. The observed age-dependent growth characteristics (Figure 1) indicated that the first chronology would show wider rings with larger growth fluctuations than the second chronology. These and other tree-ring properties were demonstrated by calculating the arithmetic mean, SD, the first-order autocorrelation, and the mean sensitivity (MS). The latter was determined by Fritts (1976) as

$$\mathrm{MS} = \frac{1}{n-1} \sum_{i=1}^{n-1} \left| \frac{2(x_i + 1 - x_i)}{x_i + 1 + x_i} \right| \qquad (2)$$

where x is the tree-ring value of year t in the series possessing n tree rings. The MS is a commonly used statistic in tree-ring analyses, and it contrasts with the SD because it measures the growth variation between consecutive years and thus on interannual time scales. The mean correlation between the tree-ring series indicated the strength of the common signal within the chronology (Briffa and Jones 1990).

Using 5-Year RACs

The method was repeated for RACs of all possible 5-year increments in a more detailed examination of the data. This resulted in a set of 66 5-year interval tree-ring chronologies being produced as RAC_{1-5}, RAC_{6-10}, …, $RAC_{326-330}$. Consequently, these incremental RAC chronologies were expected to represent the growth variations of trees with cambial ages of 1–5, 6–10, …, 326–330. Following the observed age-dependent growth properties (Figure 1), the chronologies were expected to manifest a gradual narrowing of the rings and attenuated growth fluctuations as the age of the 66 chronologies proceeded from youngest to oldest (RAC_{1-5}, …, $RAC_{326-330}$). These chronologies were quantified by their means and SDs and by the effects of climate variability on Scots pine growth of gradually changing cambial ages (see the next section).

Modeling Growth Using Climate Data

Climatic effects on tree-ring growth were evaluated for the entire set of 66 tree-ring chronologies (RAC_{1-5}, …, $RAC_{326-330}$). Dendroclimatic associations were quantified for each chronology using the instrumental temperature in centigrade. Mean monthly temperatures were recorded at the meteorological station of Karasjok (latitude 69°28′ N and longitude 25°31′ E). Dendroclimatic associations were characterized using linear multiple regression. The climate and tree-ring time series as independent and dependent variables were used in the regression model. Climate time series of July temperatures were used for predicting the growth. This variables was previously found to influence Scots pine radial growth markedly better than any other climate variable (Lindholm 1996). Variables for prior growth at a lag of 1 year were used as predictor variables along with the variables of climate (Fritts 1976). The Durbin-Watson (Durbin and Watson 1951) *d*-test showed no statistically significant serial correlation present (0.01 level) in the residuals from these regressions.

Comparing the New and Older Methods

A previous study by Helama et al. (2004) made a thorough comparison between the tree-ring standardization methods, i.e., the statistical approaches that were used to remove the age dependence, using the same initial tree-ring material as that used in the present study. In the previous study, the detrending methods commonly used in dendrochronological literature to generate dimensionless tree-ring indices (Cook et al. 1990a, Briffa et al. 1992, 1996) were described and the method-dependent effects on the resulting chronologies were detailed (Helama et al. 2004). The same study used RCS, as described by Briffa et al. (1992, 1996), which preserved the long-term (low-frequency) growth variations in the chronology while removing the nonclimatic long-term trend from the initial series. That result was in accordance with similar comparisons and conclusions made in other studies (Briffa et al. 1992, 1996, Esper et al. 2003, D'Arrigo et al. 2006, Linderholm et al. 2010). The time-series data of the RCS chronology (Helama et al. 2004) were adopted for comparisons with the RAC chronologies developed in this study to express the chronology as age-standardized growth measurements, instead of the dimensionless indices. Moreover, the RAC chronologies were also compared with a conventional tree-ring detrending method whereby the expected growth trend was statistically fitted to each series using either a modified negative exponential function (Fritts et al. 1969) or linear regression (with negative or zero slope). The dimensionless tree-ring indices in that standardization method are computed as ratios between the observed tree-ring value and the value predicted by the curve. The tree-ring index data of that method, referred to hereafter as NELR, were also adopted from a previous study that used the same initial tree-ring width data (Helama et al. 2004). The chronologies of these methods were compared visually and by quantifying their similarity using Pearson correlations. The chronologies were further low-pass filtered using 150-year smoothing spline functions (Cook and Peters 1981) to describe their low-frequency variations.

Results

Young and Old Tree-Ring Populations

In all, there were 26,657 (RAC_{1-100}) and 28,198 ($RAC_{101-330}$) rings that belonged to the respective RACs. The mean widths of these rings were 1.009 (SD, 0.531) and 0.505 (SD, 0.286) mm for RAC_{1-100} and $RAC_{101-330}$.

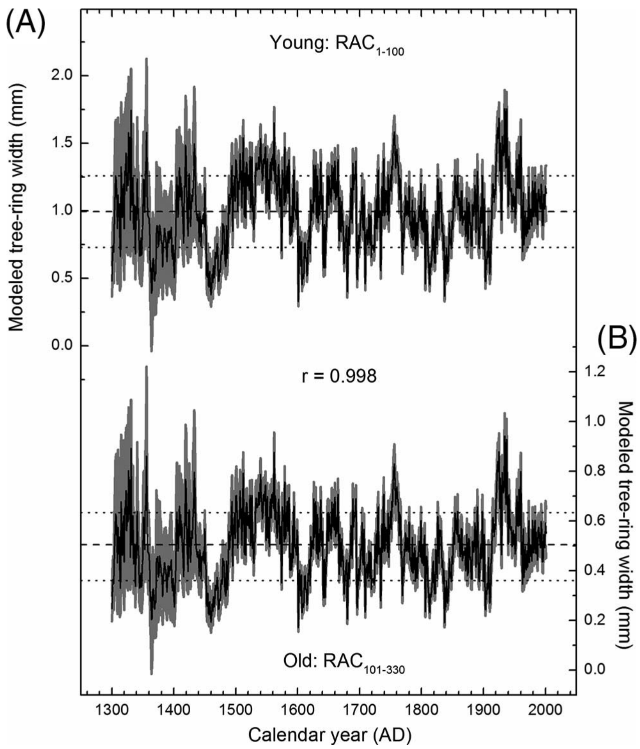


Figure 3. Age-standardized growth measurements as modeled tree-ring widths (black line) relative to tree-ring characteristics of young (A; reference cambial ages: RAC_{1-100}) and old (B; $RAC_{101-330}$) growth variations, denoted by the means (dashed lines) and SDs (dotted lines). Chronologies are shown with their 95% confidence intervals (gray area). Comparison of chronologies was quantified using the Pearson correlation (*r*).

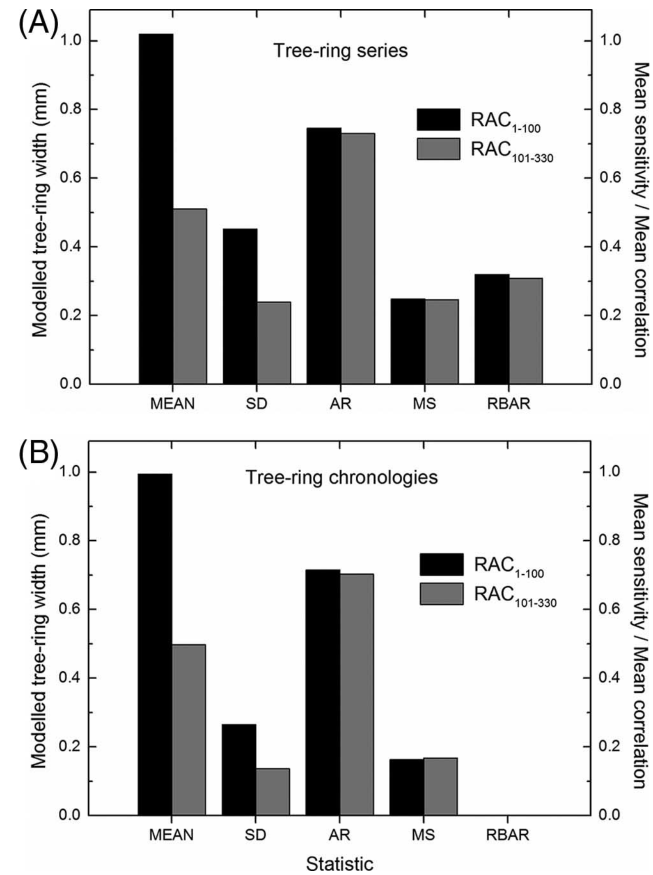


Figure 4. Characterization of the modeled young and old tree-ring growth in the series (A) and chronologies (Figure 3) (B) with their means, SDs, first-order autocorrelation (AR), mean sensitivity (MS), and correlation between the individual tree-ring series (RBAR).

The two tree-ring chronologies, expressed as age-standardized growth measurements relative to their respective RACs, demonstrated growth characteristics markedly different from each other (Figure 3). The whole time period covered in the study was AD 1300–2001: the mean chronologies averaged 0.994 (SD, 0.265) for the young (RAC_{1-100}) and 0.498 (SD, 0.137) for the old ($RAC_{101-330}$). Consequently, the young chronology exhibited higher mean variances, whereas the old chronology had lower mean variance. Thus, the resulting tree-ring chronologies (Figure 3) could be seen to mimic closely the means and SDs of their RACs. Despite the notable deviations in their growth levels and the spread, the chronologies were highly correlated with each other (Figure 3).

The means and SDs were the only statistics that showed any discernible difference between the RAC_{1-100} and $RAC_{101-330}$ populations. That is, the first-order autocorrelation (~0.7), mean sensitivity (~0.165), and mean correlation between the tree-ring series (~0.3) indicated virtually no difference between the characteristics of the two chronologies (Figure 4). This result was very similar for the individual tree-ring series (Figure 4A) and for the mean chronologies (Figure 4B).

Comparison with Earlier Methods

The tree-ring data generated by this new method were compared with the dimensionless tree-ring index data produced by the NELR and RCS methods, as described previously using the same initial tree-ring material (Helama et al. 2004). A visual comparison between the chronologies had already shown their similarity in terms of the growth variability obtained (Figure 5A). Moreover, the chronologies highly correlated with each other (Table 1). It can be seen, however, that the NELR and RCS chronologies vary around a mean index value of 1.0, as could be expected by the ratio methods used (Fritts 1976, Monserud 1986, Cook et al. 1995). Thus, the NELR and RCS chronologies remain incapable of reproducing the growth variability in the observed dimension (millimeters). Despite this common limitation, the RCS method data exhibited more similar growth variations with the RAC chronology than it did with the NELR method data. Their low-frequency band of variations closely followed each other (Figure 5B). It can be seen that the low-frequency correlations between the NELR and other chronologies decreased to between 0.5 and 0.6, whereas the corresponding correlations between the RCS and RAC chronologies remained well above 0.9 (Table 1).

These dissimilarities between the methods for the chronologies could be seen to originate from the way the methods affected the individual tree-ring series (Figure 6). Analyses were carried out by comparing the linear trends for the tree-ring width series (initial data in millimeters) and the tree-ring index series (NELR and RCS) and the modeled tree-ring growth series data for the RAC method (RAC_{1-100}/$RAC_{101-330}$). The remaining linear trends of the NELR series had lost virtually all their low-frequency information relative to the initial data (Figure 6A). The RCS (Figure 6B) and RAC methods (Figure 6C and D) preserved this information in their respective series. That is, the tree-ring series that originally contained long-term trends still showed the trends in the resulting index

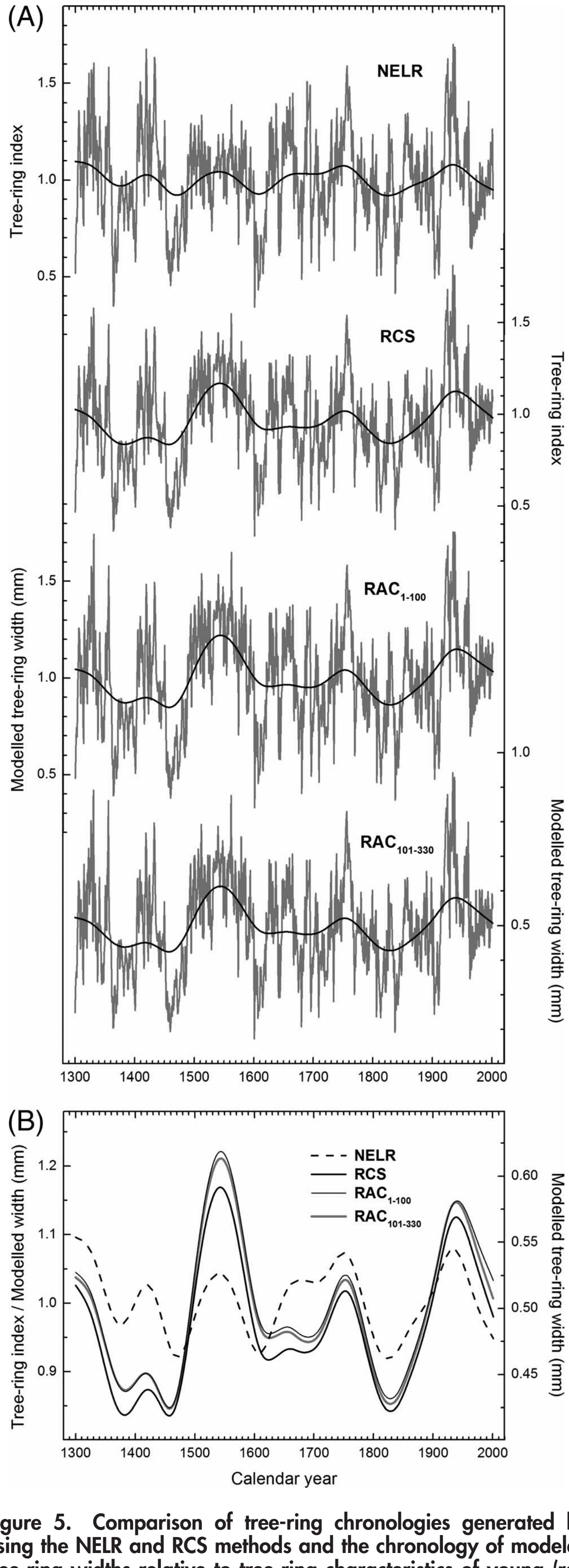


Figure 5. Comparison of tree-ring chronologies generated by using the NELR and RCS methods and the chronology of modeled tree-ring widths relative to tree-ring characteristics of young (reference cambial ages: RAC_{1-100}) and old ($RAC_{101-330}$) growth variations (A). The time-series of the chronologies were further low-pass filtered to express their low-frequency variations (B).

Table 1. Pearson correlations between the NELR and the RCS methods and the modeled tree-ring width series relative to tree-ring characteristics of young (reference cambial ages: RAC_{1-100}) and old ($RAC_{101-330}$) growth variations.

	NELR	RCS	$R_{001-100}$	$R_{101-330}$
NELR	1	0.579*	0.503*	0.561*
RCS	0.934	1	0.935*	0.996*
$R_{001-100}$	0.928	0.997	1	0.938*
$R_{101-330}$	0.926	0.996	0.998	1

Correlations were calculated by using the nonfiltered and low pass-filtered (indicated by *) chronologies.

and age-standardized series. Nevertheless, the age-dependent trend component of the initial data (Figure 1A) was generally removed. This is quantified by the regression slopes whose means were near to zero (Figure 6). In comparison, the observed tree-ring width series exhibited a mean growth decline by half a millimeter per century, as indicated by their mean regression slope of −0.500 mm/100 years (not shown). The removal of this trend in tree-ring indices and modeled tree-ring widths, as illustrated in Figure 6, obviously appears as one way to characterize the effective functioning of these methods.

Expressing Growth through 5-Year Age Intervals

The RAC method used 5-year RACs (1–5, 6–10, …, 325–330), which resulted in 66 incremental tree-ring RACs. A comparison of these chronologies by Pearson correlations showed that they were alike in terms of their year-to-year values. More precisely, the mean correlation between the chronologies was 0.998. Even the lowest correlation, obtained for a pair of chronologies, RAC_{41-45} and $RAC_{271-275}$, appeared as high as 0.984. More detailed evaluation of the 66 chronologies revealed that their data did, however, exhibit several interesting properties beyond the extent of their correlations.

The basic characteristics of the underlying tree-ring data and their means and SDs were well-represented by the set of 66 tree-ring chronologies. Using progressively older rings by incrementally older RACs resulted in chronologies with systematically lower growths, as determined by the means of the chronologies over the study period (Figure 7A). Moreover, the older the RAC, the narrower the amplitudes of the rings in the chronology, as measured by their SDs (Figure 7B).

Importantly, the transformations into modeled tree-ring growth and thus into RAC chronologies were notably linear (Figure 7). The relationships between the growth means (Figure 7A) were clearly closer to each other (as compared by the slopes) in comparison to the relationship between the SDs (Figure 7B), as observed between the underlying values and the calculated chronology. It is probable that this originates simply from the ways the averaging modifies the mean time series. Generally, the higher or lower the number of series included in the chronology and the lower or higher their interseries correlations, then the lower or higher will be the growth amplitudes the mean chronologies are expected to exhibit (Shiyatov et al. 1990, Osborn et al. 1997).

The diminishing growth variance due to calculating means was also demonstrated by the comparison of the SDs between the individual series and the mean chronologies (Figure 4). For the former case, the SDs of the RAC_{1-100} and $RAC_{101-330}$ mean chronologies were 0.452 and 0.240, respectively. These figures clearly follow the SDs of the initial data in the corresponding age classes (0.531 and 0.286), as reported above.

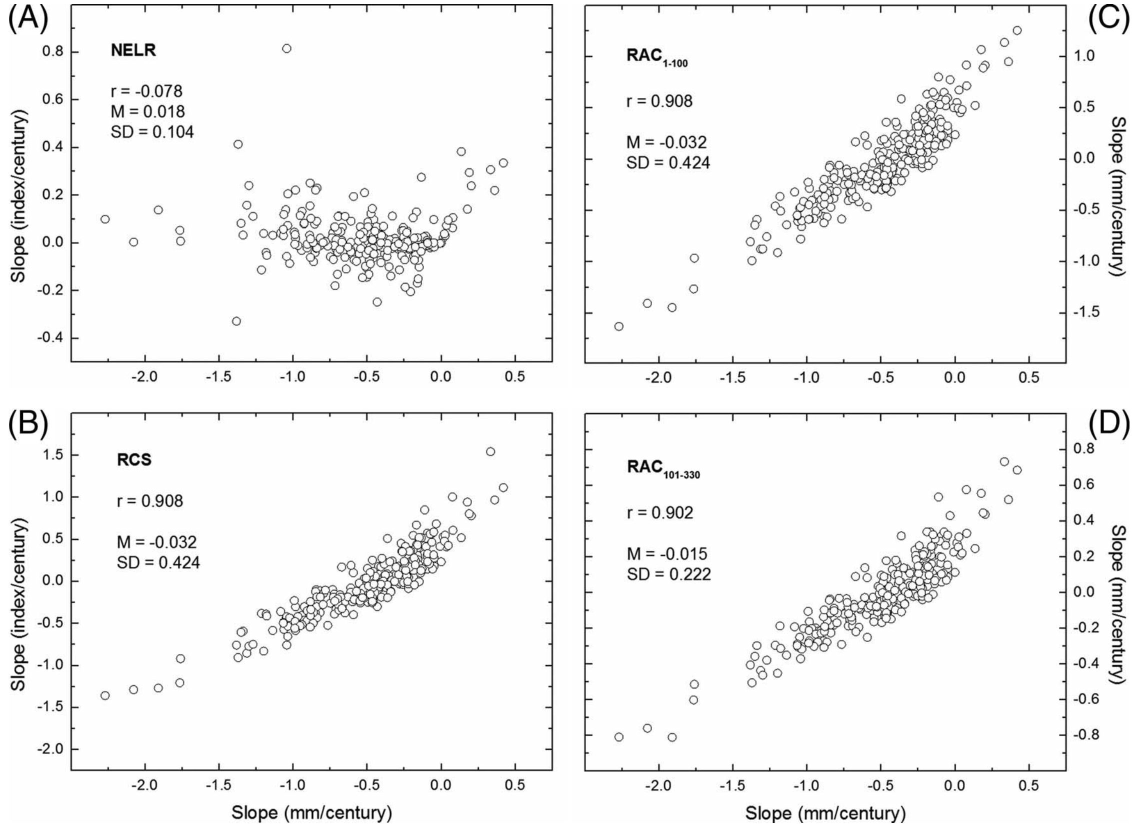


Figure 6. Relationships between the slopes calculated for observed tree-ring width series (horizontal axis) and the slopes calculated for tree-ring index time series based on NELR (A) and RCS (B) methods, and the modeled tree-ring width series relative to tree-ring characteristics of young (C; reference cambial ages; RAC_{1-100}) and old (D; $RAC_{101-330}$) growth variations (vertical axis). Each dot presents the slope estimates of a tree. The relationships are quantified using a Pearson correlation (*r*), the mean (M), and the SD of the slope estimates.

Dendroclimatic Analyses

Dendroclimatic analyses of the association between the local climate records and RAC chronologies (1900–2000) showed clear age dependencies as obtained for both the coefficients of regression slope (Figure 8A) and the intercept (Figure 8B) when the local temperature variability was used to model the growth as expressed by the set of 66 chronologies. There are nonlinear age-dependent associations between the mid-summer (July) temperature and Scots pine growth of 0.072 and 0.014 mm/° C for cambial age ranges of 1–5 to 226–330 years. Regression slopes showed positive and relatively high coefficients at younger ages compared with low coefficients at older cambial ages (Figure 8A). These findings were consistent with the age-dependent trend determined for the initial tree-ring properties (Figure 1). Importantly, the observed age dependence could be predicted from the linear transformation of the tree-ring growth properties through the chronology construction (Figure 6). However, the regression intercept mirrored the trend as observed for the slope, with negative coefficients (Figure 8B). In contrast, there appeared to be no clear linkage between the slope of the prior growth variables and the age of the rings in the RAC (Figure 8C). There was no association between the coefficient of determination (R^2) and age. R^2 varied between 0.66 and 0.70 (Figure 8D).

Discussion

Comparing the RAC with Conventional Methods

It is important that the new RAC method should not be confused with other tree-ring methods of chronology construction that extract age-dependent growth variations without defining standardization curves such as the age-band procedure described by Briffa et al. (2001). That particular method was previously described for the hemispheric tree-ring data set by using an approach that first subdivided the tree-ring series into different age classes, computed mean chronologies for those classes, normalized the growth variations in the age-dependent subchronologies over a common period, and then combined all the age-dependent subchronologies by calculating the overall mean. The new method, in comparison, does not require a common period, which may not in any case be present for a variety of age classes. It is notable that the lack of such a common period may indeed be the usual situation for tree-ring chronologies whereby the trees represent similar cambial ages such as when the sampling targets only the big trees (Brienen et al. 2012). The RAC method has no requirement for a common period; it also produces a continuous tree-ring chronology, whereas the previously proposed method described by Briffa et al. (2001) involves using age-band chronologies that may be assumed to contain gaps, such as when the sampled trees originated from episodic recruitment. Finally, the RAC method does not require the normalization of the data, unlike the age-band procedure, for which the growth variations of different age classes are transformed into an equal mean and SD. Clearly, the present RAC method represents a methodological departure from the majority of previously published standardization methods that express the tree-ring variations as dimensionless estimates.

The similarities of tree-ring chronologies using the RCS method (Briffa et al. 1992, 1996) with those of the RAC methods are illustrated (Table 1; Figure 5). These similarities are logical considering

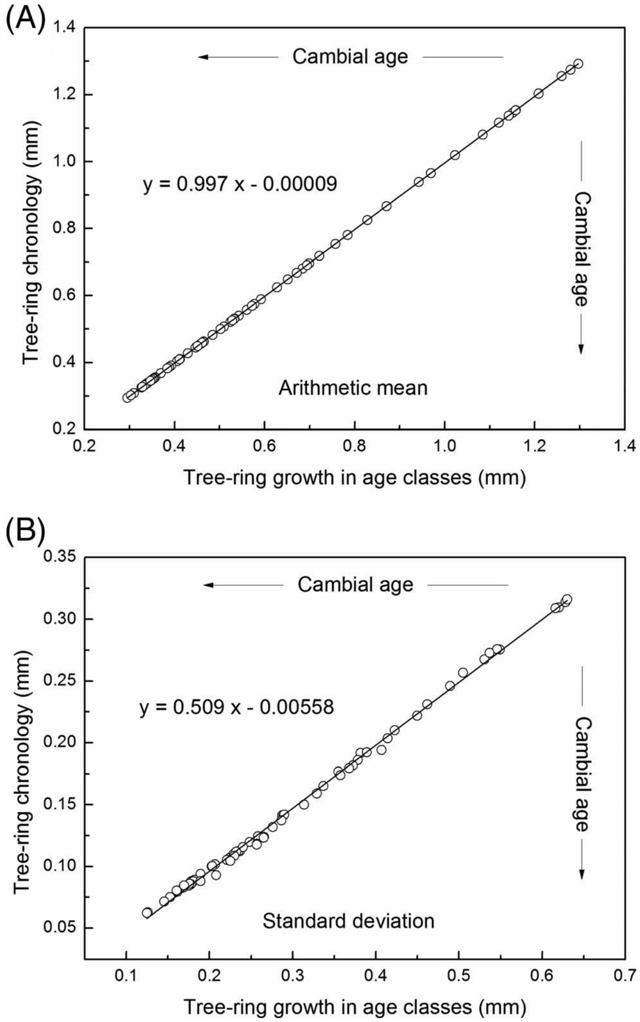


Figure 7. Characterization of the 66 tree-ring chronologies by their means (A) and SDs (B). Relationships between the observed and modeled tree-ring characteristics were quantified using a linear regression (black line).

that the RAC method builds on the available evidence of tree-ring growth levels for all the cambial age classes just as is done in the RCS method. The growth level mentioned in the RCS is determined as an age-dependent mean of tree-ring dimension (width and densities), thus leading to the construction of an expected growth curve; i.e., the RCS curve (an example of such a curve for the present data is shown in Figure 1A). In this RAC method, there is no need to define such a mean growth level, or curve; instead the original observations of tree-ring measurements are transformed to modeled tree-ring growth values through rank data conversions (Figure 2). It is notable that the RCS and RAC chronology variations were highly correlated for both the short- and long-term bands (Table 1). The smoothed series of RCS at low frequencies compared with RAC_{1-100} and $RAC_{101-330}$ chronologies appeared virtually inseparable on visual inspection (Figure 5B). These time scale-dependent patterns, however, markedly differed when the comparisons were made between the NELR and other chronologies. The NELR chronology was highly correlated with RCS, RAC_{1-100}, and $RAC_{101-330}$ chronologies. However, such correlations weakened considerably on long temporal scales (Table 1). Interestingly, the trend analysis of the tree-ring index series (NELR and RCS methods) and the series

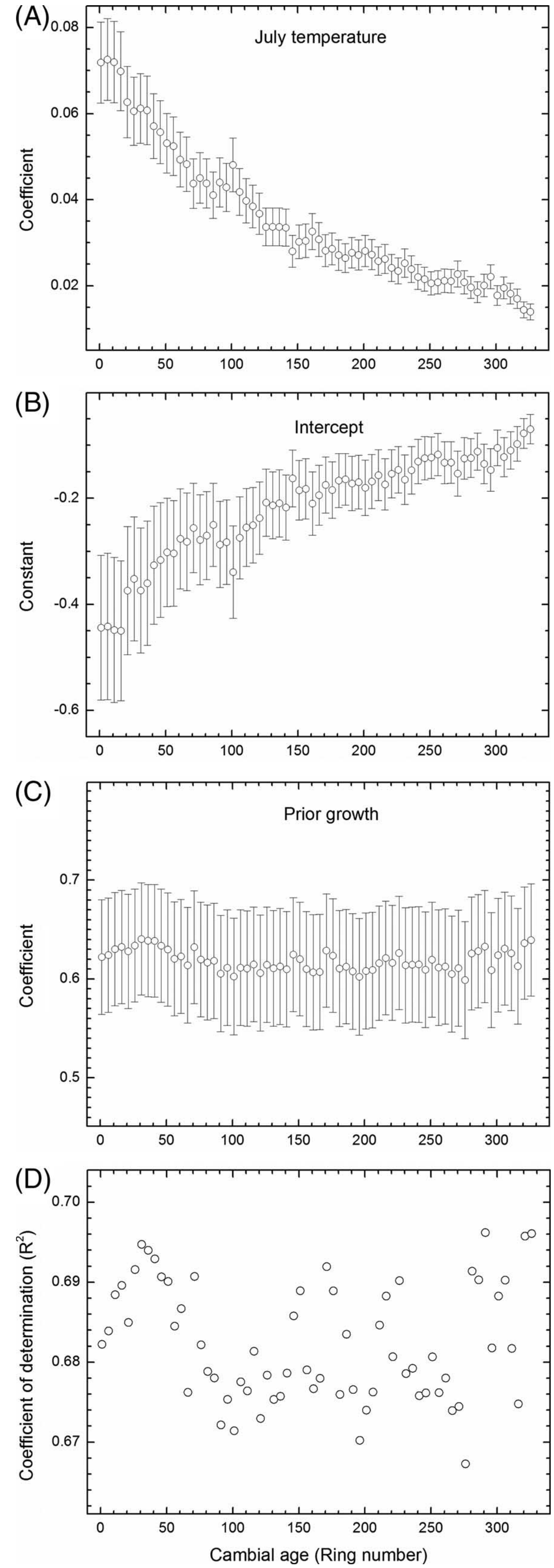


Figure 8. Dendroclimatic associations between the climate and modeled tree-ring growth as expressed by the 66 tree-ring chronologies using the functions including the regression slope of the July temperatures (A), the intercept (B), the prior growth (C), and the coefficient of determination (D). The bars indicate ±SEs for the coefficients/constant.

of the modeled tree-ring growth (RAC_{1-100} and $RAC_{101-330}$) illustrated the lack of capability of NELR to preserve long-term growth variations in the resulting chronology. More specifically, the long-term growth estimates that pertained to the series-long trends in the NELR index series did not show any association to the corresponding growth variations as observed in the measurement series (Figure 6A). This finding demonstrates the lack of reliability of the NELR method beyond the time scale of the segment length (in this case, a mean of 196 years), which is in agreement with the finding of a previous standardization study (Cook et al. 1995). These results are also in accordance with previous studies of tree-ring standardization showing that the NELR standardization has only some limited capacity for creating tree-ring chronology with preserved long-term growth variations (Cook and Briffa 1990, Lindholm 1996) but the RCS (Briffa et al. 1992, 1996, Esper et al. 2003, Helama et al. 2004, D'Arrigo et al. 2006, Linderholm et al. 2010) and RAC (this study) clearly outperformed other contemporary methods for detecting the growth variations of the lowest frequencies. In contrast to NELR, this RAC method shows promise for preserving the growth variations of long time scales to an extent similar to that of RCS, in the tree-ring chronology of this particular study. This was in addition to preserving the original growth variations typified by the selected reference cambial age.

In addition to detrending functions, the tree-ring standardization methods aim toward stabilizing the variance that may be heteroskedastic (Cook et al. 1990a, 1995). That is, the variance in tree-ring observations can be proportional to the mean over the same period. The proposed RAC method contains no mechanism for the effective removal of heteroskedasticity through its modeling framework. It is essential to note that even the other methods such as the NELR and RCS may not fully remove heteroskedasticity from the initial tree-ring data. The means and SDs of the raw data show a correlation of 0.74 as previously calculated for the data set at hand, whereas the NELR and RCS indices show weaker correlations with coefficients of 0.50 and 0.64, respectively (Figure 5 in Helama et al. 2004). Although these correlations indicate a somewhat weakened level of heteroskedasticity, they do show that full removal of heteroskedasticity would clearly require alternative methods that would be tailored to force the tree-ring variance to become homoskedastic (Cook and Peters 1997). When correlations similar to those reported in previous studies (Cook et al. 1990a, Helama et al. 2004) were calculated for the modeled tree-ring widths, the correlation coefficients of 0.61 and 0.74 for RAC_{1-100} and $RAC_{101-330}$ data sets were obtained. These figures indicate that the RAC method may indeed retain a slightly higher portion of heteroskedasticity in the resulting data in comparison to the RCS indices. It is noteworthy that not all tree-ring data display heteroskedasticity (Helama et al. 2008), however. The anticipated limitations of the new method would not affect the analyses of such tree-ring data.

Using the Modeled Tree-Ring Growth Data

The potential of the RAC method for expressing tree-ring chronologies with their low-frequency growth variations makes this novel method a valuable tool for estimating not only year-to-year growth fluctuations but also growth variations of a decadal-to-centennial scale. Previous tree-ring analyses of the *P. sylvestris* dendroclimatic anomalies in the study region demonstrated the difference in the tree-ring growth levels between the 19th and 20th centuries (Helama et al. 2002, 2009). Those earlier studies used the RCS method, thus completely relying on the corresponding tree-ring indices to provide dimensionless growth information. The visual inspection of the tree-ring chronologies obtained has already confirmed a parallel change of a growth increase in the modeled growth using both the RCS and RAC methods (Figure 5). Calculations of the time-series data of the RAC_{1-5} and $RAC_{325-330}$ chronologies yielded mean growth of 1.359 and 0.322 mm, respectively, over the 20th century (1902–2001). Over the 19th century, for the RAC_{1-5} and $RAC_{325-330}$ chronologies, means of 1.129 and 0.277 mm, respectively, were obtained. In a dendroclimatic context, this long-term interval and the direction of the observed growth change are both consistent with the known transition from the cool conditions of the Little Ice Age (Grove 1988, Matthews and Briffa 2005) to the 20th century warming. In particular, the cooling of the Little Ice Age occurred between the years 1570 and 1900 during which the Northern Hemisphere summer temperatures dropped significantly below the mean of the period 1961–1990 (Matthews and Briffa 2005). It is notable that the obtained growth means of the 19th and 20th century translate into dendrochronologically determined annual growth increases of 0.230 and 0.046 mm, as assessed by the youngest RAC_{1-5} and oldest $RAC_{325-330}$ chronologies, respectively. Such growth means are thus equivalent to the range of the most recent centurywide change in the timberline tree-ring growth in this region. However, even a larger change is evident throughout the 15th and 16th centuries (Figure 5). A calculation of the most notable growth change using the time-series data of the RAC_{1-5} and $RAC_{325-330}$ chronologies indicate improvement in tree-ring growth of 0.447 and 0.090 mm from the period of poor growth between the years 1388 and 1487 to a subsequent period of enhanced growth between the years 1488 and 1587. These figures illustrate nearly a 2-fold increase in the past long-term growth fluctuations in comparison to the recent 20th century warming increment.

The relationship between July temperature and growth was positive and clearly stronger than any other climate-growth relationship (Figure 8A), which was in accordance with previous dendroclimatic analyses for *P. sylvestris* in the same study region (Lindholm 1996, Nöjd and Hari 2001, Helama et al. 2002, 2005, 2009, Macias et al. 2004). This relationship whereby the daily increment of *P. sylvestris* can be explained through corresponding temperature data as a function of the seasonal stage of development has been previously modeled in fine detail (Hari and Sirén 1972, Nöjd and Hari 2001). The climate-growth relationships of this study were not assessed from tree-ring indices unlike the previous analyses, but by using the modeled tree-ring growth data, thus making it possible to determine the dendroclimatic relationship by which the actual age-dependent growth increment can be explained by a temperature scale (Figure 8). As a caveat to this, the RAC method cannot be used to resolve whether trees of different ages respond to different climate variables. For example, Copenheaver et al. (2011) showed that although the tree-ring growth of both young and old *Quercus alba* trees correlated with precipitation, only the old trees responded significantly to the occurrence of drought events. Despite this finding, Bogino et al. (2009) demonstrated that climate variables explained more of the tree-ring width variability in a young *P. sylvestris* stand than in older stands. Carrer and Urbinati (2004), on the other hand, showed that the older their sampled *Larix decidua* and *Pinus cembra* trees were, the higher the variance in tree-ring growth as explained by climate was. In comparison, the RAC chronologies are incapable of showing such differences for tree-ring growth at different cambial ages.

Conclusions

Estimation of tree growth variations using tree-ring data and chronologies using conventional methods produces dimensionless indices that may not preserve the low-frequency band of growth variations. The proposed standardization using the RAC method retains both the original measure of growth and the long-term growth variations. The capability of RAC to preserve the long-term growth amplitude was found to be similar to that of the RCS method, which was previously thought of as a particular method for maintaining the low-frequency demand. One benefit of this RAC method is that it now becomes possible to estimate changes in mean tree-ring growth from year to year and on interannual to centennial scales and still retain the measurement units as a detrended series. The RAC method also introduces the possibility for age-dependent modeling of climate-growth relationships. After the implementation of RAC, dendroclimatic analyses will benefit from being able to estimate the climatic constraints of adding an annual amount of biomass to tree radii. It is anticipated that these capabilities will enhance the applicability of dendrochronological data in the context of forestry research and management studies in which the estimation of absolute rather than relative change in growth is demanded.

Literature Cited

ANIOL, R.W. 1983. Tree-ring analysis using CATRAS. *Dendrochronologia* 1:45–53.

BOGINO, S., M.J. FERNÁNDEZ NIETO, AND F. BRAVO. 2009. Climate effect on radial growth of *Pinus sylvestris* at its southern and western distribution limits. *Silva Fenn.* 43:609–623.

BRIENEN, R.J.W., E. GLOOR, AND P.A. ZUIDEMA. 2012. Detecting evidence for CO_2 fertilization from tree ring studies: The potential role of sampling biases. *Global Biochem. Cycles* 26:GB1025.

BRIFFA, K.R. 2000. Annual climate variability in the Holocene: Interpreting the message of ancient trees. *Quatern. Sci. Rev.* 19:87–105.

BRIFFA, K., AND P.D. JONES. 1990. Basic chronology statistics and assessment. P. 137–152 in *Methods of dendrochronology: Applications in the environmental science*, Cook, E.R., and L.A. Kairiukstis (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

BRIFFA, K.R., P.D. JONES, T.S. BARTHOLIN, D. ECKSTEIN, F.H. SCHWEINGRUBER, W. KARLÉN, P. ZETTERBERG, AND M. ERONEN. 1992. Fennoscandian summers from AD 500: Temperature changes on short and long timescales. *Clim. Dyn.* 7:111–119.

BRIFFA, K.R., P.D. JONES, F.H. SCHWEINGRUBER, W. KARLÉN, AND S.G. SHIYATOV. 1996. Tree-ring variables as proxy-climate indicators: Problems with low-frequency signals. P. 9–41 in *Climate variations and forcing mechanisms of the last 2000 years,* Jones, P.D., R.S. Bradley, and J. Jouzel (eds.). Springer-Verlag, Berlin, Germany.

BRIFFA, K.R., T.J. OSBOR, H. SCHWEINGRUBER, I.C. HARRIS, P.D. JONES, S.G. SHIYATOV, AND E. VAGANOV. 2001. Low-frequency temperature variations from a northern tree ring density network. *J. Geophys. Res.* 106:2929–2941.

CARRER, M., AND C. URBINATI. 2004. Age-dependent tree-ring growth responses to climate in *Larix decidua* and *Pinus cembra. Ecology* 85:730–740.

CONOVER, W.J. 2012. The rank transformation—An easy and intuitive way to connect many nonparametric methods to their parametric counterparts for seamless teaching introductory statistics courses. *WIREs Comput. Stat.* 4:432–438.

COOK, E. 1990. Conceptual linear aggregate model for tree rings. P. 98–104 in *Methods of dendrochronology: Applications in the environmental sciences*, Cook, E.R., and L.A. Kairiukstis (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

COOK, E., AND K. BRIFFA. 1990. A comparison of some tree-ring standardization methods. P. 153–162 in *Methods of dendrochronology: Applications in the environmental sciences*, Cook, E.R., and L.A. Kairiukstis (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

COOK, E.R., AND K. PETERS. 1981. The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree Ring Bull.* 41:45–53.

COOK, E.R., AND K. PETERS. 1997. Calculating unbiased tree-ring indices for the study of climatic and environmental change. *Holocene* 7:359–368.

COOK, E.R., K.R. BRIFF, M. MEKO, D.A. GRAYBILL, AND G. FUNKHOUSER. 1995. The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. *Holocene* 5:229–237.

COOK, E., K. BRIFFA, S. SHIYATOV, AND V. MAZEPA. 1990a. Tree-ring standardization and growth-trend estimation. P. 104–123. in *Methods of dendrochronology: Applications in the environmental sciences*, Cook, E.R., and L.A. Kairiukstis (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

COOK, E., S. SHIYATOV, AND V. MAZEPA. 1990b. Estimation of the mean chronology. P. 123–132 in *Methods of dendrochronology: Applications in the environmental sciences*, Cook, E.R., and L.A. Kairiukstis (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

COPENHEAVER, C.A., C.J. CRAWFORD, AND T.M. FEARER. 2011. Age-specific responses to climate identified in the growth of *Quercus alba. Trees* 25:647–653.

D'ARRIGO, R., R. WILSON, AND G. JACOBY. 2006. On the long-term context for late twentieth century warming. *J. Geophys. Res.* 111: D03103.

DOBBERTIN, M. 2005. Tree growth as indicator of tree vitality and of tree reaction to environmental stress: A review. *Eur. J. For. Res.* 124:319–333.

DURBIN, J., AND G.S. WATSON. 1951. Testing for serial correlation in least squares regression II. *Biometrika* 38:159–178.

ESPER, J., E.R. COOK, P.J. KRUSIC, K. PETERS, AND F.H. SCHWEINGRUBER. 2003. Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Res.* 59:81–98.

ESPER, J., D.C. FRANK, G. BATTIPALAGIA, U. BÜNTGEN, C. HOLERT, K.S. TREYDTE, R.T.W. SIEGWOLF, AND M. SAURER. 2010. Low-frequency noise in $\delta^{13}C$ and $\delta^{18}O$ tree ring data: A case study of *Pinus uncinata* in the Spanish Pyrenees. *Global Biogeochem. Cycles* 24:GB4018.

ESPER, J., D. FRANK, U. BÜNTGEN, AND A. KIRDYANOW. 2009. Influence of pith offset on tree-ring chronology trend. *Tree Rings Archaeol. Climatol. Ecol.* 7:205–210.

FRITTS, H.C. 1976. *Tree rings and climate.* Academic Press, London, UK. 567 p.

FRITTS, H.C., AND T.W. SWETNAM. 1989. Dendroecology: A tool for evaluating variations in past and present forest environments. *Adv. Ecol. Res.* 19:111–188.

FRITTS, H.C., J.E. MOSIMAN, AND P. BOTTORFF. 1969. A revised computer program for standardizing tree-ring series. *Tree Ring Bull.* 29:15–20.

GROVE, J.H. 1988. *The Little Ice Age.* Routledge, London, UK. 498 p.

HARI, P., AND G. SIRÉN. 1972. Influence of some ecological factors and the seasonal stage of development upon the annual ring width and radial growth index. Royal College of Forestry, Department of Reforestation, Stockholm. *Res. Notes* 40:1–22.

HELAMA, S., M. LINDHOLM, J. MERILÄINEN, M. TIMONEN, AND M. ERONEN. 2005. Multicentennial ring-width chronologies of Scots pine along north-south gradient across Finland. *Tree-Ring Res.* 61:21–32.

HELAMA, S., M. LINDHOLM, M. TIMONEN, J. MERILÄINEN, AND M. ERONEN. 2002. The supra-long Scots pine tree-ring record for Finnish Lapland: Part 2, interannual to centennial variability in summer temperatures for 7500 years. *Holocene* 12:681–687.

HELAMA, S., M. LINDHOLM, M. TIMONEN, AND M. ERONEN. 2004. Detection of climate signal in dendrochronological data analysis: A comparison of tree-ring standardization methods. *Theor. Appl. Climatol.* 79:239–254.

HELAMA, S., N.G. MAKARENKO, L.M. KARIMOVA, O.A. KRUGLUN, M. TIMONEN, J. HOLOPAINEN, J. MERILÄINEN, AND M. ERONEN. 2009. Dendroclimatic transfer functions revisited: Little Ice Age and Medieval Warm Period summer temperatures reconstructed using artificial neural networks and linear algorithms. *Ann. Geophys.* 27:1097–1111.

HELAMA, S., M. VARTIAINEN, T. KOLSTRÖM, H. PELTOLA, AND J. MERILÄINEN. 2008. X-ray microdensitometry applied to subfossil tree-rings: Growth characteristics of ancient pines from the southern boreal forest zone in Finland at intra-annual to centennial time-scales. *Veg. Hist. Archaeobot.* 17:675–686.

HOLMES, R.L. 1983., Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* 43:69–75.

LINDERHOLM, H.W., B.E. GUNNARSON, AND Y. LIU. 2010. Comparing Scots pine tree-ring proxies and detrending methods among sites in Jämtland, west-central Scandinavia. *Dendrochronologia* 28:239–249.

LINDHOLM, M. 1996. *Reconstruction of past climate from ring-width chronologies of Scots pine (Pinus sylvestris L.) at the northern forest limit in Fennoscandia.* PhD dissertation, Univ. Joensuu, Joensuu, Finland. 169 p.

MACIAS, M., M. TIMONEN, A.J. KIRCHHEFER, M. LINDHOLM, M. ERONEN, AND E. GUTIÉRREZ. 2004. Growth variability of Scots pine (*Pinus sylvestris*) along a west-east gradient across northern Fennoscandia: A dendroclimatic approach. *Arctic Antarctic Alp. Res.* 36:565–574.

MATTHEWS, J.A., AND K.R. BRIFFA. 2005. The 'Little Ice Age': Re-evaluation of an evolving concept. *Geogr. Ann.* 87A:17–36.

MELVIN, T.M., K.R. BRIFFA, K. NICOLUSSI, AND M. GRABNER. 2007. Time-varying-response smoothing. *Dendrochronologia* 25:65–69.

MONSERUD, R.A. 1986. Time-series analyses of tree-ring chronologies. *For. Sci.* 32:349–372.

MURPHY, J.O., AND J.G. PALMER. 1992. A comparison of two tree-ring-index standardization methods. *Can. J. For. Res.* 22:1922–1928.

NÖJD, P., AND P. HARI. 2001. The effect of temperature on the radial growth of Scots pine in northernmost Fennoscandia. *For. Ecol. Manage.* 142:65–77.

OSBORN, T.J., K.R. BRIFFA, AND D. JONES. 1997. Adjusting variance for sample-size in tree-ring chronologies and other regional mean time-series. *Dendrochronologia* 15:89–99.

SCHWEINGRUBER, F.H., T. BARTHOLIN, E. SCHÄR, AND K.R. BRIFFA. 1988. Radiodensitometric-dendroclimatological conifer chronologies from Lapland (Scandinavia) and the Alps (Switzerland). *Boreas* 17:559–566.

SHIYATOV, S., V. MAZEPA, AND E. COOK 1990. Correcting for trend in variance due to changing sample size. P. 133–137 in *Methods of dendrochronology: Applications in the environmental sciences*, Cook, E.R., and L.A. Kairiukstis (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

SPIECKER, H. 2002. Tree rings and forest management in Europe. *Dendrochronologia* 20:191–202.

STRAND, M., M.O. LÖFVENIUS, U. BERGSTEN, T. LUNDMARK, AND O. ROSVALL. 2006. Height growth of planted conifer seedlings in relation to solar radiation and position in Scots pine shelterwood. *For. Ecol. Manage.* 224:258–265.

VAN DEUSEN, P.C. 1990. Popular formulations for modeling tree rings from climate: A unifying approach. *J. Environ. Qual.* 20:823–827.