

Removing the Tree-Ring Width Biological Trend Using Expected Basal Area Increment

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Abstract—One of the main elements of dendrochronological standardization is the removal of the biological trend, i.e., the progressive decline of ring width along a cross-sectional radius that is mostly caused by the corresponding increase in stem diameter over time. A very common option for removing this biological trend is to fit a modified negative exponential curve to the ring-width measurements. Because this method has numerical and conceptual drawbacks, we propose an alternative way based on a simple assumption, namely that a constant basal area increment is distributed over a growing surface. We then derive a mathematical expression for the biological trend, which can be easily calculated and used for dendrochronological standardization. In turn, this “C-method” provides an empirical test of existing theories on life-long progression of tree basal area increment. The proposed method was applied to tree-ring records from ponderosa pines (*Pinus ponderosa* Douglas ex P.Lawson & C.Lawson) located at the G. A. Pearson Natural Area in northern Arizona, U.S.A. Master ring-index chronologies built with the C-method reproduced stand-wide patterns of tree growth, and are therefore preferable for ecological applications. Other advantages of the C-method are that it is theoretically derived, it is applicable to individual series, and it does not require fitting a growth curve using nonlinear regression.

Introduction

As trees grow older and increase in size, annual ring width generally decreases along a cross-sectional radius, mostly because of the geometrical constraint to add new wood layers over an expanding surface (Cook 1987, Douglass 1919, Fritts 1976). In shade-intolerant, open grown trees, this trend dominates the temporal sequence of annual wood formation throughout the life history of the tree (Helama and others 2005, Husch and others 2003). In shade-tolerant, forest interior trees this period of ring-width decline normally occurs after the tree has become dominant, and is commonly preceded by one or more periods of growth suppression and release while the tree occupies lower canopy levels (e.g., Canham 1990, Fraver and White 2005, Piovesan and others 2005). Regardless of their overall shape, such individual growth trends are associated with a change in the year-to-year ring-width variation, so that when ring widths are larger, their variability is larger as well (Cook and Peters 1997). A number of ways have been proposed in the literature to remove growth variations in both mean and variance that are specific to an individual tree, i.e. to “standardize” ring-width series prior to combining them into a master chronology (Biondi 1993, Cook and Kairiukstis

1990, Warren and Leblanc 1990). Most of these techniques require the elimination of the biological trend by fitting a curve to the raw ring-width measurements. Recently, debate has focused on which standardization option should be used to retain climatic variability at long timescales, i.e., “low-frequency” modes (e.g., Bunn and others 2004, Esper and others 2003, 2005, Helama and others 2005, Melvin and others 2007, National Research Council 2006). In fact, the length of individual ring-width series used to produce a master chronology (rather than the length of the chronology itself) can determine the maximum timescale of retrievable climatic fluctuations (Cook and others 1995). As a contribution to the debate on tree-ring standardization, we have focused on those methods that remove the biological trend by fitting a modified negative exponential function to individual ring-width series. This option is commonly implemented through the software program ARSTAN (Cook and Holmes 1986), and is widely adopted in dendrochronological investigations under the loose term of “conservative” detrending (e.g., Salzer and Kipfmüller 2005, Villalba and others 1998, Woodhouse and Lukas 2006). In this paper we propose an alternative method, which is mathematically derived from the simple assumption of distributing a constant basal area increment over an expanding surface. By formally describing this process, a purely empirical approach

to tree-ring standardization is replaced with a theoretical one. An illustration of the method is provided using data from the G. A. Pearson Natural Area. This approach to ring-width standardization can also be used to empirically test existing theories on expected patterns of basal area increment for individual trees.

Model Specification

A mathematical representation of the modified negative exponential option for ring-width standardization is as follows:

$$w_t = ae^{-bt} + k \quad (1)$$

where w_t is ring width at year t , a is ring-width at year zero (if k is negligible), b is the slope of the decrease in ring width (hence, the “concavity” of the curve), and k is the minimum ring width, which is asymptotically approximated for large values of t . When the estimated value of either a or b is negative, a linear regression is fit to the data, usually with slope ≤ 0 (Fritts and others 1969; Cook and Holmes 1986). Historically, the asymptote of the modified negative exponential equation was introduced to allow for the relatively constant ring width of very old conifers in the Western United States (Fritts and others 1969). This modification, however, makes the equation “open form” because fitting this model is equivalent to estimating a nonlinear regression equation, hence model parameters are computed iteratively (Press and others 2002). This implies that the method is sensitive to several choices made for estimation purposes. For instance, depending on the tolerance assigned for the goodness-of-fit statistic, the starting values, the number of iterations allowed, and the resolution of the incremental changes made to the initial parameter values, different results can be obtained. In other words, instead of fitting a modified negative exponential, a straight line could be selected simply because of numerical instabilities (for an example, see Figure 3B). This can have important consequences, especially if the estimated curve parameters are then used for drawing climatic or ecological inferences (as was done by Helama and others 2005).

Even more relevant for tree-ring standardization is the presence of an asymptote in equation (1), given its implications for basal area increment (BAI), which represents overall tree growth better than ring width (Husch and others 2003, LeBlanc 1990, Valentine 1985). Because BAI at year t is equivalent to the annual radial increment (e.g., Biondi 1999, LeBlanc 1993, Phipps and Whiton, 1988), one can write

$$BAI_t = \pi R_t^2 - \pi R_{t-1}^2 \quad (2)$$

where R_t is the stem radius at the end of the annual increment, and R_{t-1} is the stem radius at the beginning of the annual increment (Figure 1). Considering that annual ring width (w_t) is equivalent to the annual radial increment ($w_t = R_t - R_{t-1}$), it follows that:

$$BAI_t = \pi (w_t^2 + 2 w_t R_{t-1}) \quad (3)$$

From equation (3) one can see that the asymptote of equation (1) corresponds to a constant increase of BAI over time. Although such a pattern can occasionally be found (Phipps 2005), it is at odds with the majority of observations and theories found in the scientific literature. Forest ecologists have shown that BAI of dominant, healthy trees can rise for varying periods of time during their life, but even in the best growing conditions, BAI is bound to approach an asymptotic level (Duchesne and others 2002, 2003, Elvir and others 2003, Pederson 1998, Poage and Tappeiner II 2002, Valentine and Mäkelä 2005).

The biological trend of ring width can be estimated using a simple assumption, namely that a constant basal area increment is distributed over a growing surface over time. From equation (3), this assumption can be written as

$$w_t^2 + 2w_t R_{t-1} = c \quad (4)$$

with c being the constant BAI. It is easily shown that (4) is a quadratic equation in the variable w_t , and that the only logical solution (given that $w_t \geq 0$) is as follows:

$$w_t = R_{t-1} + \sqrt{R_{t-1}^2 + c} \quad (5)$$

Considering that R_{t-1} is the sum of all ring widths from year 0 (the pith date) to year $t-1$, one can write

$$w_t = \sqrt{\left(\sum_{i=0}^{t-1} w_i\right)^2} + c - \sum_{i=0}^{t-1} w_i \quad (6)$$

For $t=0$ there is yet no ring width, hence an expression of the *tree potential for growth* can be derived from the previous equation, as follows:

$$w_0 = \sqrt{c} \quad (7)$$

Using equations (6) and (7), it is straightforward to verify that, for any time t , the *expected ring width* (Ew_t) when *basal area increment remains constant* is given by

$$Ew_t = \sqrt{c(t+1)} - \sqrt{ct} \quad (8)$$

This relationship implies that the biological trend in ring-width of mature trees can be removed by knowing the value of c , which, in turn, can be mathematically derived from equation (8), with the following result:

$$c = \frac{(Ew_t)^2}{2t+1 - 2t\sqrt{1 + \frac{1}{t}}} \quad (9)$$

For estimation purposes, one can then use

$$= \frac{\text{median}_{t=1, \dots, n} \left(\frac{w_t^2}{2t+1 - 2t\sqrt{1 + \frac{1}{t}}} \right)}{\quad} \quad (10)$$

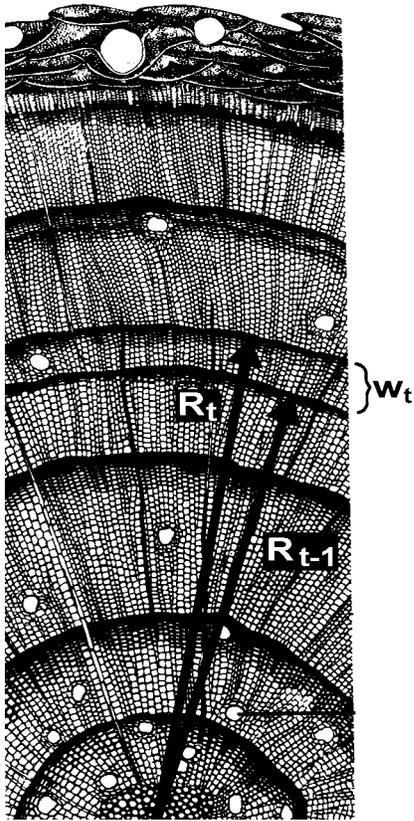


Figure 1. Schematic representation of a conifer cross section, modified from Fig. 2.3 of Fritts (1976). At each year, annual ring width (w_t) is equal to the difference between the current tree radius (R_t) and the prior year radius (R_{t-1}).

with \hat{C}_i = estimated constant basal area for tree i , \hat{C}_t = estimated constant basal area for year t , and n = number of years in the ring-width series. Given its notation, this approach is described as the “C-method” in the remainder of the article.

Application to Ponderosa Pines at the G. A. Pearson Natural Area

Tree-ring records from a long-term monitoring forest research area in northern Arizona were used to illustrate the model (Table 1, Figure 2). The area is occupied by a ponderosa pine (*Pinus ponderosa* Douglas ex P.Lawson & C.Lawson) ecosystem, which has been thoroughly studied in relation to impacts on forest vegetation of land use changes caused by Euro-American settlement (Biondi 1999, Covington and others 2001, Moore and others 2006). This dataset was selected because several increment cores either included the pith or came close to it, hence allowing for accurate ages to be assigned to each ring (Table 1). Furthermore, it was possible

Table 1. Summary of tree-ring samples collected from ponderosa pines at the G.A. Pearson Natural Area (35.27°N, 111.74°W, 2230-2260 m asl), northern Arizona, U.S.A. (Biondi 1999), and used for illustrating the C-method of ring-width standardization.

Tree Type*	Site Information			Increment Core Summary			Ring-Width Statistics					
	DBH (cm)	Height (m)	Length (yrs)	Total No. of Rings	Years to pith	Period (yrs)	LAR	Mean (mm)	SD (mm)	Min (mm)	Max (mm)	A_1
Small (“Blackjack”)	31.8 19.5-46.8	14.4 9.6-23.4	78 53-144	4509	7 1-34	1847-1990	7 (0.16%)	1.45 0.92-2.23	0.78 0.30-1.48	0.34 0-0.94	3.75 1.96-7.21	0.78 0.26-0.95
Large (“Yellow pine”)	82.4 50.4-114.8	29.0 18.3-36.0	283 92-418	16408	64 1-249	1570-1990	194 (1.18%)	1.08 0.48-2.05	0.61 0.23-1.24	0.08 0-0.65	3.17 1.20-5.50	0.73 0.38-0.92

* 58 cores from 29 trees were used for each of these two size classes.

DBH: diameter at breast height (the average as well as the min-max are shown).

Length: number of years included in the 58 wood cores (the average as well as the min-max are shown; the total is given in the next column).

Years to pith: estimated gap from the innermost ring of the core to the stem pith (the average as well as the min-max are shown).

Period: first and last year of the time interval covered by the combination of all measured rings.

LAR = locally absent rings (ring width equal to zero; the percentage refers to the total number of rings).

SD = standard deviation of the ring-width measurements (the average as well as the min-max are shown).

A_1 = first-order autocorrelation of the ring-width measurements (the average as well as the min-max are shown).

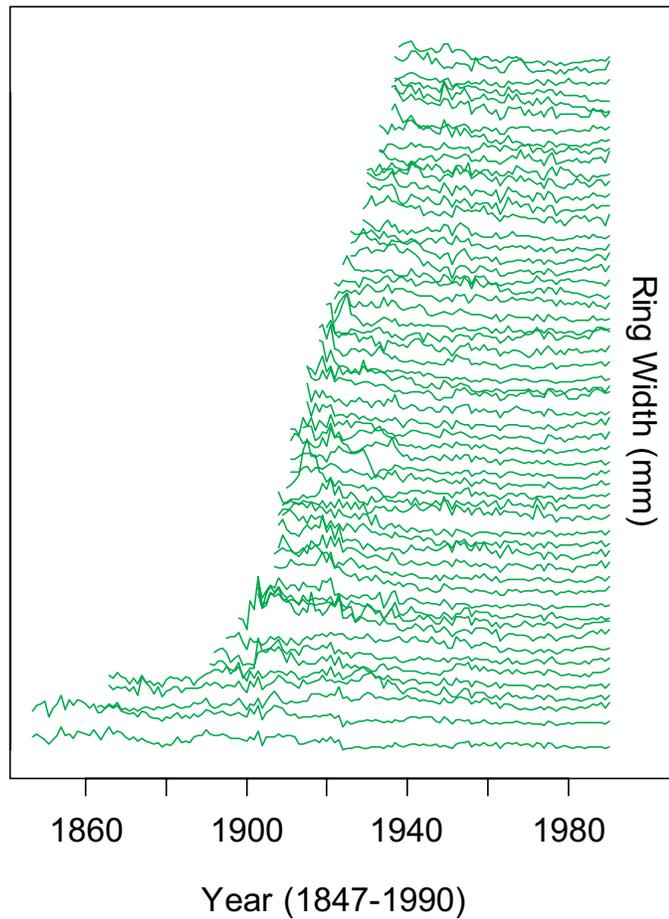
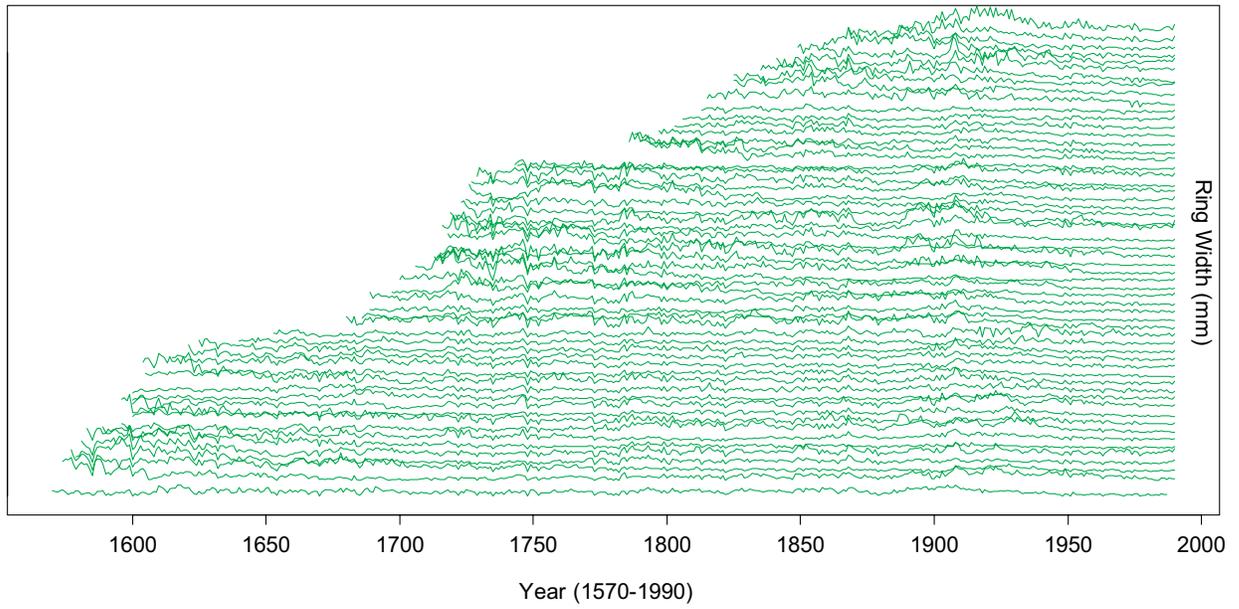


Figure 2. Time-series plots of ring-width measurements, sorted by first year, from wood increment cores taken at the G. A. Pearson Natural Area, Arizona, U.S.A. (see text for details). The vertical scale (not shown) was the same for all segments.
 Ponderosa pines with DBH > 50 cm
 Ponderosa pines with DBH < 50 cm

to make comparisons between young “blackjacks” (DBH < 50 cm), whose xylem rings formed mostly during the 20th century, when lack of fire and successful regeneration increased the density of the stand, and old “yellow pines” (DBH > 50 cm), whose annual growth had occurred under widely different conditions prior to Euro-American settlement (Biondi 1996, Mast and others 1999). Finally, the dataset had already been used to compare the outcome of various standardization methods, knowing what the overall growth trend in the forest had been over the 20th century because of repeated timber inventories that were conducted at the study area (Biondi and others 1994, Biondi 1999).

Ring-width series were visually cross-dated, measured with a resolution of 0.01 mm, and checked for errors using computer-aided techniques (Grissino-Mayer 2001, Holmes 1983). Pines with DBH < 50 cm had a much lower number of years between the innermost measured ring width and the stem pith (Table 1). Pith location was usually easier to identify in cores from these trees than in cores from pines with DBH > 50 cm (Biondi 1999). Time series plots of the original measurements (Figure 2) showed clearly the age difference between the two groups of trees, which was also reflected in the number of locally absent rings (Table 1). Old “yellow” pines had more than seven times the percentage of locally absent rings than young “blackjacks.”

The C-method was used to standardize the ponderosa pine ring width series after aligning them according to biological age (i.e., years since pith formation). The method was applied to individual ring width series, and in each case the resulting curve did not need additional smoothing. Ring indices were obtained as ratios between the ring width measurements and their expected values, then indices were realigned according to calendar years, and the master chronology computed as either the mean or the median of the indices by calendar year.

Common patterns among index time series were quantified by pairwise linear correlation coefficients (Wigley and others 1984), by pairwise Baillie-Pilcher’s *t*-values (Baillie and Pilcher 1973), and by the first principal component (Jolliffe 1986) for the 1938-1987 period common to all samples.

There was little difference between computing chronologies either as the mean or the median of the indices for each year, hence only the latter is plotted in Figures 3 and 4. A greater amount of common variability was found in the older ponderosas than in the younger ones; ring indices of pines with DBH > 50 cm had higher cross-dating statistics (Table 2). Despite changes in sample depth from 1-2 samples per year in the early part of the chronologies to 58 samples per year in the most recent period, the C-method generated master chronologies with relatively stable variance over time (Figures 3 and 4).

Estimated constant basal area increment (\hat{C}_i , Table 2) was about twice as large for pines with DBH > 50 cm as for those with DBH < 50 cm. This was most likely related to the overall slower decline in ring size with biological age seen in the older trees compared to the younger ones. In other words, the increasing stand density during the 20th century, which prompted drastic changes in individual growth rates (Biondi and others 1994, Biondi 1996), also caused this difference in C-method statistics between pre- and post-settlement trees.

From a comparison with other detrending options applied to the same dataset (Biondi 1999), it was already known that applying ‘conservative’ standardization methods generated chronologies with trends that did not match those of repeated forest inventories. In this study, C-method chronologies shared the ability of ring-area chronologies to reproduce the stand-wide decline of tree growth during the 20th century (Biondi 1996). In addition, C-method chronologies mimicked

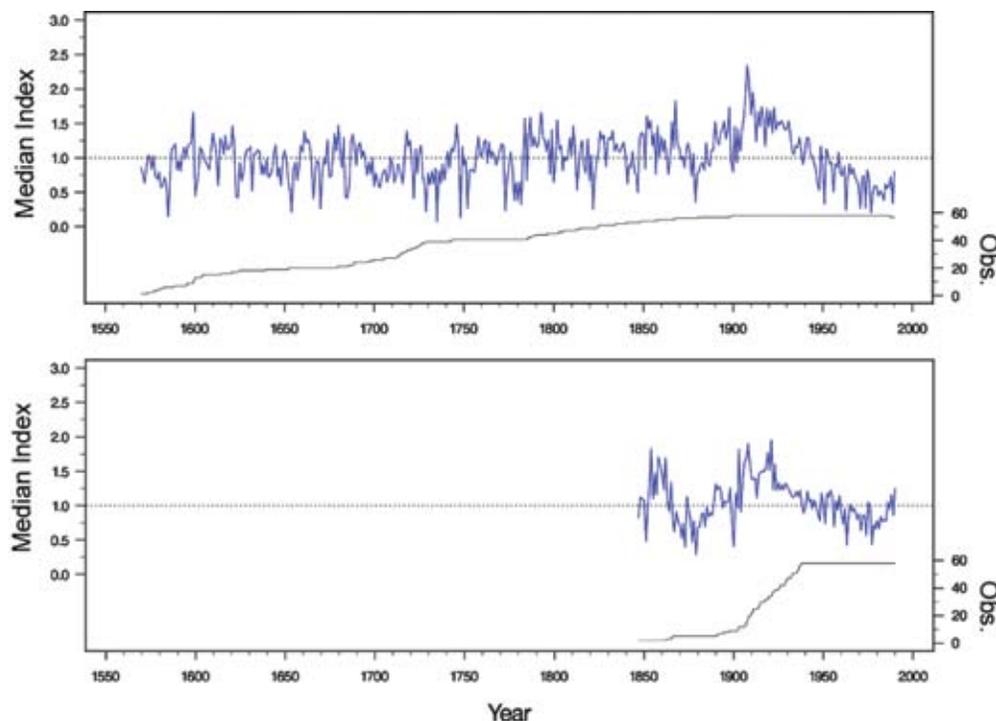


Figure 3. Tree-ring chronologies (Median Index) obtained using the C-method for ponderosa pines with DBH < 50 cm (lower panel), and ponderosa pines with DBH > 50 cm (upper panel). The number of samples per year (Obs.) is also shown (black line).

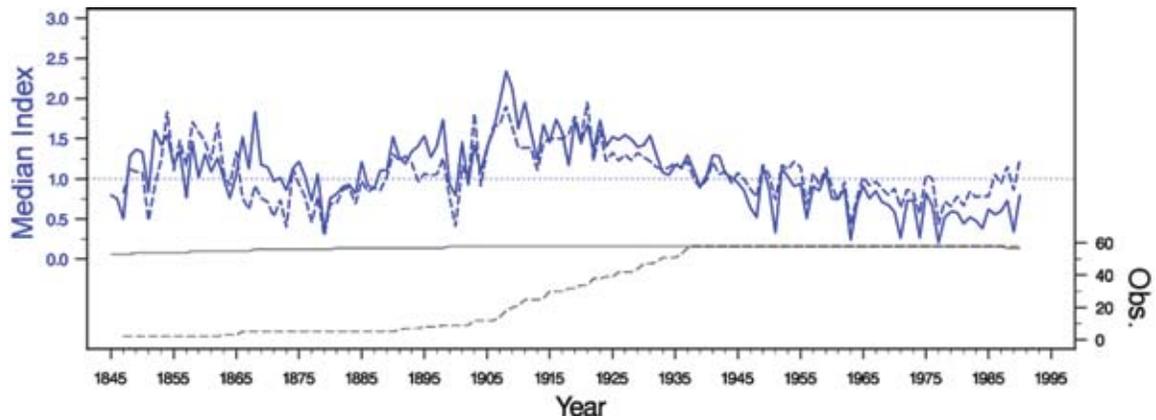


Figure 4. Tree-ring chronologies (Median Index) for ponderosa pines with DBH < 50 cm (dashed lines), and ponderosa pines with DBH > 50 cm (solid lines) obtained using the C-method. The number of samples per year (Obs.) is also shown (black line).

Table 2. Statistics of standardized ring-width indices obtained from the division between the original measurements and the expected ring width from the C-method. The arithmetic average and the minimum-to-maximum interval are shown for most parameters.

DBH (cm)	Mean	SD	Min	Max	A_1	Pairwise r-value	Pairwise t-value	1 st PC % Var.	\hat{C}_i (mm ² yr ⁻¹)
< 50	1.05	0.40	0.27	2.14	0.56	0.33	4.8	43	271
	0.96-1.29	0.22-0.86	0-0.57	1.35-3.94	0.09-0.87	-0.43 to 0.90	-0.1 to 28.3		75-713
> 50	1.08	0.55	0.08	3.12	0.68	0.47	9.9	63	563
	0.98-1.32	0.29-1.08	0-0.45	1.91-5.34	0.43-0.87	-0.48 to 0.92	1.9-37.9		225-1269

SD, A_1 = see definitions under Table 1

1st PC % Var. = percentage of overall variance during the common period 1938-1987 explained by the first principal component

\hat{C}_i = estimated constant basal area increment for each ring-width series

the steeper decrease of annual increment found in large pines compared to small ones, so that while large pines were growing faster than small pines in the early 1900s, the opposite was true at the end of the 1900s (Figure 4). This reversal in the order of individual growth rates was not so accurately reproduced even by the ring area method (see Figures 4 and 5 in Biondi 1999).

The C-method performance (Table 2, Figures 3 and 4) provides support for its simple assumption, namely that the biological trend is mostly caused by the geometrical constraint to distribute a constant basal area increment over an expanding surface. The well-established pipe theory (Valentine 1985) suggests that sapwood cross-sectional area averaged over the length of the bole approximates the sapwood area at the base of the crown (Valentine and Mäkelä 2005). Considering that most ring-width series with any climatic information come from mature, dominant trees (Fritts 1976), which have already reached their maximum height, the assumption of constant annual basal area increment translates directly into a constant rate of wood accumulation. Basal area increment usually outperforms ring width for measuring

overall tree growth, as it has been repeatedly shown with regard to tree mortality (Bigler and Bugmann 2003, 2004b, a, Bigler and others 2004a, b).

The C-method, just like basal area increment computed from ring-width data, requires knowing the biological age of each growth ring. However, both the C-method and the calculation of ring area can fit individual ring-width series, so they are well suited for relatively small sample sizes (< 100 series). Another advantage of the ring area and C-method approaches is their numerical simplicity, since all computations can be done in a spreadsheet, and there is no need to fit a growth curve using nonlinear regression methods.

In any method based on biological ring age, it is risky to assume that the innermost ring is the closest one to the pith, especially when dealing with very old trees or irregular stems. As detrending methods based on the biological age of growth rings become more commonly used, specific metadata on the difference between ring order and ring age will have to be included in archived and publicly available datasets.

While benchmarking dendrochronological standardization methods against forest growth data is ecologically

sound, additional research should be aimed at comparing this (and other) methods of removing the biological trend in terms of their ability to properly reconstruct climatic signals for a variety of biogeographic regions, ecosystems, and tree conditions (species, age, etc.). For instance, it is possible that, when dealing with ring-width series from extremely old trees with irregular growth forms, from forest interior environments, from shade-tolerant species, and from relict or subfossil wood, the best standardization method would simply be a smoothing algorithm with a known frequency response, such as the cubic spline option in the ARSTAN package (Cook and Peters 1981, Cook and Holmes 1986). Still, the C-method already provides a superior alternative in all those cases where fitting a modified negative exponential curve (or a straight line) is used for removing the biological growth trend from ring-width series.

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