

The limits of freely-available tree-ring chronologies

Bethany L. Coulthard¹, Scott St. George^{2,3}, and David M. Meko⁴

¹Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, NV, 89119, USA

²Department of Geography, Environment and Society, University of Minnesota, Minneapolis, MN, 55455, USA

³Department of Geography, Johannes Gutenberg University, Mainz, 55128, Germany;

⁴Laboratory of Tree-Ring Research, University of Arizona, AZ, Tucson, 85721, USA.

Corresponding author email: bethany.coulthard@unlv.edu*

1 Trees rank as some of the longest-lived organisms on our planet. Because their growth is affected
2 by both biotic and abiotic factors, many species that form annual rings provide an exceptional,
3 long-term archive of past environmental and ecological change. As testament to the deeply-
4 rooted culture of data-sharing by dendrochronologists, tree-ring records are now freely available
5 from thousands of locations worldwide and used extensively in climate science and forest
6 ecology. Many of these datasets are presented in the form of a tree-ring ‘chronology’ — a
7 composite series made by averaging together measurements of tree-ring width, wood density,
8 isotopic composition, or other anatomical or biogeochemical variables from several dozen or
9 more trees at the same location (Cook and Kairiukstis 1990). Low-cost environmental datasets of
10 such rich time resolution and spatial coverage are understandably attractive, but using tree-ring
11 chronologies requires a deep understanding of the methods applied to produce them and the
12 limits those methods impose. In this comment, we discuss several important but often
13 unrecognized aspects of tree-ring chronologies that can are needed for their interpretation, and
14 highlight ways to make these data more suitable for widespread use.

15
16 Most annual radial measurements from individual trees contain strong trends due to endogenous
17 (biological) factors, so before they can be compiled and interpreted as evidence of exogenous
18 (environmental) influences, those age/size trends must be removed through a procedure known
19 as detrending or standardization (Fritts 1976). Total ring-width sequences often exhibit a gradual
20 decline from wide to narrow rings as a tree ages and forms a similar volume of wood about the
21 ever-increasing circumference of its stem. Maximum latewood density sequences, however,
22 increase rapidly during early decades as trees transition from juvenile to mature wood, then
23 reduce as they dedicate fewer resources to thickening their cell walls (Esper et al. 2010). Some

stable isotope records have also been reported to have age-dependent trend (Esper et al. 2010). To disentangle the multiple competing signals in tree-ring sequences, dendrochronologists have developed a suite of empirical methods to estimate and remove growth trends, each of which has its own advantages and limitations. At one extreme, if a detrending method is used that removes all variance longer than a few decades, the final chronology (Fig. 1a,b) will highlight year-to-year growth patterns perhaps useful for dating or certain ecological studies, but will not retain information about more gradual patterns occurring over decades, centuries, or longer. If we prefer instead to target those slower changes which might be linked to century- or millennial-scale variations in climate or ecology, we apply so-called ‘conservative’ detrending methods that preserve longer-term fluctuations (Fig. 1a,b), albeit at the risk of allowing biological ‘noise’ to be inadvertently retained. And no matter what standardization method is chosen, it is nearly impossible to recover environmental signals that have wavelengths greater than the average length of the tree-ring series used to construct the chronology (the ‘segment length curse’, Cook et al. 1995). A rare exception are methods that, rather than fitting empirical curves to individual tree-ring width series, instead estimate the age trend typical to a whole stand and use this as the detrending curve, but these approaches come with their own strong caveats (e.g., Regional Curve Standardization, Briffa and Melvin 2011). In sum, detrending fundamentally influences statistical properties of chronologies such as range of variance, spectrum, and trend, and may impart other known features (e.g., end effects, trend in signal bias, Briffa and Melvin 2011). Unfortunately, standard formats for tree-ring measurements and chronologies were established in the 1970s and early 1980s, and their limited metadata does not describe methods used to construct chronologies. Peer-reviewed publications virtually never report detrending methods for

each tree-ring measurement series. As a result, new investigators may not know which patterns have been deliberately preserved or excluded from the final product.

During their production, tree-ring chronologies are often modified to adjust the serial correlation (temporal autocorrelation) of the final time series (Fig 1c). Detrended ring-width sequences often still exhibit persistence over several years due to biology (arising from carbohydrate storage or needle retention) or climate (driven by lags in temperature or hydrology) (Fig. 2). Because these carry-over effects can obscure connections between exogenous forcings and tree growth, dendroclimatologists often apply autoregressive modeling to estimate and remove the temporal autocorrelation in ring-width chronologies, a procedure known as ‘prewhitening’ (Cook 1985). The same adjustments are not usually made to the other major tree-ring variables because biological persistence has a weaker influence on tree-ring density (Esper et al. 2015) and stable isotope composition. Here again, standard metadata rarely describe steps taken to treat autocorrelation, and it is not always clear whether persistence properties of final chronologies reflect a pre-determined result imposed by those steps, or inherent tree growth behavior.

A chronology ‘signal’ describes how well a chronology records a particular environmental pattern (Fritts 1976). The signal might vary in strength within and among chronologies and over time, (eg. the ‘fading record problem’; Swetnam et al. 1999), and is influenced by disturbance, the number of samples combined in a chronology (replication), detrending, the intensity of environmental limitation at the study site, and many other factors (Fritts 1976). The ‘divergence problem’ is a form of temporal signal instability in which some mainly high-latitude tree-ring records have recently (since the late 20th century) dissociated from regional temperature trends.

While it poses a legitimate challenge for paleoclimatology, many examples of purported divergence stem from misinterpretation of chronology noise, a lack of low-frequency signal preserved in chronologies, and other issues of analysis (Esper and Frank 2009).

Not all tree-ring chronologies record the same environmental signal. In cold Arctic or alpine forests, summer temperature is the primary factor that controls ring width and wood density. But in warmer locales, those same tree-ring variables mainly reflect moisture availability during the growing season. Most tree-ring collections have purposefully been made at sites where growth is likely to be limited by a single climate variable. This strategy does enhance the fidelity of climate signals preserved in the rings, but also means that many chronologies are more climate-sensitive compared with trees from the same species that grow in less extreme settings (Klesse et al. 2018).

Careful scientific study design and data interpretation are the best lines of defense for using tree-ring chronologies appropriately. These datasets should always be interpreted with a firm knowledge of chronology development procedures so that patterns that stem directly from those procedures can be differentiated from other latent environmental patterns recorded by tree rings. For instance, [1] research questions that depend on long-term trends over several centuries in length should usually be avoided, since most of those problems cannot be addressed without examining raw tree-ring measurements; [2] chronologies should rarely serve as evidence for an absence of long-term environmental trend; [3] trend at chronology ‘tails’ should be interpreted with caution and, where possible, corroborated by other non-tree-ring evidence (e.g. remotely-sensed data), and; [4] questions that depend on persistence over time should be handled with care

since autocorrelation structures and sources may be unknown. Further, [5] chronologies that have been produced using different methods or that have different signal sources (e.g., temperature- versus moisture-limited chronologies) should not usually be combined as a group since they represent different environmental information. And [6] not all chronologies are created equal. Before a chronology is developed, annual rings are assigned dates through crossdating, and the diagnostic statistics from this process reflect aspects of the chronology's overall quality, signal strength, and reliability as an environmental proxy record (Wigley et al. 1987).

Usual practice has tree-ring chronologies stored as individual records within an archive but recently, owing in part to the widespread adoption of formal open-data policies, researchers and consortiums have made public curated datasets that include many chronologies with one or more characteristics in common (eg. PAGES2k Consortium 2017). These custom sets have higher inter-comparability than compilations of one-off chronologies by individual investigators, since a common signal has been identified among all the chronologies, and chronology construction has been conducted in a manner suitable for group use. We anticipate future made-for-purpose collections built upon the same tree-ring parameter, tree species, climate sensitivity, or detrending approach would be received enthusiastically by the broader community. Of course, many of the challenges connected to the use of freely-available tree-ring chronologies would be alleviated by better metadata. Standard formats for tree-ring measurements and chronologies established in the 1970s and early 1980s do not include details about chronology construction, and new data standards and frameworks that are able to store much richer metadata (Brewer 2014, McKay and Emile-Geay 2016) are not yet fully supported by online archives. Adopting modern formats and frameworks that document all steps in the chronology-building process, as

well as open source code-sharing for chronology development procedures, should be a priority of modern dendrochronology.

Tree rings may appear to be simple, but the interpretation of tree-ring chronologies is usually not straightforward. The major online repository for tree-ring data does not place any restrictions on access, and there is certainly no obligation for users to consult with domain experts before using the data. Even so, we suggest scientists from ecology, climate, and the earth sciences would benefit from closer collaboration with dendrochronologists to avoid pitfalls when interpreting the rich and expanding network of freely-available tree-ring chronologies.

References

Brewer, P. W. (2014). Data management in dendroarchaeology using Tellervo. *Radiocarbon*, 56(4), S79-S83.

Briffa, K. R., & Melvin, T. M. 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. In *Dendroclimatology*, pp. 113-145. Springer, Dordrecht, 2011.

Cook, E. R. (1985). A time series analysis approach to tree ring standardization (dendrochronology, forestry, dendroclimatology, autoregressive process) (Unpublished doctoral dissertation). University of Arizona, Tucson, USA.

Cook, E. R., Briffa, K. R., Meko, D. M., Graybill, D. A., & Funkhouser, G. (1995). The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. *The Holocene*, 5(2), 229-237.

Cook, E. R., & Kairiukstis, L. A. (Eds.). (2013). *Methods of dendrochronology: applications in the environmental sciences*. Springer Science & Business Media.

Cook, E. R., & Peters, K. (1981). The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin*, 41, 45-53.

Esper, J., & Frank, D. (2009). Divergence pitfalls in tree-ring research. *Climatic Change*, 94(3), 261-266.

- Esper J, Frank DC, Battipaglia G, Büntgen U, Holert C, Treydte K, Siegwolf R, Saurer M (2010) Low-frequency noise in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ tree ring data: a case study of *Pinus uncinata* in the Spanish Pyrenees. *Global Biogeochemical Cycles* 24(3), GB4018.
- Esper J, Schneider L, Smerdon J, Schöne B, Büntgen U (2015) Signals and memory in tree-ring width and density data. *Dendrochronologia* 35, 62-70.
- Fritts, H. C. (2012). *Tree Rings and Climate*. Elsevier.
- Klesse, S., DeRose, R. J., Guiterman, C. H., Lynch, A. M., O'Connor, C. D., Shaw, J. D., Evans, M. E. K. (2018). Sampling bias overestimates climate change impacts on forest growth in the southwestern United States. *Nature Communications*, 9(1), 5336.
- McKay, N. P., & Emile-Geay, J. (2016). The Linked Paleo Data framework—a common tongue for paleoclimatology. *Climate of the Past*, 12(4), 1093-1100.
- Meko, D. M. (1981). Applications of Box-Jenkins methods of time series analysis to the reconstruction of drought from tree rings (Unpublished doctoral dissertation). University of Arizona, Tucson, USA.
- Melvin, T. M., & Briffa, K. R. (2008). A “signal-free” approach to dendroclimatic standardisation. *Dendrochronologia*, 26(2), 71-86.
- PAGES2k Consortium. (2017). A global multiproxy database for temperature reconstructions of the Common Era. *Scientific Data*, 4(2017), 170088.
- Swetnam, T. W., Allen, C. D., & Betancourt, J. L. (1999). Applied historical ecology: using the past to manage for the future. *Ecological Applications*, 9(4), 1189-1206.
- Wigley, T. M. L., Jones, P. D., & Briffa, K. R. (1987). Cross-dating methods in dendrochronology. *Journal of Archaeological Science*, 14(1), 51-64.
- Acknowledgements**
We thank Jan Esper, Kevin Anchukaitis, and Grant Harley for their thoughtful comments on this manuscript. B.L.C acknowledges funding from the U.S. National Science Foundation (grant #1803995, ‘Spatiotemporal variability in Western United States snowpack during the Common Era’) and US Geological Survey (grant #G16AC00266, ‘Water resource relevant hydroclimatic reconstructions for Western North America’). S.S.G. acknowledges funding from the U.S. National Science Foundation (grant #1602512, ‘Quantifying the risk of widespread megadrought in North America’) and support from the Alexander von Humboldt Foundation (fellowship, ‘Decadal to multidecadal variability in the Earth’s climate viewed through the lens of ancient trees’).
- Author contributions**
B.L.C. led the writing and all authors contributed to the final manuscript.

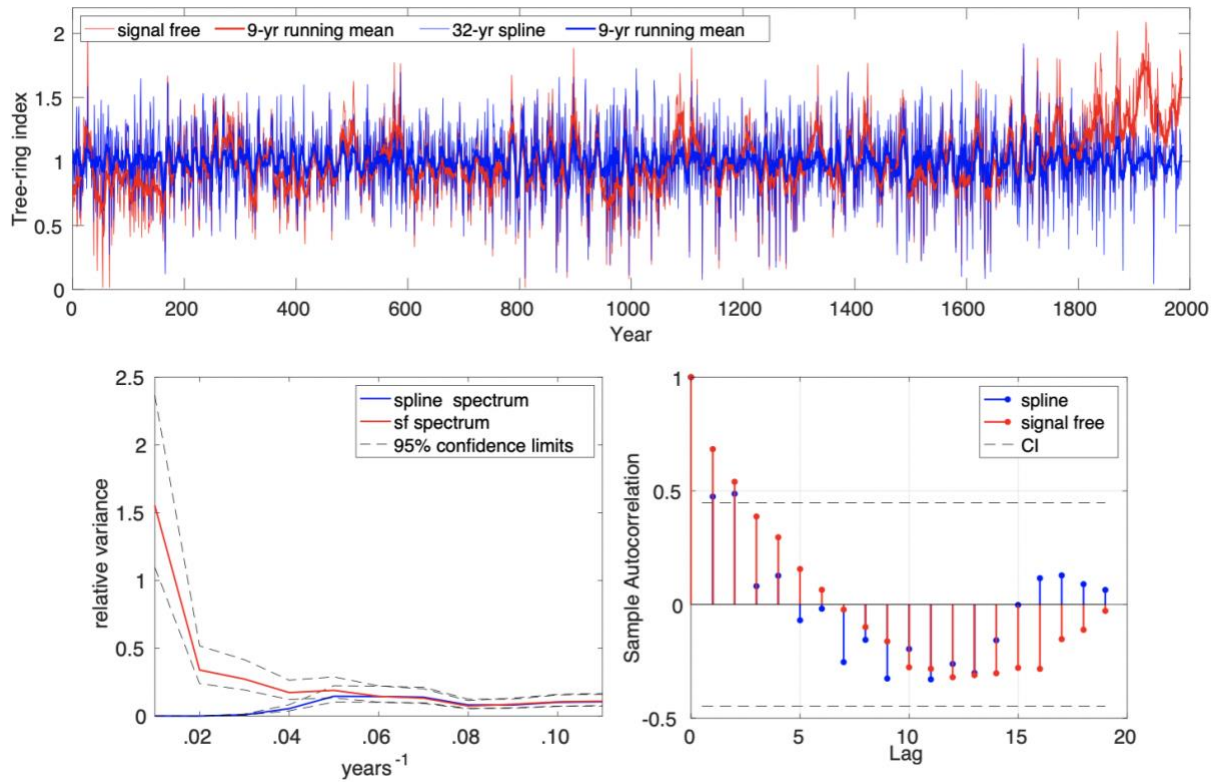


Figure 1. Comparisons of two tree-ring chronologies derived from the same ring-width measurements (obtained from a stand of Great Basin bristlecone pine from Indian Garden, Nevada, PAGES2k Consortium 2017). In panel (a), the red line represents a chronology built using methods intended to preserve long-term variability in the final time series (specifically, signal-free detrending with age-size trends modeled as modified negative exponential functions), while the blue line shows a chronology tailored to emphasize year-to-year variations in tree growth (with age/size trends estimated using a 32-year spline). The bottom panels highlight (b) the spectral characteristics and (c) persistence structure of both chronologies with confidence intervals (CI).

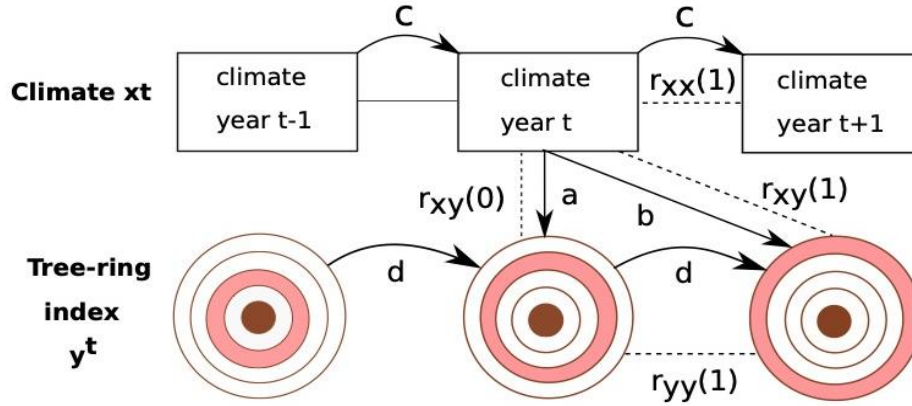


Figure 2: Schematic diagram illustrating the main sources of temporal autocorrelation in tree rings. Solid lines *a*, *b*, *c*, and *d* represent possible direct pathways of influence among tree rings and climate across successive and contemporaneous years. For example, biological persistence due to carbohydrate storage or needle retention (*d*) causes tree growth to be correlated with growth one or more years prior (*d*). Pathways of possible influence between climate (r_{xx}), tree-rings (r_{yy}), and climate and tree rings (r_{xy}) which have no specific causal interpretation are denoted by hatched lines for the current year (0) or as lag-1 autocorrelation (1). For example, climate factors (x) that influence tree growth (y) also often exhibit autocorrelation (r_{xx}) due to lag effects in temperature or hydrology. In sum, tree rings may have an autocorrelation structure that reflects the combined influence of both known and unknown carry-over effects arising from both biology and climate. Adapted from Meko (1981).