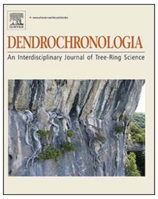
Dendrochronologia 44 (2017) 174–186

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro



ORIGINAL ARTICLE

Hierarchical regression models for dendroclimatic standardization and climate reconstruction

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ABSTRACT

Tree-ring based paleoclimate reconstructions entail several sequential estimation or processing steps. Consequently, it can be difficult to isolate climatic from non-climatic variability in the raw ring width measurements, estimate the uncertainty associated with a reconstruction, and directly infer how specific techniques used to sequentially fit growth curves or to reconstruct climate influence the final estimates. This paper explores the use of hierarchical regression models to address these problems. The proposed models simultaneously model the entire reconstruction process in a way that is consistent with the existing step-by-step estimation framework, but allow for uncertainty estimation and propagation across steps, which can help determine how best to improve a candidate model. The utility of hierarchical models is tested for an example, the reconstruction of summertime temperatures in northern Sweden in a cross-validated framework relative to 1) a sequential process of growth curve fitting followed by chronology development, 3) an iterative, "signal-free" approach, and 2) a signal-free regional curve standardization (RCS-SF). Further, an exploration of different structures within the unifying hierarchical framework is provided to illustrate how one could easily test a variety of choices of model design. We focus on a subset of choices relevant to recent dendroclimatic studies using hierarchical methods and related to 1) data transformation, 2) the benefits of biological detrending and climate reconstruction in a single step 3) partial pooling of the age model across trees, 4) the homogeneity of variance across tree-ring residuals, 5) the structural form of the age model, and 6) the inclusion of autoregressive processes for the tree-ring residuals. The work described here represents part of a series of ongoing explorations of potential advances over current dendroclimatic reconstruction approaches and commonly implemented ways in which they have and are specifically implemented. The results show that hierarchical modeling appears to offer improved climate reconstructions over the standardization techniques explored in this exercise, substantially so for the non-RCS sequential and iterative methods.

1. Introduction

Paleoclimate reconstructions from tree rings have proven enormously useful for understanding past climate variability prior to instrumental or historical records. The development of these reconstructions requires that variability in tree-ring width measurements (or other growth-related data) related to external climate forcing be isolated from other variability in the tree-ring measurements associated with internal growth processes, such as biological age-related trends. These trends emerge as the stem expands over the life of the tree and subsequently radial ring widths slowly decline.

In dendroclimatology, methodologies to separate climatic from non-climatic variability in the raw ring width measurements are referred to as standardization techniques (Fritts, 1976). These techniques generally follow a three-step, sequential procedure in which 1) age-related growth trends are estimated and removed from each tree-ring series, 2) trend-adjusted series are averaged across trees to develop a single chronology, and 3) a target climate series of interest is modeled as a function of the chronology to develop the reconstruction. The possible removal of part of the climate signal with the biological age-related trend is a common problem that arises in the first two stages of this procedure. This problem, known as the 'segment length curse' (Cook et al., 1995; Briffa et al., 1996), arises because the age-related growth trend is fit to the length of each tree-ring series using deterministic (e.g.,

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http://dx.doi.org/10.1016/j.dendro.2017.05.003
Received 21 January 2017; Received in revised form 3 May 2017; Accepted 24 May 2017

monotonic decreasing linear, modified negative exponential growth) or flexible (e.g., smoothing splines) curves that, by construct, assume trends across the length of the data series consistent with the growth model are associated with biological and not climatic variability. Thus, decadal to centennial scale climate variability present in the tree rings but with period longer than the length of the tree-ring series is subsumed into the biological trend model and removed from the chronology and subsequent climate reconstructions.

A variety of approaches have been proposed to mitigate the loss of climate information when fitting and removing age-related trends. Regional curve standardization (RCS) is an empirical curve fitting technique that assumes a homogenous growth rate across all trees of the same age (or age class) and estimates that rate based on the average ring width for all tree rings in a given age class, with post-average smoothing (Briffa et al., 1992). The RCS approach assumes that the distribution of age classes is sufficiently random across trees in any given time period so that climate-related variance in that time period is averaged out in the calculation of age-related growth for each age class. Because the biological growth curve is estimated using all tree-ring series, it is not constrained by the length of any one series and the resulting chronology can exhibit variability on long timescales up to the length of the full chronology (Esper et al., 2002; Peters et al., 2015). However, the assumptions made in the RCS procedure, namely that a single, homogenous growth curve can be applied to all trees in a stand, are often violated due to variations in local conditions (e.g., soil, competition, microclimate, etc.) experienced by individual trees (Briffa and Melvin, 2011).

To circumvent these challenges and minimize the effects of the segment-length curse, Melvin and Briffa (2008) proposed the "signal-free" method of standardization. In this approach, biological age-related trends are estimated and removed for individual trees and a chronology then estimated, similar to a traditional standardization. However, the chronology is then removed from each tree and the individual age models re-estimated. A new chronology is developed and the entire procedure iterated until the chronology converges to a sufficiently fixed time series. Through this iteration, the signal-free approach removes the influence of common, climate-forced signal in individual tree-ring width series prior to biological trend estimation, thus improving the chances that the biological trend does not subsume the climate signal while still allowing for heterogeneity in biological trends. The signal-free method has also been extended to the RCS approach (i.e., RCS-SF standardization) to better manage situations where only a few older trees with common germination dates are available to estimate the climate series from early parts of the chronology (Briffa and Melvin, 2011; Melvin and Briffa, 2014a).

While the signal-free approach improves the retention of external climate forcing in the final chronology, some amount of climate signal may still be lost in the early iterations of the procedure. Recently, hierarchical regression models have been proposed as an alternative approach for isolating climate and non-climate variance in tree-ring series. In hierarchical models, the biological age-related trend and the shared climate signal across trees are estimated jointly and simultaneously in a single-step modeling procedure. To the authors' knowledge, only a handful of studies have utilized hierarchical regression models for ring width detrending and chronology development. Concurrently, Duncan et al. (2010) and Bontemps et al. (2010) were the first to propose such an approach. Duncan et al. (2010) found that cross-validated temperature reconstructions in New Zealand were substantially improved over a reconstruction based on a sequential procedure that utilized individual smoothing splines for detrending. The model proposed in Bontemps et al. (2010) was compared against an RCS procedure and found to produce similar chronologies (Bontemps and Esper, 2011), although they did not present a comparative, cross-validated assessment of reconstructed climate. Schofield et al. (2016) adopted a Bayesian hierarchical approach and proposed a novel framework in which the model linking the chronology to the climate series targeted for reconstruction was calibrated simultaneously with the models of biological trend for each tree-ring series. In that study, a variety of model variants were developed to test different underlying assumptions in model structure, and these different model versions were compared to both standard and RCS procedures. While Schofield et al. (2016) did present a novel framework and a thorough discussion of hierarchical model development and inter-comparison, they were unable to show substantive improvements in cross-validated reconstructions of Scandinavian summer temperature over other standardization techniques. Through our work we find that this was primarily due to the length of the temperature series used in the analysis. Schofield et al. (2016) also did not compare their results to signal-free approaches designed to better separate age- and climate-related variability in the ring width series. Our results show that a RCS-SF approach is quite robust and has comparable out-of-sample performance to the hierarchical models, although the two approaches do lead to different chronologies and reconstructions prior to the instrumental record.

This study builds directly from the work presented in Schofield et al. (2016) and further explores the use of hierarchical regression models for dendroclimatic standardization and climate reconstruction and how they compare to existing approaches. Similar to Schofield et al. (2016), we adopt a hierarchical Bayesian framework, although this is not necessary to implement the hierarchical construct. Our work differs from the original study presented in Schofield et al. (2016) in three primary ways. First, we consider a variety of additional model choices not explicitly assessed in the original study and test their implications for the fidelity of climate reconstructions. These choices include 1) the type of data transformation, 2) biological detrending and climate reconstruction in a single modeling step, 3) partial pooling of the age model across trees, 4) the homogeneity of error variance across tree-ring residuals, 5) the structural form of the age model, and 6) the inclusion of autoregressive processes for the tree-ring residuals. Second, we compare the hierarchical models to signal-free approaches for standard and RCS detrending, which are better designed to avoid subsuming the climate signal into the biological trend. Finally, we use a substantially longer instrumental temperature record to better differentiate the reconstruction skill of different hierarchical and conventional standardization approaches.

The remainder of the paper will introduce the hierarchical modeling framework considered in this work, develop model variants that represent alternative hypotheses of the underlying data generating process, detail the estimation and cross-validation frameworks used to assess the fidelity of different model-based reconstructions, and present the results of the comparison.

2. Data

To motivate the model developments presented in this work and compare them against the results of Schofield et al. (2016), we use the same tree-ring data set composed of annual growth increments of 247 living and subfossil Scots pine (*Pinus sylvestris*) growing near the latitudinal tree-line in Torneträsk, northern Sweden (Grudd et al., 2002; Briffa et al., 2008). After cross-dating, the earliest ring widths in this dataset extend back to 1497 and the most recent rings end in 1997. All series have at least 25 annual increments, with the average and maximum series length equal to 179 and 484 years, respectively. Fig. 1 shows the distribution of tree-ring data across years.

Schofield et al. (2016) developed their methods based on an 83-year (1913–1995) record of Torneträsk summertime (JJA) temperatures recorded at the Abisko weather station. We also test our standardization approaches against a slightly longer Abisko record (1913–1997) to facilitate a direct comparison against the results in Schofield et al. (2016). However, we focus our attention primarily on tests using a 182-year record of summer temperature from 1816 to 1997 at Tornedalen, Sweden (Klingbjer and Moberg, 2003). Though there may be some degradation in the signal between the tree rings and temperature at the