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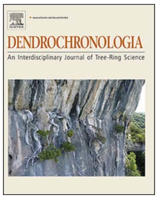

ORIGINAL ARTICLE

A likelihood-based time series modeling approach for application in dendrochronology to examine the growth-climate relations and forest disturbance history

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ABSTRACT

A time series intervention analysis (TSIA) of dendrochronological data to infer the tree growth-climate-disturbance relations and forest disturbance history is described. Maximum likelihood is used to estimate the parameters of a structural time series model with components for climate and forest disturbances (i.e., pests, diseases, fire). The statistical method is illustrated with a tree-ring width time series for a mature closed-canopy Douglas-fir stand on the west slopes of the Cascade Mountains of Oregon, USA that is impacted by Swiss needle cast disease caused by the foliar fungus, *Phaecryptopus gaeumannii* (Rhode) Petrak. The likelihood-based TSIA method is proposed for the field of dendrochronology to understand the interaction of temperature, water, and forest disturbances that are important in forest ecology and climate change studies.

1. Introduction

Tree rings record growth in response to abiotic and biotic factors and can infer the timing and characteristics of past disturbance events including temporal and spatial variability. Tree-ring chronologies covering decades to several millennia are key data sources for dendrochronological studies investigating climatic effects on tree growth, reconstructing past climate patterns, dating natural disasters (e.g. eruptions of volcanoes, floods) and forest disturbance events (pests, diseases, fires), as well as tracking ecological processes (e.g., tree-line movement) (Cook and Kairiukstis, 1990). But growth-climate relations are difficult to infer because the effects of temperature and water on annual stem growth are nonlinear, seasonal, and interact with each other as well as with forest disturbances (Isebrands et al., 2000; Lloyd et al., 2013; Lee et al., 2013, 2016). Moreover, climate plays an important role in the population dynamics of forest pathogens and pests, which in turn affect tree growth (Alfaro et al., 1982, 2014; Black et al., 2010; Lee et al., 2013) and further complicate inferences of growth-climate relations.

Tree growth has been described conceptually by Cook (1985, 1987) as a structural time series (STS) model with components for age trend (A_t), climate (C_t), and disturbance (D_t), i.e., $E(Y_t) = A_t + C_t + D_t$ where $E(Y_t)$ is the mean response function for the tree-ring width chronology (Y_t). The correct specification of the mean function of tree growth is extremely difficult because growth is influenced by multiple climate factors and possibly latent disturbance factors that interact and are confounded. The form of A_t is typically an exponential-decay function such as a negative exponential or a simple linear function (Cook and Kairiukstis, 1990). Specification of the form of C_t and D_t is the focus of two important applications of dendrochronology, namely growth-climate relations and forest disturbance history. The climate component, C_t, represents the interactions of temperature, precipitation, soil moisture, and evapotranspiration demand on tree growth and applies for all trees within a stand (Fritts, 1976). Further, C_t may have a climate-related growth trend, particularly in the Pacific Northwest (PNW) where tree growth rates have changed in response to increasing temperature above the species' temperature optimum due to climate change (Barber et al., 2000; D'Arrigo et al., 2004; Beedlow et al., 2013; Lee et al., 2016). A multiple regression model is often used to describe the climate relations with tree growth (e.g., Fritts, 1971; Meko, 1981) but recent evidence suggests a more complex and nonlinear relationship between tree growth and climate (Briffa et al., 1998; Lloyd and Fastie, 2002; Wilmking et al., 2004, 2005; Ohse et al., 2012; Lloyd et al., 2013; Lee et al., 2016). D_t has been conceptually described as a pulse function for a discrete event (Cook, 1987; Mäkinen, 1997) but more recently, has been generalized to have other forms and possibly longer duration and

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is expressed as a combination of pulse, step and multi-year trend functions (Downing and McLaughlin, 1990; Druckenbrod et al., 2013; Lee et al., 2013, 2016). Depending upon the dendrochronological application of interest, the mean function is specified for either C_t or D_t but not both (Cook and Kairiukstis, 1990).

The reconstruction of a past species-specific forest disturbance does not require specification of C_t, assuming that the effects of climate and disturbance are additive. Past outbreaks of pests or disease can be identified through the comparison of the host chronology with a sympatric nonhost chronology, assuming that the host and nonhost time series share the same climate signal, C_t (Black et al., 2010; Alfaro et al., 2014). The control chronology may be either a coexisting but different species unaffected by the disturbance agent or the same species from other geographic areas not affected by the disturbance (Black et al., 2010). However, the growth-climate relation can vary by tree species and site conditions (Rozas, 2001; Friedrichs et al., 2009; Beedlow et al., 2013; Lee et al., 2016), raising concerns on the host-nonhost reconstructions of past disturbance regimes. Recent evidence suggests an interaction of temperature, water, and disturbance is responsible for tree pathogens (e.g., *Phaecryptopus gaeumannii* (Rhode) Petrak) altering the climate relations of trees by impacting physiological processes and carbon assimilation (Lee et al., 2016). The interactions among climatic stressors (X) and forest disturbance agents (Z) are not the typical cross-product of X and Z because historical records of outbreaks of forest pests and diseases are generally not available nor quantifiable for input in a regression model. As an alternative to the use of a control chronology as a climate proxy, time series intervention analysis (TSIA) has been used to isolate the disturbance signal (D_t) by explicitly characterizing the growth-climate relation (C_t) of the host species (Lee et al., 2016).

A tree-ring width chronology represents a stationary time series that can be approximated by a Box-Jenkins autoregressive moving average (ARMA) model (Fritts, 1976; Cook, 1985; Monserud, 1986; Guiot, 1986). Autocorrelation, age-related and climate trends, and the interactions of temperature, water, and disturbances pose problems in dendrochronology to understand these impacts on forested ecosystems. Numerous disturbance detection methods have been developed for inferring forest history events, but these methods do not allow for autocorrelation (Rubino and McCarthy, 2004) nor examine the growth-climate relations, and are difficult to apply in areas where field records of disturbance events are incomplete or not available.

Time series intervention analysis is well suited for both determining growth-climate relations and reconstructing forest history, but the modeling approach has been seldom applied in dendrochronology (Druckenbrod et al., 2013). This study builds on the TSIA approach for the detection of past disturbance events and the regression approach for climate-growth relations in dendrochronology to describe growth-climate-disturbance relations using a maximum likelihood framework for estimation. This statistical approach extends naturally to an intra-annual tree-ring series (i.e., earlywood and latewood width) that captures the seasonal patterns of climate including annual summer drought typical of a Mediterranean climate regime. The TSIA approach can detect suppression episodes, the years of the disturbance events, and quantify the magnitude and duration of the growth anomalies associated with one or multiple disturbance agents (Druckenbrod et al., 2013). Disturbance events are identified as outliers which can be detected based on a likelihood ratio or Wald test. Data requirements are fairly minimal but inferences of the growth-climate relations are limited to the time period when instrumental records for the region are available.

Key issues to be addressed include: (1) detecting of forest disturbance events (i.e., outbreaks of tree pathogens, forest pests, wildfires); (2) inferring radial stem growth response to the interacting effects of temperature, water, and forest diseases and pests; and (3) applying time series analysis to annual and intra-annual tree-ring width chronologies to understand the seasonal effects of multiple climate and latent disturbance factors.

2. Methods

2.1. Intervention analysis of dendrochronological data

Tree-ring width data ($Y_1, Y_2,\ldots,Y_n$) represent either an annual or intra-annual time series. We employ a regression model of the general form

$$y_t = f(\mathbf{X},\mathbf{D},t) + N_t$$

where $y_t = F(Y_t)$ is some appropriate power transformation of Y_t, f ($\mathbf{X},\mathbf{D}$,t) = deterministic effects of time, t, climate variables, $\mathbf{X}$, and interventions, $\mathbf{D}$, and N_t is a stationary time series with absolutely summable covariance function V and zero mean. Power transformations are used to homogenize the variance in tree-ring width series but are difficult to apply in the presence of outliers. Estimation of the variance of the tree-ring time series to inform the power transformation requires specification of the mean response function which is difficult to infer for a tree-ring chronology having years with anomalously low growth (i.e., outliers). Alternatively, we prefer a log transformation to infer the multiplicative effects of climate and disturbances on growth and to stabilize the variance of ring widths (Cook, 1987).

In Section 2.2 we discuss the general linear model for representing the mean response function $f(\mathbf{X},\mathbf{D},t)$ that has components for climate and forest disturbances assuming N_t is normally and independently distributed. We use grafted polynomials to infer the climate-induced growth trend associated with climate stress that is not accounted for by the measured variables. In Section 2.5 we extend the statistical approaches for modeling growth-climate relations and forest disturbance history using TSIA assuming a regular or seasonal autoregressive model for representing the noise N_t. The associated parameter estimation procedures are given in each section using a likelihood framework (Fig. 1). For the field of dendrochronology, we developed an alternative to a second-order or higher response surface model involving two or more variables and their cross-products to examine the interactions of temperature, water, and forest disturbance agents.

2.2. Growth-climate relations and disturbance detection model

The two important applications of dendrochronology, growth-climate relations and forest disturbance history, can be examined simultaneously in a likelihood framework. Initially, we assume that ($Y_1,Y_2,\ldots,Y_n$) are normally and independently distributed with mean f ($\mathbf{X},\mathbf{D}$,t) and variance σ^2. Typically, the age-related growth trend, A_t, is removed from the tree-ring time series in the dendrochronological standardization process using a combination of detrending methods including a negative exponential function, a cubic spline smoother, or a regional growth trend. We assume that the tree-ring time series has been detrended to remove age-related trends while preserving the low frequency variability associated with a climate trend. We examine time series methods for growth-climate relations and disturbance detection by specification of a mean response function that separates the confounding effects of temperature, water, and disturbance on tree growth (Lee et al., 2016). We assume that growth response to temperature and water can be represented by a multiple regression equation, i.e., $C_t = \mathbf{X}_t'\boldsymbol{\beta}$ for $t = 1,2,\ldots,n$ where $\mathbf{X}_t' = (X_{1t}, X_{2t}, \ldots,X_{pt})$ is a vector of measured climate variables, and $\boldsymbol{\beta}' = (\beta_1, \beta_2,\ldots \beta_p)$ are the unknown model parameters. In dendrochronology, the mean function is highly complex and nonlinear, varies by tree species and site condition, involves multiple climate variables that interact with each other, and displays seasonality, and possibly, climate-mediated growth trend (Lee et al., 2016).

2.3. Pulse intervention to detect disturbance events

Time series intervention analysis is used to detect forest