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Detection of a Sulfur Dioxide Signal in a Tree-Ring Record: a Case Study from Trail, British Columbia, Canada

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ABSTRACT: Dendroecological analysis of tree-ring chronologies was used to determine radial growth responses of a western larch *(Larix occidentalis* Nutt.) stand to climate and ambient SO_2 exposure. A unique, 32-year long record of ambient SO_2 concentrations was exploited to estimate annual SO_2 dose with a 0.25 ppm threshold. Tree-ring data were a subset from a previous study including three control sites and one polluted site that was near the location of the SO_2 monitor. An autoregression model was employed in a stagewise procedure that first removed climate effects by autoregression on the average of the controls and then estimated a dose-response relationship by autoregression of the residuals from the first stage on SO_2 exposure. Significant growth losses from air pollution were demonstrated that were approximately equal in magnitude to the variation explained by annual fluctuations of climate.

Introduction

The lead/zinc smelter located in the Columbia River Valley at Trail, British Columbia, Canada has operated since 1896. Sulfur emissions from the smelter increased steadily with metal production until 1930 (peak emissions = 1.1×10^5 t/yr). Because of tree damage to the south in the United States, international litigation was filed and the company was subsequently forced to curtail production when meteorological conditions promoted accumulation of air pollution. Integral to this pollution control system was an intensive monitoring program for SO_2, the air pollutant primarily responsible for vegetation damage in the area (Katz 1939; Dean and Swain 1944; Scheffer and Hedgcock 1955).

Our previous research found that radial growth of western larch *(Larix occidentalis* Nutt.) up to 15 km from the smelter was related to annual sulfur emissions (Fox et al. 1986). In partial regression models relating variation in tree-ring chronologies (standardized ring-width indices averaged within each site) from 5 Columbia Valley stands to sulfur emissions and mean chronologies for three control sites, we found that variation explained by sulfur emissions decreased with distance from the smelter and, concomitantly, variation explained by ring-width indices from control sites increased with distance. The objective of the present study was to estimate a dose-response relationship for radial growth responses in western larch to ambient SO_2 levels using available monitoring data.

Methods

In 1937, an automatic recorder was installed at Columbia Gardens, BC, which is approximately 10 km S of the smelter, and operated continuously until 1968. The recorder was crude by today's standards, but sufficient to estimate annual SO_2 dose for trees in the vicinity. Only twice in this unique 32-year record of ambient SO_2 concentrations was the total time the recorder was inoperable greater than 200 h/yr. Available data allowed dose to be expressed as annual ppm-hours (sums of products of concentration and duration of exposure for each year) above various threshold concentrations from zero to 0.5 ppm. Results presented here will focus on ppm-hours greater than 0.25 ppm, which is nearly twice the US National Ambient Air Quality Standard for a 24 h average concentration (0.14 ppm or 365 ug/m^3). This estimate of SO_2 dose ranged from 5 to 210 ppm-hours corresponding to a range in annual average concentration of 0.01–0.06 ppm.

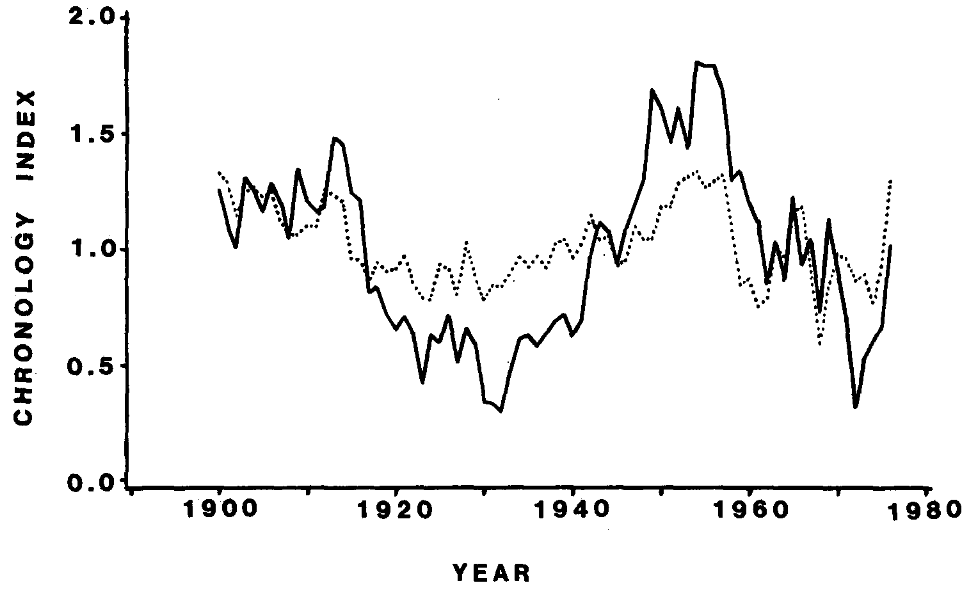


Fig 1
Boundary chronology (solid) and average of the three control chronologies (dashed).

Tree-ring data were a subset of those used by Fox et al. (1986) including one polluted site (Boundary, Washington, USA) and three control sites. Crossdating was verified using a quality control procedure (Holmes 1985) and new chronologies were produced using an autoregressive standardization procedure (Cook 1985). The Boundary site was actually 6 km downriver from the SO_2 monitor, but comparison of the Columbia Gardens measurements with similar measurements from Northport, Washington (20 km downriver from the smelter) support the assumption that the valley topography produced relatively homogenous distributions of SO_2 concentrations over these short distances. The control sites were located within 40 km of the smelter, but outside areas known to have been affected by smelter emissions (Dean and Swain 1944; Scheffer and Hedgcock 1955).

Our statistical approach assumes that tree-ring indices from the polluted sites can be decomposed into climate and pollution components as well as an autoregressive error component. We also assumed that the controls reflected patterns of growth that would have occurred at the polluted sites in the absence of pollution.

That is, $I_t = \mathbf{B}_o + \mathbf{B}_1 C_t + \mathbf{B}_2 S_t + \mathbf{V}_t$

where,

I_t = chronology index at time t
C_t = average of controls at time t
S_t = SO_2 exposure at time t
$\mathbf{V}_t$ = AR (p) process
= $\mathbf{E}_t - \mathbf{a}_1 \mathbf{V}_t - \ldots - \mathbf{a}_p \mathbf{V}_t - p$
$\mathbf{E}_t$ = independent normal error terms
$\mathbf{a}_i$ = coefficients of the AR (p) process
$\mathbf{B}_i$ = regression coefficients.

Under these assumptions, a stagewise autoregression procedure was employed to maximize use of available information. (1) An autoregression of the polluted site chronology on the average of the controls was used to remove variation attributable to climate. Structural (deterministic climate effects, C_t) and autoregressive (V_t) components were jointly estimated for the years 1900–1976. (2) Residuals were obtained from this regession for the year 1937–1968 corresponding to the years for which SO_2 data were available. The autoregression component was not included in the calculation of these residuals because some of the autocorrelation in the time series may have been related to the pollution effect. (3) Finally, an autoregression of the residual chronology on the SO_2 dose was performed to estimate the pollution effect (S_t) on variation in radial growth while jointly re-estimating the autoregressive error component.

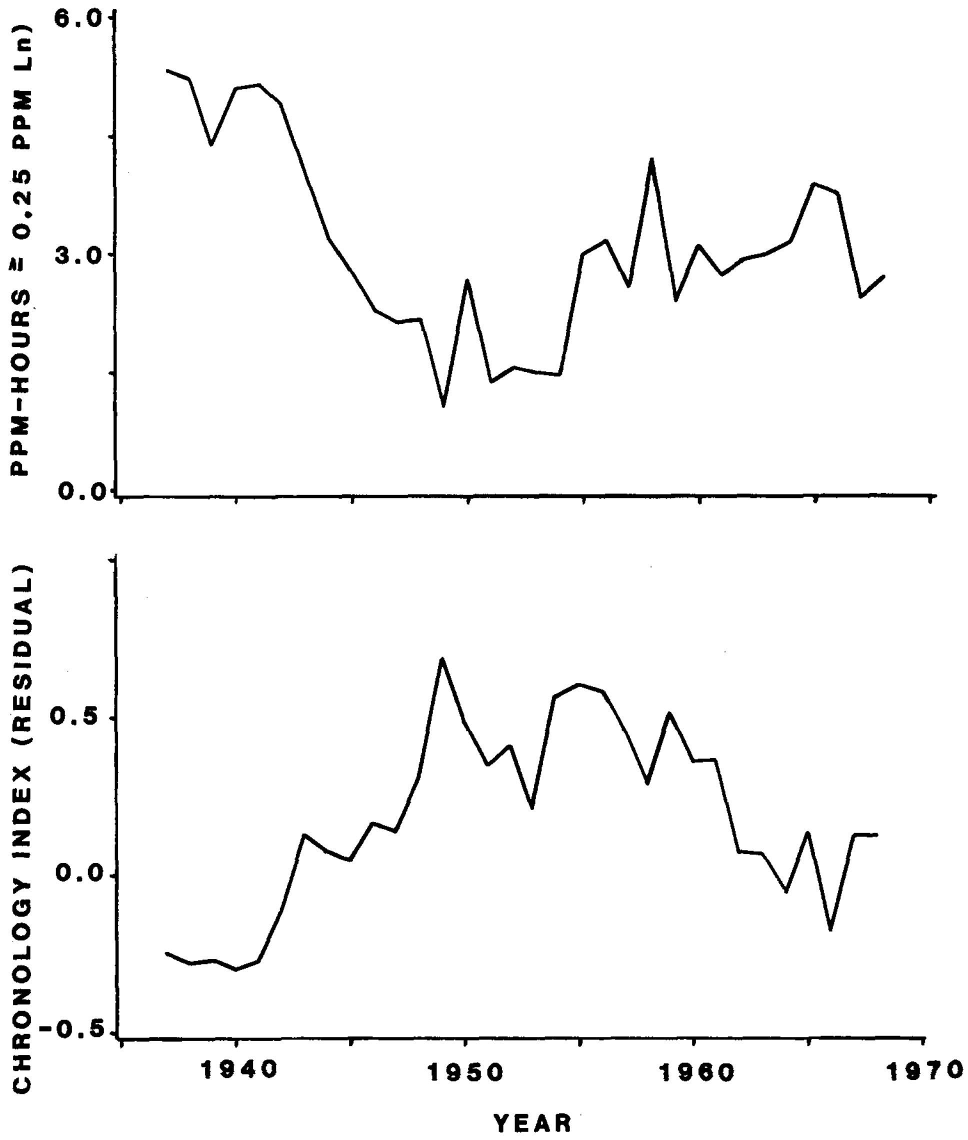
Results

Comparison of the Boundary and average control chronologies reveals similarity in high frequency variation (short period), but differences in the low frequency variation (long period) from 1910 to 1960 (Fig 1). Because of differences in sample size, the period prior to 1880 should not be rigorously compared. The period of relatively reduced growth in the polluted site chronology is centered on the peak of smelter emissions in 1930.

The autoregression model of the Boundary chronology on the average of the controls gave good predictions of the observed variation with a first-order autoregressive error term (total $R^2 = 0.83$). The control average alone explained only 28% of the total variation ($I_t = 0.11 + 0.84\ C_t$). Residuals including only the latter effect are nearly a mirror image of the log of SO_2 dose (Fig 2).

The SO_2 effect on radial growth after removing effects of climate was estimated in an autoregression on the residual chronology on the log of the ppm-hours

Fig 2
SO_2 dose (top) expressed as the log of ppm-hours greater than a threshold of 0.25 ppm and residuals from regression on controls (bottom).



greater than the 0.25 ppm threshold for the years 1937–1968. Again, the estimated model fit the data quite well with an autoregressive error term (total $R^2=0.73$). Time series diagnostics indicated that a simple first-order autoregressive process (AR (1)) was sufficient to account for the autocorrelation in this model as well as in the climate effects model described above. SO_2 dose accounted for 27% of the total variation in the residual chronology (Fig 3). The apparent lack of fit of the regression line was a result of jointly estimating the line with an autoregressive error term. It was this structural portion of the model that would be used to predict the responses to SO_2 exposure for an independently obtained western larch chronology after removing climatic effects (i.e., residual $I_t=0.52-0.11\ S_t$). The use of residuals with zero mean and release of trees from growth limitation by pollution are responsible for the false impression that low concentrations of SO_2 actually enhance radial growth.

Discussion

Dendroecological analysis of tree-ring chronologies was used to estimate radial growth responses of a western larch stand to climate and SO_2 exposure. The clear inverse relationship between dose estimates and residual chronological indices (Fig 2) supports the inference that SO_2 had direct effects on radial growth. These significant SO_2-related growth losses were approximately equal in magnitude to variation attributable to climatic effects.

Results presented here represent a unique effort to estimate an empirical model of SO_2 effects on mean growth of mature trees for a stand. We know of no other study having as extensive a record of ambient SO_2 concentrations. These data allowed estimation of SO_2 exposures for trees in so far as the monitoring data accurately reflect the concentrations actually experienced by the trees at the Boundary stand. Unfortunately,

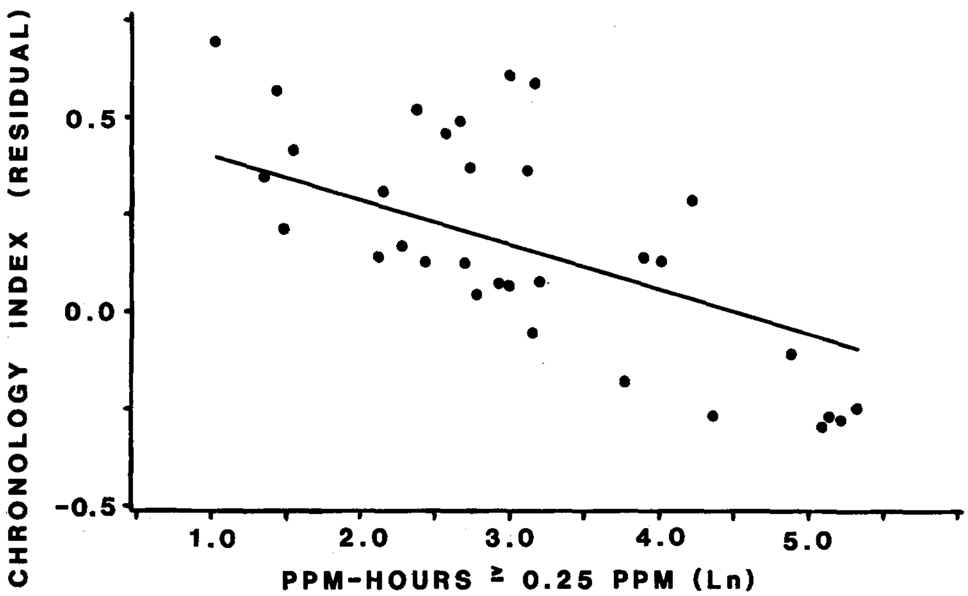


Fig 3
Residuals from regression on controls (points) and their predicted values from autogregression on SO_2 dose (solid line) including only the structural portion of the model as functions of the log of SO_2 dose.

no records exist to allow estimation of seasonal doses, which would certainly be better for determining pollutant effects on this deciduous conifer.

The monitoring data available did, however, allow incorporation of thresholds into the estimates of dose. The 0.25 ppm threshold was selected in preliminary analyses using thresholds of zero, 0.05, 0.10, 0.25 and 0.50 ppm. These results indicated that dosages with higher thresholds accounted for more variation in the residual chronology than did those with lower thresholds. Absence of a threshold in the estimate of overall average concentration corresponded with its inability to explain any significant variation in the residual chronology. Even though these results demonstrated that threshold effects were present, they are not sufficient to establish a specific threshold for growth responses of western larch to SO_2 exposure.

On the one hand, our growth loss estimate is conservative because some of the pollution signal in the chronologies may have been lost in the modeling of climate. Our previous research at Trail found some confounding of climate and smelter emissions in the period immediately preceding the years that were the focus of this study (Fox et al. 1986). On the other hand, the implied SO_2 relationship may be overstated because the present study does not specifically differentiate between growth release effects per se and direct SO_2 relationships. Consequently, the SO_2 relationship may be partically confounded with growth release that may have occurred as ambient SO_2 concentrations decreased from the peak years in the early 1930's.

Although unique in attempting to estimate growth responses in mature trees, radial increment is not equivalent to net primary production or even production of wood. However, it can be a useful preditor of wood production if not for net primary production because diameter at breast height is correlated with tree biomass (Whittaker and Woodwell 1968) and, therefore, radial increment must be directly related to biomass increment. Environmental stresses may, however, differentially affect height growth or even allocation of growth along the stem. Until detailed studies are done to establish these relationships, ring widths remain our best indicator of historical growth patterns.

Acknowledgement

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