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Tree-ring Variation in Western Larch (Larix occidentalis)
Exposed to Sulfur Dioxide Emissions

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ABSTRACT

A Tree-ring analysis was conducted to determine the relationship of sulfur emissions from the lead/zinc smelter at Trail, B.C. to radial growth in western larch (Larix occidentalis Nutt.). Tree cores were collected from five stands known to have been polluted and from three control stands. Age effects were removed from crossdated ring-width series by fitting theoretical growth curves, and, subsequently, tree-ring chronologies were developed for each stand. We assumed that macroclimatic variation was estimated by the average of the control chronologies and two lagged values thereof. These control variables along with annual estimates of sulfur emissions were used in regression models to predict variation in the tree-ring chronologies from each of the polluted stands. Separate analyses were performed for years before and after installation of two tall stacks, for drought and nondrought years, and for years prior to initiation of smelting. In each case following initiation of smelting, the variation explained by sulfur decreased with distance from the smelter, and, concomitantly, the variation explained by the control variables increased with distance. Furthermore, chronology statistics suggested an increase in synchronous high frequency variation in chronologies from polluted sites that persisted beyond implementation of pollution controls, which reduced emissions ten-fold.

Introduction

Air pollution in general and sulfur dioxide in particular are well known to adversely affect forested ecosystems (Smith 1981). Physiological and morphological responses of plants to sulfur dioxide are well documented (Heck and Brandt 1977; Mudd and Kozlowski 1975; Barrett and Benedict 1970). Such responses may manifest themselves within the tree as reduced tree-ring widths, a phenomenon which has been experimentally demonstrated for sulfur dioxide by Keller (1980). Reduced ring widths have been
10 found in several areas where sulfur dioxide was known to occur in
11 elevated concentrations (Linzon 1971; Scheffer and Hedgcock 1955;
12 Thompson 1981; Vins and Mrkva 1973). However, relatively few
13 studies have quantitatively related tree-ring variability to
14 sulfur emissions (Dassler and Smith in Horntvedt 1970; Phillips
15 et al. 1977). The objective of the current study is to
16 quantitatively relate tree-ring variation in western larch (Larix
17 occidentalis Nutt.) to sulfur emissions from the lead-zinc
18 smelter at Trail, British Columbia. In doing so, we acknowledge
19 the potential effects of other pollutants but feel there is ample
20 evidence that sulfur dioxide was primarily responsible for damage
to the vegetation in the area (Katz 1939, Dean and Swain 1944,
Scheffer and Hedgcock 1955).

Tree rings vary as a function of a variety of factors. A major portion of year to year variation in tree-ring series is directly attributable to climatic variation (Fritts 1976), a factor important to growth not only in the year during which the

tree ring develops but also in succeeding years. Tree age, tree geometry, and local site factors also influence tree-ring variation (Fitts 1976). By applying the principles of dendroecology (Fritts 1976, Thompson 1981, Puckett 1982, Cook 1985), we can account for these effects and quantitatively relate sulfur emissions to variation in annual growth of western larch.

Site Description and History

The lead-zinc smelter at Trail is located in a relatively narrow and deep portion of the Columbia River valley where the mountain slopes rise steeply but rarely precipitously from terraces along the river (ca. 400 m) to elevations exceeding 1300 m within a few km (Scheffer and Hedgcock 1955; Archibold 1978). This topography constitutes a natural channel for the smelter gases which are confined to the valley and drift up or down the valley with approximately equal frequency (Katz 1939, 1949; Hewson 1944; Dean and Swain, 1944).

The history of smelting activity at Trail since its initiation in 1896 is well documented by Katz (1939). The Trail smelter was originally designed to treat copper ore from the nearby Rossland mine. However, with the discovery of lead and zinc in the area, along with the depletion of copper, the smelter evolved into a lead-zinc operation with lead and zinc refining beginning in 1901 and 1916 respectively.

Maximum sulfur emissions occurred during the five-year period from 1926 to 1930 when the amount of sulfur released into the

atmosphere exceeded 1.1×10^5 tons per year. Sulfur emissions of this magnitude coupled with the installation of two high stacks (over 120 m) in 1925 resulted in visible injury to crops and other vegetation in northern Stevens County, Washington (Katz 1939; Scheffer and Hedgcock 1955). As a consequence, in 1926, the United States government filed a smoke damage claim against the Trail smelter, and in the following year an International Commission was appointed to investigate the alleged damage. The results of their study confirmed that damage had occurred in an area extending from 23 km north of Trail to 95 km south, and in the late 1930's pollution abatement measures were adopted by the smelting facility. By 1941, emissions were considered to be at a level tolerable to the native vegetation (Wadey 1970). Since 1949, sulfur emissions have averaged approximately 1.0×10^4 tons per year.

The area has also been affected by a second smelter at Northport, Washington, in the Columbia River valley, 16 km south of the United States--Canada border. This smelter operated intermittently from 1896 to 1908 and continuously from 1916 to 1921. Approximately 2100 tons of sulfur per month were released during the first period and 900 tons during the latter period (Scheffer and Hedgcock 1955). These amounts of sulfur output were relatively small, according to Scheffer and Hedgcock (1955), and affected only a local area.

Methods

The selection of sampling sites and tree species to be cored was based on four criteria. (1) Perhaps the most important criterion was that the trees must be datable. That is, it must be possible to accurately assign specific years to each of the annual growth rings. (2) To establish a satisfactory control period, the trees must date prior to 1896 (i.e. prior to the initiation of smelting activity). (3) The tree species sampled must occur at a site in sufficient numbers (approximately 20) to ensure adequate replication in terms of the dating and ring-width analysis. (4) All sites, including the control sites, should be as homogeneous as possible in terms of macroclimate, topography, soil type, elevation, slope, exposure, fire (i.e. lack thereof), and other biotic and abiotic factors to facilitate between site comparisons. Maximizing homogeneity between sites will minimize the variability arising from site specific factors and thereby facilitate our assessment of air pollution effects on radial growth.

The only tree species found to meet these four criteria and occur in relatively homogeneous stands near the Trail smelter was western larch. Five sampling sites of western larch (Table 1 and Fig. 1) were chosen along a distance gradient from the smelter within the area known to have been affected by the sulfur dioxide emitted from the Trail smelter (Fox 1980; Lathe and McCallum 1939; Scheffer and Hedgcock 1955). Three control sites (Fig. 2)

were established in a region documented to be free from the smelter effects (Katz 1939; Scheffer and Hedgcock 1955) but as similar as possible to the other sites (Fig. 1).

The 5 polluted sites and the Ross control were sampled in 1977; 2 additional controls were obtained in 1982. At each site, two cores were taken from each tree at breast height (1.5 m) with a 5 mm Haglöf increment borer. All trees of suitable age were sampled except for trees growing immediately adjacent to each other. The latter were excluded to avoid growth reduction associated with severe competition. Sampling in this manner minimizes the effects of changes in stand density on the tree growth patterns (Fritts 1976).

The cores were air dried, mounted on a wooden backing, sanded to clarify ring structure, and examined under a binocular microscope to identify crossdatable sequences of rings. Crossdating involves matching synchronous patterns of wide and narrow rings among all cores from a site (reflecting the commonality of climatic effects on all trees), correcting for missing or false rings in individual cores, and assigning the exact calendar year to each ring in each core (Stokes and Smiley 1968). Lack of this crucial dating control procedure has been a major criticism of a number of air pollution studies (Thompson 1981).

To ensure the reliability and accuracy of the dates assigned, an independent verification of the dating was performed by

personnel of the Laboratory of Tree-Ring Research (University of Arizona). Ring widths were then measured to the nearest 0.01 mm using an electronic microcaliper (Henson Full Range Measuring Machine) and checked for accuracy following the procedure developed by Fritts (1976).

To remove growth trend effects (from tree age and ring geometry) and to amplify common variation in ring-width sequences from regional climate, pollution, or other growth limiting factors, tree-ring sequences from each core were standardized by fitting negative exponential or straight line with zero or negative slope through each series of raw ring widths (Fritts et al. 1969; Graybill 1979). Curves with positive slope were never used even though increasing ring widths were frequently observed at polluted sites during later years. Dividing each ring width by the value of the fitted curve for each year resulted in a new variable referred to as a tree-ring index that can be averaged, regardless of the age of the tree at the time the ring was formed, to yield a new variable referred to as the site chronology. Site chronologies were developed for each site and used in all subsequent regression analyses.

Analysis of the site chronologies was initiated by calculating three basic statistical parameters: mean sensitivity, serial correlation, and standard deviation. Mean sensitivity is a measure of the relative change in the ring-width index from one year to the next and reflects the proportion of high frequency variance (short period) in the tree-ring series.

It was calculated as the average of twice the absolute difference between adjacent indices divided by the mean of the two indices (Fritts 1976). Serial or autocorrelation is an estimate of the autoregressive structure commonly present in tree-ring series (Fritts 1976). It is a measure of nonrandomness and reflects the proportion of low frequency variance (long period) in the tree-ring series where the radial growth for a particular year is correlated to the condition or growth of a previous year.

Standard deviation, which includes both high and low frequency components measured by mean sensitivity and autocorrelation, was calculated in the usual manner (Fritts 1976).

The sites were further characterized using an analysis of variance approach to examine the sources of variation (Fritts 1976). This analysis was applied to ring-width indices for those years that were common to all cores from each site (common period: 74-117 years). Variance components were computed to estimate the variation explained by the total chronology, the differences among trees in the stand, and the differences among cores from each tree. To allow comparison among sites with different variance and autocorrelation, the variance components were reduced to percentages of the total variation.

To assess the relative effects of air pollution and climate, we performed a series of regression analyses. Preliminary autoregressions (second order) of the polluted and control chronologies on the sulfur emissions were performed to elucidate the basic interrelationships among these variables. These

analyses revealed a substantial association of the control and sulfur data in addition to the expected relationships of the polluted chronologies with the control and sulfur emissions. Because the controls were documented to be free from air pollution effects (Archibold 1978; Scheffer and Hedgecock 1955), we suspected collinearity of climate effects and sulfur emissions. An independent assessment of drought in Washington state verified our suspicion (Lasher 1977). Thirteen of 20 drought years since 1900 occurred in 1920-1940, coincident with peak sulfur emissions. Therefore, we determined that separate analyses of drought and nondrought years were necessary to minimize the confounding of the control and sulfur variables. This precluded our use of autoregression in subsequent analyses because each time series was fragmented. Hence, we applied ordinary least squares regression analysis to 4 subsets of years in the dataset: poststack drought, poststack nondrought, prestack nondrought, and prepollution with sample sizes of 15, 35, 21 and 25, respectively. In doing so, we relied upon the breaking-up of the time series to reduce the dependence of the variates; the Durbin-Watson statistic and careful analyses of residuals revealed few significant problems with the assumed independence. Nevertheless, we considered all F-tests as being only approximate and therefore relied primarily on consistent patterns in the results to make inferences.

Our general regression model was

$$Y_t = \beta_0 + \beta_1 S_t + \beta_2 C_t + \beta_3 LC1_t + \beta_4 LC2_t + \epsilon_t ,$$

where Y_t is any polluted site chronology, S_t is the estimated sulfur emission, C_t is the weighted average of the 3 control chronologies, $LC1_t$ and $LC2_t$ are the one- and two-year lags of the average control chronology, ϵ_t is the error term, and the β 's are the regression coefficients. We assumed that the control
10 chronologies were good estimates of the ring-width variation that
11 would have occurred at the polluted sites in the absence of
12 pollution. The validity of this assumption was supported by
13 regression analysis of the prepollution chronologies (1870-1896).
14 Hence, macroclimate was modeled using the weighted average of the
15 controls and one- and two-year lags thereof, which were included
16 because of the often demonstrated effects of growth in prior
17 years (Fritts 1976).

18 Coefficients of multiple determination (R^2) and coefficients
19 of partial determination were used to assess the goodness-of-fit
20 of the regression model and to examine its relationship to
distance. The former measures the proportionate reduction in
variation of the dependent variable (the polluted site
chronologies) achieved by the full set of independent variables,
whereas the latter measures the marginal contribution of an
independent variable (say sulfur or the control chronologies)
given that all other independent variables are already included

in the model (Neter et al. 1983). The coefficient of multiple determination (R^2) statistic is familiar to most as a ratio of the regression sum of squares (SSR) and the total sum of squares (SST). However, because coefficients of partial determination are less commonly used, we provide a short description of their application in our study.

In our general regression model, several sources of variation can be defined. The residual variation in a chronology (Y) when all variables are in the model is given by error sum of squares, $SSE(S, C, LC1, LC2)$. $SSE(S)$ measures the variation in Y when only sulfur (S) is included, and $SSE(C, LC1, LC2)$ measures the variation when only the control variables are included in the model. Hence, the relative marginal reduction in the variation in Y associated with sulfur when the control variables are already in the model is:

$$\frac{SSE(C, LC1, LC2) - SSE(S, C, LC1, LC2)}{SSE(C, LC1, LC2)} .$$

Similarly,

$$\frac{SSE(S) - SSE(S, C, LC1, LC2)}{SSE(S)}$$

is the relative marginal reduction in Y associated with the control variables when sulfur is already in the model. These measures are called coefficients of partial determination and were used to assess the relative importance of the sulfur and control variables as a function of distance from the smelter.

An alternative interpretation of the coefficient of partial determination was used to isolate the effect of sulfur emissions on tree-ring variation. Linear relationships between the chronologies and the sulfur emissions were estimated that accounted for the macroclimatic effects reflected in the controls and, therefore, corresponded directly to the variance reduction measured by the coefficients of partial determination. These linear relationships were obtained by first regressing both the chronologies (Y) and the sulfur emissions (S) on the control variables and obtaining residuals for each (Y minus predicted Y). This procedure by definition adjusts both the chronology and sulfur variables for their linear relationships to the control variables. Then the chronology residuals were regressed on the sulfur residual with several beneficial consequences (Neter et al. 1983): (1) regression coefficients obtained from these residual on residual regressions are equivalent to the coefficients of the sulfur effect in the full model, (2) multiple linear regression relationships can be depicted on 2-dimensional plots of the chronology residuals versus the sulfur residuals, and (3) simple coefficients of determination (R^2) obtained from residual on residual regressions are equivalent to the coefficients of partial determination calculated from the full regression model.

Results

Comparison of the chronologies reveals distinct similarities of growth patterns of western larch among the sites (Figs. 2 and 3). Each of the chronology plots was truncated on the left when the sample size fell below 10 trees or 20 cores. During the prepollution period (prior to 1896), each of the chronologies exhibited growth reduction in the early 1880's and mid 1890's. The control chronologies (Fig. 2) were also similar in their relatively reduced growth during the period from about 1918 to about 1940 and in 1968. Corresponding to these slow growth periods was reduced growth in ponderosa pine from many sites in eastern Washington (Brubaker 1980; Lasher 1977). Relatively good growth occurred after the turn of the century and during the 1950's (Fig. 2). The similarity of these control chronologies reveals the common influence of macroclimate over the study area; hence, they were averaged (weighted by sample size) to reflect the general pattern of variation that would have occurred in the absence of pollution (Fig. 3).

The polluted site chronologies display the signature years (those years with marked reduction in growth) during the prepollution period (1882,1896) and in 1968 (Fig. 3). They also show that relatively good growth occurred after the turn of the century and during the 1950's. Extremely slow growth was apparent during the 1920's and 30's corresponding to the peak in sulfur emissions in 1920-30 and the fluctuating emission levels of the 1930's. Emissions were substantially reduced in 1944

resulting in resumption of relatively normal growth. Around the turn of the century, the Sheep Creek site was subject to effects of a second smelter at Northport, WA. Release from these effects was concurrent with increasing emissions from Trail, B.C., which should have affected this site only during peak years because of the nearly 20 km distance separating them.

Mean ring width did not show any consistent variation with distance from the smelter (Table 2). We include it because mean ring width can influence other chronology statistics, especially as it operates through the standardization process. Lack of correspondence between mean ring width and any of the chronology statistics suggests that it was of little consequence in determining the patterns discussed hereafter.

Mean sensitivity statistics indicate that western larch is complacent (i.e., shows little relative year to year variation) relative to other western conifers (Table 2; Fritts 1976). The usually north-facing aspect of most larch stands may reduce their susceptibility to drought, which commonly limits growth in other species (Table 1). Control sites had the lowest values for mean sensitivity, ranging from 0.127-0.144 (Table 2). The mean sensitivity for polluted sites however increased consistently with decreasing distance from the smelter. This suggests that some common set of limiting factors was contributing to the high frequency variation in areas successively closer to the smelter.

In contrast to mean sensitivity, the autocorrelation coefficients did not exhibit any discernible pattern in relation

to distance from the smelter. They were high relative to other western species and were probably a consequence of the relatively inflexible growth curves used to standardize these data. High autocorrelations indicate that a large proportion of the variance is related to low frequency trends or cycles in the time series that were not removed in the standardization process. Such trends could result from long-term climatic changes, but we know of no other data from this region supporting this possibility.

Standard deviation reflects the total variation in the ring-width series at all frequencies. Standard deviations for the control data were consistently lower than those from the polluted sites. They ranged from 0.206 to 0.250, whereas the polluted sites were 0.298-0.503 (Table 2). These results roughly parallel those for mean sensitivity; discrepancies can be attributed to those chronologies with elevated low frequency variance. In particular, Sheep Creek had the most low frequency variation (autocorrelation) and relatively little high frequency variation (mean sensitivity), resulting in a relatively low standard deviation. Thus, while the proportion of high frequency variance observed in our western larch data was somewhat lower than other western conifers and the low frequency variance higher, the total variance was comparable to that observed elsewhere. However, within our western larch stands, the proportion of high frequency variance was consistently greater for polluted sites.

Variance components were computed following Fritts (1976) to estimate the sources of variation in ring width (Table 2). The control sites were quite similar in having 33-35% of the total variation retained in the chronology after all tree and core indices were averaged. This is a relatively low amount and again reflects the relative complacency of western larch in this area. Variance components for trees and cores from control stands were similar in magnitude to those for site indicating that this species is normally as limited by microscale factors as it is by macroscale factors. The polluted sites were different in their sources of variation. The variance components for sites ranged from 42-61%, and in each case this was the dominant variance component (Table 2). There was no clear distance relationship, but the trees within polluted sites as a whole appeared to be more limited by a common set of external factors than were the controls. That is, the polluted site trees were more synchronized with less variation among trees and cores within trees.

Thus, the control stands of western larch exhibited relatively less variation in ring width from year to year and more variation among trees and cores within stands. The polluted stands however had a greater proportion of high frequency variance in common, but were proportionately less variable among trees and cores within stands. One interpretation of these results is that the trees within each of the polluted stands were

more limited by a set of common external factors than the control stands. Evidence presented below supports the hypothesis that air pollution was an important factor in these differences.

The general regression model discussed in the Methods was applied to each of the 5 polluted stands of western larch for each of the data subsets. Goodness-of-fit statistics are plotted in Fig. 4 as a function of distance from the smelter. The top curve (solid line) in each panel is the coefficient of determination for the full model. For the prepollution period, the full model included only the average of the 3 controls and 2 lags of this average. The amount of variance explained by this model was relatively high at all distances from the smelter (Fig. 4) except for Gorge Creek, which was higher in elevation than the other sites (Table 1), and Boundary, which differed in its pattern of growth during the late 1880's (Fig. 3). Thus, the control chronologies matched the polluted chronologies to varying degrees, but they were deemed sufficient to describe the macroclimatic signal in the data.

The fit of the full model (including control and sulfur variables) to each of the data sets during the pollution period was consistently high (Fig. 4; solid line) (the Sheep Creek points at 19.4 km were not connected for the prestack data because of the probable effects of the Northport smelter (Fig. 3)). Coefficients of partial determination, which give the marginal contributions of selected variables, varied systematically with distance from the smelter. The variance

explained by sulfur given that the control variables were already in the model (Fig. 4; longdashed line) diminished with increasing distance, whereas the variance explained by the control variables given that sulfur was already in the model (Fig. 4; shortdashed line) increased with distance. During poststack drought years, the variance explained by sulfur emissions at sites closest to the smelter was greater than that explained by the control variables (i.e., macroclimate) at more distant sites. Thus, the distance from the smelter was directly related to the relative amounts of control and sulfur information in the polluted site chronologies. This pattern is compelling empirical evidence for the biological significance of sulfur emissions as a growth controlling factor in western larch.

To further isolate the effects of sulfur emissions on tree growth, we performed a series of residual on residual regressions as described in the Methods. Residuals of regressions of each of the polluted chronologies on the control variables are given versus similar residuals for sulfur emissions (Figs. 5 and 6). Again, these regressions were performed for poststack, drought and nondrought, and for prestack nondrought years. Although F-tests are only approximate for these data, significant regressions were obtained in all cases except for Boundary and Sheep Creek during the poststack drought years, Sheep Creek during poststack nondrought years, and Boundary during prestack nondrought years. The goodness of fit of these regressions is as indicated by the coefficients of partial determination in Fig. 4 (longdashed line).

The inverse effect of sulfur emissions on ring width during poststack years is revealed by the negative slopes of the regression lines (Fig. 5). These results indicate that for given climatic conditions we can expect a reduction in average tree-ring index for any increase in sulfur emissions (within the range of the data). As the distance from the smelter of the sites increased, the slope of the regression lines decreased reflecting the decrease in emission effects as pollutant concentrations decrease with distance because of normal transport phenomena.

During the prestack years, chronology residuals were also inversely related to sulfur emissions at the three sites closest to the smelter, whereas a positive relationship was exhibited at the more distant sites Boundary and Sheep Creek. The latter result was most likely related to the presence of the Northport smelter from which sulfur emissions declined concomitantly with increasing emissions from the Trail smelter.

Separate analyses of drought and nondrought years during the poststack period allowed us to assess the interaction of drought and pollution. Slopes of regression lines for nondrought data were consistently steeper than slopes of corresponding drought data, indicating that pollution effects were greater under nondrought conditions. Nondrought years also exhibited greater variability about the regression lines. Larger ring widths, which normally occur in the absence of water stress, constitute a greater potential for growth reduction and can have more total variance to contribute to residual variation.

Discussion

Our analysis demonstrated the effects of air pollution on ring-width variation in western larch growing near the smelter at Trail, B.C. Effects of tree age and ring geometry within stands were accounted for by standardizing the raw ring-width series with theoretical growth curves. Three control chronologies were used to model normal variation from climate in the polluted site chronologies; some variation among these sites was apparent, but their average value captured the common macroclimatic signal. We found that 65% of the 20th century drought years occurred during years of peak sulfur emissions causing pollution and climate to be correlated. This collinearity problem was mitigated by separate analysis of drought and nondrought years.

In multiple regression analyses, the variation accounted for by sulfur emissions after accounting for control effects was consistently greater at those sites nearest the smelter. The variation explained (as measured by the coefficient of partial determination) for sulfur decreased with increasing distance from the smelter, and, conversely, the variation explained by the controls (macroclimate) increased with distance. These trends were observed in each data subset examined and are consistent with other point source studies (e.g., Linzon 1971; Stone and Skelly 1974; Phillips et al. 1977; Westman 1974).

Pollution effects were consistently greater in nondrought years; slopes in residual on residual regressions (or equivalently in multiple regressions) in nondrought years

were always more negative when compared to drought years at each site. Such a result might be expected for two reasons.

(1) Nondrought years are by definition more favorable for growth and therefore produce larger tree rings. Greater mean ring width implies a greater potential loss to anthropogenic stresses.

(2) Tree susceptibility to air pollution may be reduced during drought years. Under water stress, stomata are more frequently closed (Kramer and Kozlowski 1979), and, because stomatal entry is an often cited pathway for air pollution injury, the potential for sulfur dioxide effects may be reduced.

Also associated with nondrought years was increased variability about the regression lines. This could have been a result of nonindependence of mean and variance in ring widths and increased growth during nondrought years, or it could have been a result of an inability of the sulfur emission estimates to predict the actual sulfur dioxide concentrations to which the trees were exposed. The latter could have been especially important during later years when smelting was limited during periods in which meteorological conditions promoted the accumulation of smelter emissions. However, variability about the regression lines was greatest at lowest levels of sulfur emissions (during nondrought years) when trees were least limited by either pollution or climate (Fig. 5). Chronology statistics suggest that under low stress western larch is quite complacent and exhibits a relatively large amount of random variation among

trees within sites. Thus, the variability about the regression lines during nondrought years was likely a manifestation of the normal growth pattern of western larch.

The chronology statistics also suggest an indirect effect of air pollution on western larch. Mean sensitivity displayed a consistent distance gradient, and the variance in common to all trees and cores from a site was higher for the polluted sites. Thus, ring widths from stands subject to pollution stress had more high frequency variance, and the trees within these sites were more synchronized in their growth. This pattern implicates smelter emissions as an external factor limiting radial growth. However, sulfur emissions, as illustrated in Fig. 3, appear to have been a low frequency signal that would have more likely reduced the proportion of high frequency variance than increased it.

It is possible that the sulfur series had a higher frequency effect than was apparent because sulfur emissions in tons per year may not have captured the actual pollution effect to which the stands were subjected. We have already mentioned the temporal and spatial variation in dispersion and concentration of the smelter emissions. There may also have been temporal variation in susceptibility to sulfur dioxide from interactions with climate such as those already mentioned with respect to drought. Inspection of the chronologies reveals increased variability after 1940 in the polluted sites relative to the controls. This variability has relatively high frequency and

therefore may be responsible for the elevated mean sensitivity observed. Thus, it appears that the indirect effect of pollution on these stands that affected their growth pattern occurred after sulfur emissions returned to more moderate levels -- levels which are supposedly not detrimental to tree growth (Katz 1939; Scheffer and Hedgecock 1955; Dean and Swain 1944; Archbold 1977).

Possible mechanisms for this indirect effect of smelter emissions on western larch probably involve climate. Synchronous high frequency variation generally characterizes ring-width series in tree species limited by climate. Puckett (1982) has suggested that increased sensitivity to climate was the primary effect of air pollution in southeastern New York. The importance of climate for western larch has been demonstrated by the crossdating of the sites used in this study. In the simplest scenario, pollution and climate are independent limiting factors but with the former having greater influence. When pollution was reduced after 1940, the controlling influence of climate was expressed resulting in increased high frequency variance and synchrony among trees. However, the lack of similar variance in the control chronologies and the decrease in high frequency variance with distance from the smelter indicate that this explanation may be too simple and other factors, which might interact with climate, should be considered.

Archibold (1976, 1978) documented the vegetation recovery in the Columbia River Valley near Trail following nearly three decades of reduced pollution. He found the original degree of vegetation destruction to be most important in determining the degree of vegetation recovery; sites with severe or moderate

damage still form clusters distinct from more distant sites in a principal components ordination. Alteration in community structure could change climate exposure directly, but it would more likely change the competition regimes within stands, which might initially promote competitive release and, subsequently, increased competition as the aspen and birch understory regenerated. Increased transpiration from the regenerated biomass after reduction in pollution could decrease available soil moisture promoting water stress. Ultimately, these stands would be more limited by climate, and they would have more synchronous high frequency variance than stands not affected by pollution.

Trace metals can be a significant problem near any smelting operation with estimates of residence time in the soil varying from several decades to several centuries (Tyler 1978 in Smith 1981). Previously unpublished results of a trace metal survey are presented in Table 3. Our only control information comes from the Ross site where levels of zinc, lead, and cadmium may have been high relative to other localities because this is an ore bearing region. Concentrations of these metals in the soil at sites nearest the smelter were 5-10 times greater than those at Ross (Table 3). The pH did not vary greatly among the sites. A consistent distance relationship was not apparent for any of the measures, but interactions with topography and parent material may have produced some variation.

Trace metals in the soils may have a long-term influence on tree growth primarily by altering nutrient cycling (Smith 1981); direct effects were presumably swamped out by the more acute sulfur dioxide toxicity prior to pollution control. Impaired nutrient cycling in these forests from trace metal toxicity to litter decomposers and symbiotic microorganisms (such as mycorrhizae) may constitute a chronic stress increasing the sensitivity of these trees to climatic fluctuations. It is also possible that trace metals alone or in combination with chronic sulfur dioxide exposure were responsible for the increase in variability observed. Elevated cadmium in the soil has been shown to reduce growth of seedlings (Kelly et al. 1979), and trace metal concentrations in annual rings have been associated with reduced radial growth (Symeonides 1978, Robitaille 1981, Baes and McLaughlin 1984).

Alternative and more direct than the above mechanisms for the increase in synchronous high frequency variance is the direct effect of chronic low levels of sulfur dioxide still occurring. Sulfur emissions today are still on the order of 10,000 tons/yr, and fumigations of 1 ppm SO₂ (for at least 20 min) were occasionally recorded as far as 11 km from the smelter (at least until 1968). The pollution control strategy at Trail has been keyed to meteorological conditions since the late 1930's; exposures are now managed to produce a chronic low-level stress, which in conjunction with normal climatic fluctuations may magnify climatic responses. This is probably the most

parsimonious explanation for the persistent variability observed, but the competitive release and trace metal mechanisms are also plausible. Thus, we have evidence of a persistent, indirect effect of smelter emissions on tree-ring variation in western larch in addition to the direct reduction in radial growth attributable to sulfur dioxide toxicity.

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Table 1. Site characteristics.

Site	Latitude	Longitude	Elevation(m)	Slope ⁺	Aspect [#]	Distance(km)*
Gorge Creek	49°04'	117°41'	1050	21°	30°E	2.9
Cambridge Creek	49°06'	117°44'	800	17°	0°N	4.0
Montrose	49°06'	117°32'	750	7°	40°W	11.8
Bondary	48°57'	117°39'	500	20°	30°W	15.4
Sheep Creek	48°56'	117°47'	400	4°	40°E	19.4
Ross	49°10'	117°28'	900	16°	0°N	Control
Summit Lake	48°57'	118°08'	700	18°	30°E	Control
7-mile Dam	49°02'	117°30'	550	30°	30°W	Control

⁺ average over stand.

[#] relative to 0°N.

* from smelter.

Table 2. Characteristics of the tree-ring chronologies from polluted and control sites.

Site	N of trees/cores	Length of chronology	Mean ring width (mm)	Mean sensitivity	Auto- correlation	Standard deviation	Variance components (%)		
							Site	Trees	Cores
Gorge Creek*	36/72	1839-1976	1.473	.233	.711	.385	50	28	22
Cambridge Creek	33/61	1849-1977	1.688	.200	.845	.503	61	17	22
Montrose	29/58	1776-1977	2.388	.178	.766	.300	49	33	18
Boundary	29/58	1673-1977	1.635	.170	.722	.298	42	36	22
Sheep Creek	18/36	1813-1977	1.765	.167	.855	.385	59	24	17
Ross ⁺	26/47	1846-1977	1.624	.140	.777	.248	33	29	38
Summit Lake	19/38	1808-1980	1.307	.144	.805	.250	34	37	29
7-Mile Dam	15/30	1782-1980	1.460	.127	.660	.206	35	22	42

* Polluted sites are arranged in order of increasing distance from the smelter.

+ The last 3 sites are controls.

Table 3. Trace metals[‡] and pH in the soil at 2 depths.
Mean $\pm$ SE.

Site	Depth ⁺	Zn	Pb	Cd	pH
Gorge Creek	0-2.5	823 $\pm$ 1	1220 $\pm$ 1	18 $\pm$ 2	5.0 $\pm$.1
	15	149 $\pm$ 5	43 $\pm$ 3	3 $\pm$ 1	5.2 $\pm$.4
Cambridge Creek	0-2.5	463 $\pm$ 9	930 $\pm$ 1	11 $\pm$ 1	3.9 $\pm$.7
	15	124 $\pm$ 3	25 $\pm$ 2	3 $\pm$ 2	6.4 $\pm$.6
Montrose	0-2.5	747 $\pm$ 3	85 $\pm$ 3	24 $\pm$ 1	4.7 $\pm$.3
	15	256 $\pm$ 6	20 $\pm$ 1	4 $\pm$ 1	5.8 $\pm$.3
Boundary	0-2.5	898 $\pm$ 1	1242 $\pm$ 3	21 $\pm$ 2	5.32 $\pm$.2
	15	160 $\pm$ 7	28 $\pm$ 3	4 $\pm$ 1	5.4 $\pm$.2
Sheep Creek*	0-2.5	987 $\pm$ 1	1962 $\pm$ 2	22 $\pm$ 2	4.5 $\pm$.3
	15	176 $\pm$ 3	25 $\pm$ 1	3 $\pm$ 1	4.7 $\pm$.3
Ross	0-2.5	125 $\pm$ 1	127 $\pm$ 3	4 $\pm$ 1	4.8 $\pm$.2
	15	91 $\pm$ 3	12 $\pm$ 1	2 $\pm$ 1	5.7 $\pm$.2

* may include effects of Northport smelter.

+ depth in cm.

[‡] total mg/g as determined by atomic absorption spectrometry using a Perkin-Elmer Model 403 spectrometer.

FIGURE LEGENDS

- Fig. 1 -- Map of northeast Washington and southeast British Columbia showing sampling sites and the 2000 ft (610 m) contour above the Columbia River valley.
- Fig. 2 -- Chronology plots for the 3 control stands. Each was truncated on the left when the sample size was less than 10 trees or 20 cores.
- Fig. 3 -- Chronology plots for the 5 polluted stands, the average of the 3 controls in Fig. 2, and the estimated smelter emissions. Chronology plots were truncated when the sample size fell below 10 trees or 20 cores. The dashed line on the sulfur plot indicates the year when 2 tall stacks (>150 m) were installed.
- Fig. 4 -- Relationship of variance explained to distance from the smelter in our regression models (see text). Solid line is the coefficient of determination for the full model including sulfur and the controls. Longdashed line is the coefficient of partial determination for sulfur given that the controls were already in the model. Shortdashed line is the coefficient of partial determination for the controls given that sulfur was already in the model. Although the points for the most distant site (Sheep Creek) during pre-stack years had the same rank order as Boundary, they were not connected to indicate the probable influence of emissions from the Northport smelter.

Fig. 5 -- Relationship during post-stack years of polluted site chronologies to sulfur emissions after variation accounted for by the controls was removed from both variables by regression (see text). Residuals were rescaled from units of original variables to simplify presentation. The solid line and diamonds are for the nondrought years, and the dashed line and asterisks are for the drought years. Boundary drought and both Sheep Creek regressions were not significant. Coefficients of determination (R^2) for these regressions are given by the longdashed line in the appropriate panels of Fig. 4.

Fig. 6 -- Same as Fig. 5 for pre-stack years, but there were not enough drought years for analysis. Boundary regression was not significant, and Sheep Creek was affected by the smelter at Northport, Washington during this period.

CHRONOLOGY INDEX

Fox et al. Fig. 3

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