WESTERN SPRUCE BUDWORM OUTBREAKS IN NORTHERN NEW MEXICO: TREE-RING EVIDENCE OF OCCURRENCE AND RADIAL GROWTH IMPACTS FROM 1700 TO 1983

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ABSTRACT

Douglas-fir tree-ring chronologies were analyzed for evidence of past outbreaks of western spruce budworms. Tree-ring chronologies from ponderosa pine, which is not defoliated by budworms, were used to estimate potential growth in the Douglas-fir during current and past outbreaks. At least eight outbreak periods were identified in the Douglas-fir chronologies between 1700 and 1983. The average interval between initial years of reduced growth periods caused by budworm was 33.8 years. The average duration of reduced growth periods was 14.0 years, and the average maximum and periodic growth reductions were 42.5% and 23.5% of potential growth.

INTRODUCTION

Repeated outbreaks of western spruce budworms (Choristoneura occidentalis Freeman) have occurred throughout forested regions of western North America, including the mixed conifer and spruce-fir forests of the southwestern United States. Defoliation of conifers by this insect causes radial and height growth reduction, top-killing, reduced generation and mortality (Carlson et al. 1983; MacLean 1985). Appropriate responses to this problem by forest managers depends on accurate assessments of the economic, social and other resource impacts caused by the budworm, as well as consideration of the long term ecological role of this insect in forest dynamics.

A long term perspective of the incidence (frequency, extent, duration, and severity) of budworm outbreaks is needed to evaluate the importance of this insect in the regulation of productivity, age class structure, and species composition of natural and managed stands. Histories of budworm incidence may be useful in the study of interactions with other natural and anthropogenic disturbances and environmental factors, such as fire, climate, harvesting practices, and air pollution (Volney 1985).

The extent of defoliation, topkilling, and mortality have been documented recently for an outbreak which began in 1974 on the Carson National Forest in Northern New Mexico (Rogers 1984), and records of past infestations (beginning in 1922) are available. However, the timing of occurrence of budworm outbreaks before 1922, and the effects of past and current outbreaks on radial growth were not known. This study was undertaken to determine if dendroecology techniques could be used to estimate the timing and duration of reduced growth periods caused by past budworm outbreaks, and to quantify the resulting losses in radial growth (Swetnam 1986). Differences in budworm incidence in the twentieth century and earlier periods was also investigated.

The working hypothesis was that recognizable periods of low growth would be observed in budworm host (food) trees (Douglas-fir, *Pseudotsugae menziesii*, and white fir, *Abies concolor*) during budworm outbreaks, while the growth in non-host trees (ponderosa pine, *Pinus ponderosa* and piñon, *Pinus edulis*) would be similar during periods between outbreaks, but greater during the outbreak periods. Similar strategies for identifying effects of insects on trees have been used by Blais (1962, 1965), Brubaker and Greene (1979), and Carlson and McCaughey (1982). Results of the analysis of Douglas-fir and ponderosa pine chronologies from New Mexico are reported in this paper. Additional analysis of white fir tree-ring series and collections from the Front Ranges of the Colorado Rocky Mountains are in progress.

METHODS

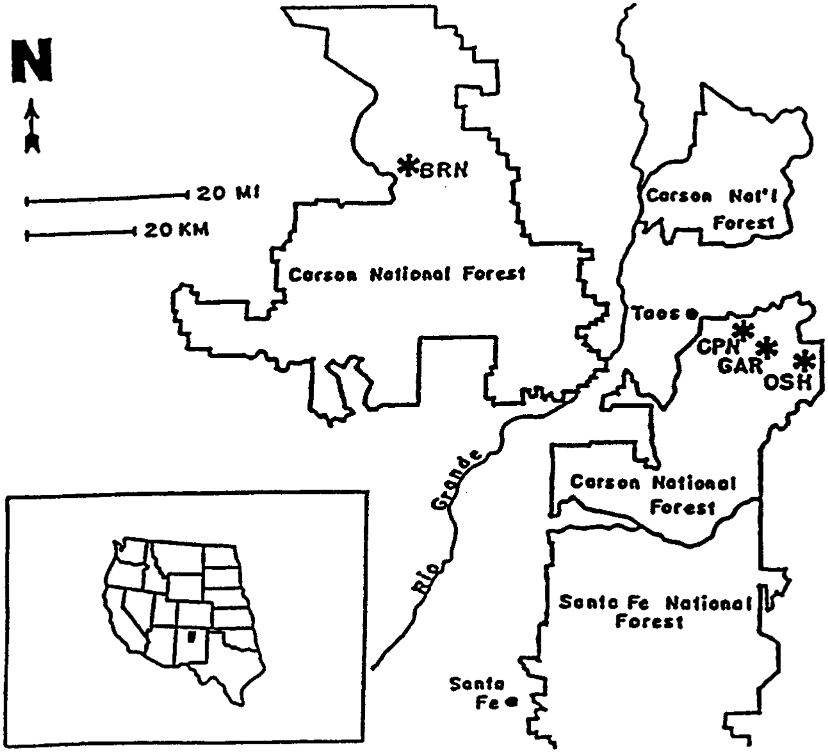
Two increment cores were extracted at approximately breast height (1.37 m above ground level) from each of 15 to 20 randomly selected host trees growing within 11, 0.4 ha (1.0 acre) mixed conifer plots that had originally been established by the Forest Service for monitoring budworm populations and assessing damages (Rogers 1984). An additional five to ten of the oldest host trees within or near the study plots were also sampled to assure that the collection included the maximum record length. Fifteen to 20 non-host trees were sampled within or near each of the plots to serve as controls. A total of 377 host trees and 87 non-host trees were sampled. Data from the 11 sampled plots were grouped into four study areas (Fig. 1).

Details of sampling, dating, measuring, and processing ring measurements for the study of past budworm outbreaks were described by Swetnam *et al*. (1985). The general approach followed in the analysis of paired tree-ring chronologies from host and non-host trees included the following steps:

1. Average host and non-host chronologies were compared graphically to determine whether the two species were generally responding in a similar manner between known outbreaks during the twentieth century, but differently during the outbreaks. Digital filtering techniques (Fritts 1976; LaMarche 1974) were used to facilitate these comparisons.

2. Average chronologies were statistically compared using cross-correlation and cross-spectral analysis (LaMarche 1974).

Figure 1. Map of northern New Mexico, U. S. A. Study areas are indicated with asterisks and three-letter codes: BRN = Burned Mountain, CPN = Capulin Canyon, GAR = Garcia Park, OSH = Osha Mountain.



3. Climatic effects in the host chronologies were reduced by subtracting a rescaled version of the non-host chronology from the same site, producing a "corrected" host chronology. This was accomplished by (a) obtaining the residual of the non-host indices (non-host yearly indices - 1.00), (b) rescaling the non-host residuals using a ratio of standard deviations (standard deviation host indices/standard deviation non-host indices X non-host residuals), and (c) subtraction of the non-host residuals from the host indices (Nash _et_ _al_. 1975; Swetnam _et_ _al_. 1985).

4. Periods of reduced growth in the corrected chronologies were compared with U. S. Forest Service records of budworm outbreaks within the study areas to assess the precision of the host chronologies in reconstructing past budworm incidence.

5. The corrected chronologies were used to estimate the timing, duration and amounts of growth reduction caused by known (post-1920) and inferred (pre-1920) outbreaks. Periods of reduced growth before 1920 were identified as past budworm outbreaks (inferred outbreaks) based on characteristics of the post-1920 reduced growth periods that were known to be outbreaks from Forest service documents. These characteristics were (a) three or more years of growth index values less 1.00 (expected or potential growth level for a tree-ring index series), _and_ the lowest growth value during this period was greater than 1.28 standard deviations from the mean of the series ($p < 0.10$ for a one sided z-score significance test).

RESULTS AND DISCUSSION

Absent Rings

Crossdating revealed that one or more of the rings were locally absent in the ring series from approximately 40% of the host trees. In nearly all cases the absence of annual rings was observed to be associated with low growth during periods of budworm outbreaks. Absent rings were also identified in the ring series from the non-host trees, but they did not occur during identified outbreaks as consistently as in the host trees. This was most clearly evident during the recent outbreak, with more than 26% of all Douglas-fir ring absences occurring since 1977, while only 2.6% of all ponderosa pine ring absences occurred during this same period. A greater proportion of absent rings were recorded during the recent outbreak in the Douglas-fir than during any previous outbreak. This finding suggests that the recent outbreak may be more severe than any other outbreak that was recorded by the sampled trees.

Host and Non-Host Tree-Ring Comparisons

Graphical comparisons of the host and non-host chronologies from most of the study areas showed that the growth trends and relative changes in year-to-year growth of the two species were generally synchronous, especially between known outbreak periods (Fig. 2A). Figure 2B compares the chronologies from one study area after smoothing the index values with a thirteen-weight digital low pass filter (Fritts 1976; LaMarche 1974). The low pass filter comparisons de-emphasize the short term or climate induced fluctuations common between the host and non-host species, while emphasizing the longer term growth differences that are most likely due to the effects of budworm defoliation (Swetnam *et al.* 1985). Outbreaks were evident as low growth indices in the host series that were not correspondingly low in the non-host series (Fig. 2A, 2B).

The synchrony of the relative year-to-year changes in the two species growth indices in the higher frequencies (i.e., climate signal) was also apparent in the results of cross-correlation and cross-spectral analyses (time and frequency domains respectively)(Tab. 1, Fig. 3). The average correlation for the full length of all of the host and non-host site index chronology comparisons was 0.65, while correlations for periods between known and inferred outbreaks were usually greater than 0.80 (Fig 3A). The correlation coefficients shown in Figure 3A were computed by correlating successive 20 year periods, incremented forward by one year for each period, along the lengths of the ponderosa pine and Douglas-fir chronologies. The low correlations (the troughs) generally correspond to identified outbreak periods. The examples shown in Figure 3 are from a study area in the Colorado Front Range that is currently being analyzed.

Figure 2. A. Comparison of Douglas-fir (line with triangles) and ponderosa pine (line) tree-ring width indices from Garcia Park New Mexico. B. The same chronologies after smoothing with a digital filter. C. The corrected Douglas-fir growth indices derived by subtracting a rescaled version of the ponderosa pine indices. Open arrows indicate timing of known outbreak periods verified by Forest Service records. Closed arrows indicate timing of inferred outbreaks.

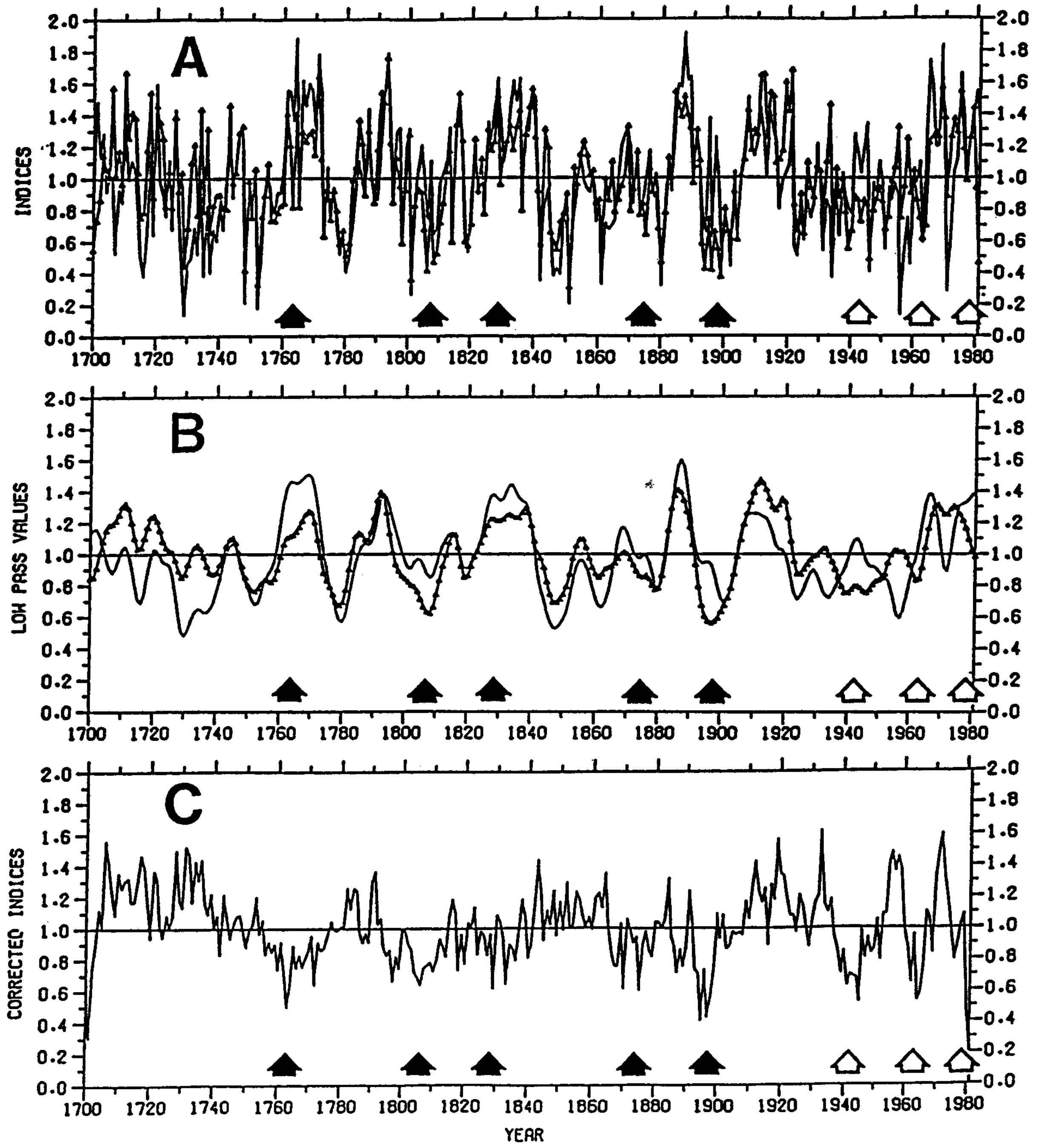


Figure 3. A. Correlation coefficients for 20 year moving periods across the length of the ponderosa pine and Douglas-fir chronologies from Ormes Peak, Colorado. Correlations of the standard index chronologies are plotted with a solid line, and correlations of white noise residuals, computed from second order autoregressive models (Cook 1985) are shown as dashed lines. Arrows correspond to maximum growth reduction years of known and inferred budworm outbreaks derived from corrected index chronologies. Note that the low correlations during the early 1780s correspond to high positive corrected indices, that appear to be due to a growth release within this Douglas-fir stand that was not matched in the ponderosa pine trees sampled from another nearby area. B. Coherence between the Ormes peak ponderosa pine and Douglas-fir chronologies. Analysis was computed at 25 lags, for standard index series (solid line), and white noise residuals (dashed line).

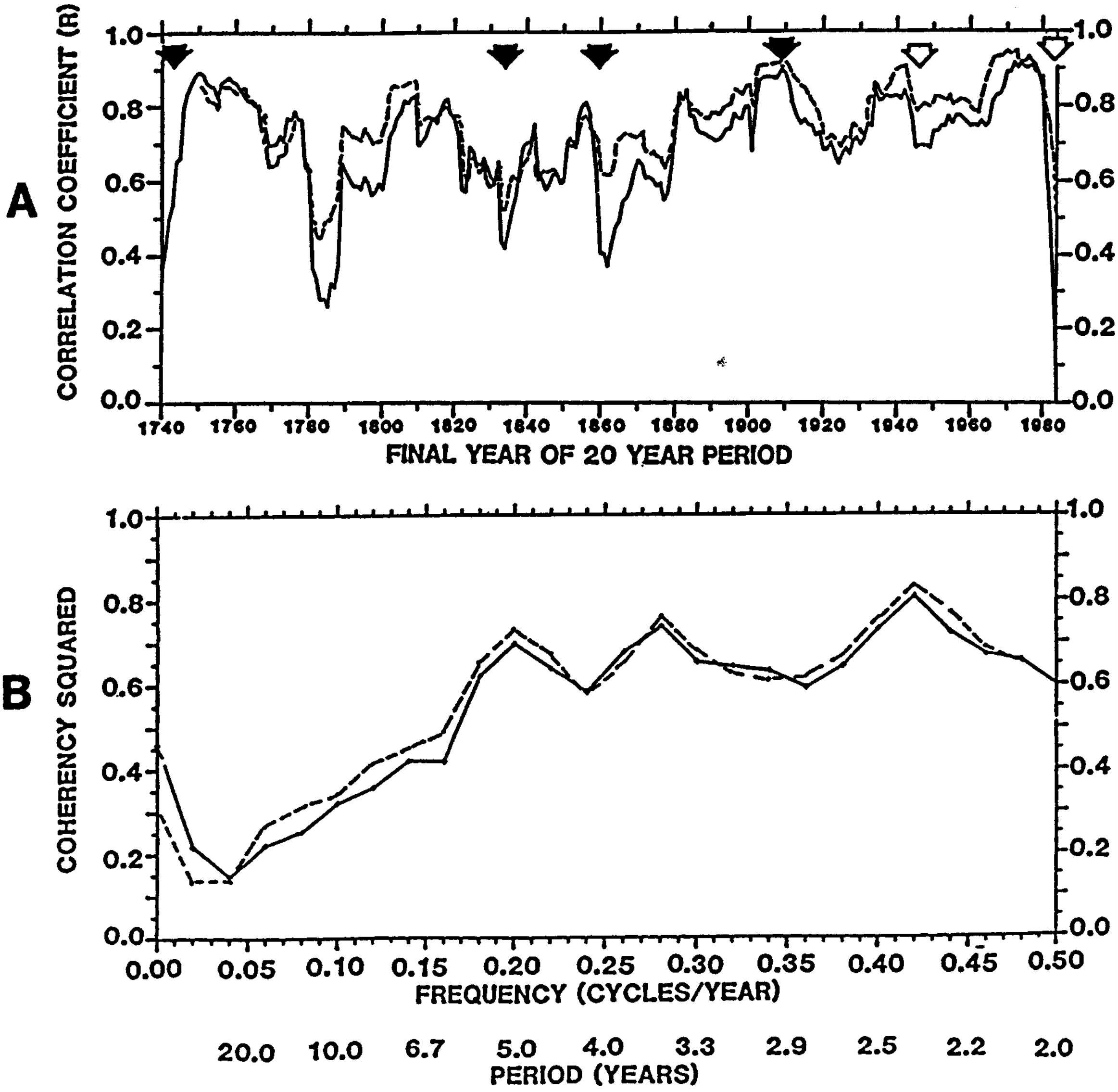


Table 1. Correlation coefficients for Douglas-fir and ponderosa pine paired chronologies from Colorado and New Mexico stands. All coefficients are significant at $p < 0.05$.

Stand Name	Period of Comparison	No. of Years	Correlation Coefficients Indices	 Low Pass	 High Pass
Burned Mountain	1790-1983	194	0.640	0.652	0.672
Capulin Canyon	1790-1981	192	0.665	0.602	0.719
Garcia Park	1710-1981	272	0.745	0.699	0.803
Osha Mountain	1700-1981	282	0.537	0.492	0.632
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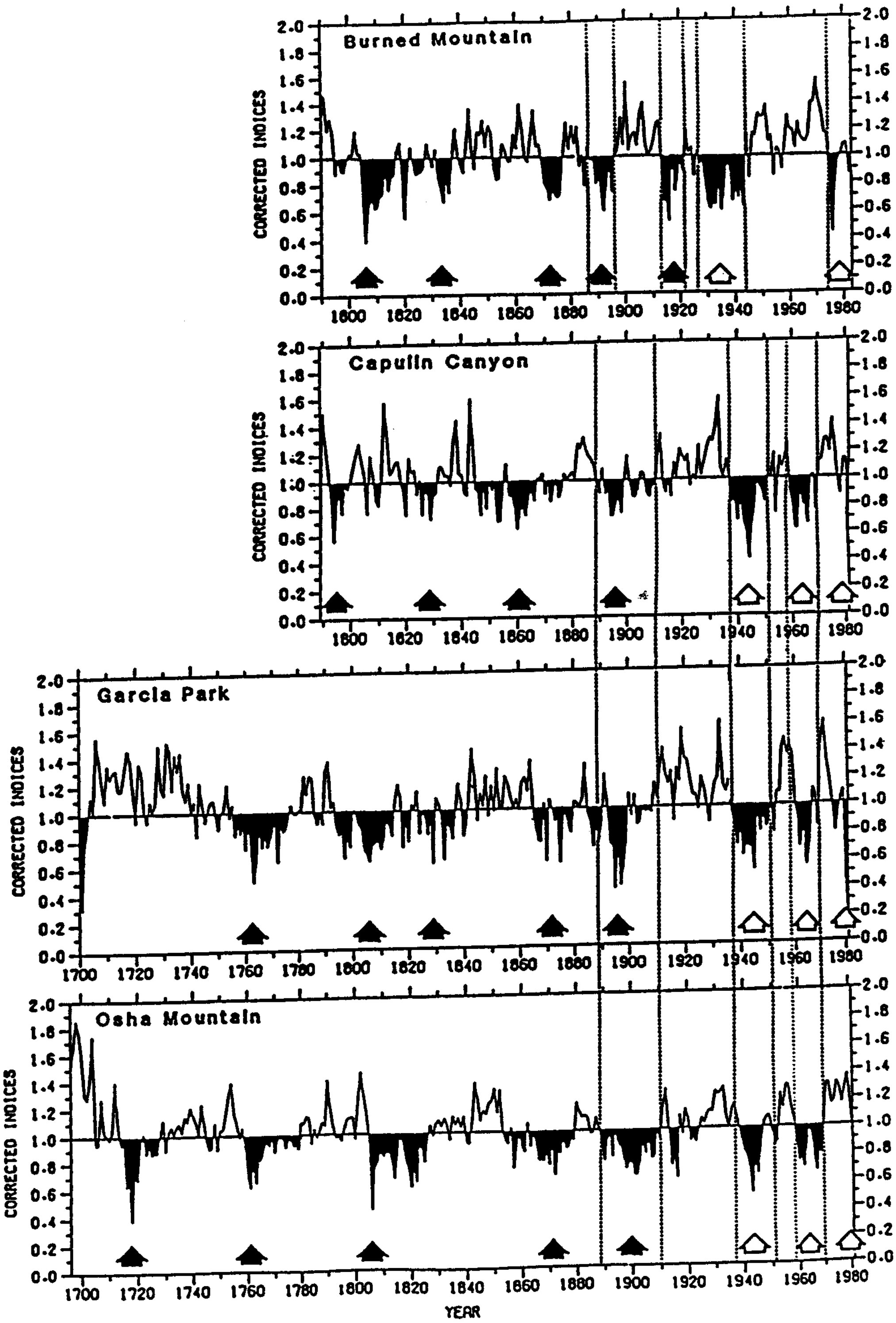
		Mean:	0.646	0.611	0.707

Cross-spectral analyses also showed that host and non-host chronologies generally correlate highest in the higher frequencies, and lower in the low frequencies (Fig. 3B). The coherency squared values in Figure 3B are the cross-spectral analog of the squared correlation coefficient, and thus provide a measure of the covariance between the ponderosa pine and Douglas-fir series across a range of frequencies (LaMarche 1974). These data support the working hypothesis that chronologies from host and non-host species may have similar climate signals, which predominate in the high frequencies, but differ in response to budworm effects, which are primarily recorded in the low frequencies only in host trees. These results provided a logical basis for proceeding to the next step, which involved subtracting a rescaled version of the ponderosa pine chronologies from the corresponding Douglas-fir chronologies from each study area. This resulted in corrected Douglas-fir chronologies from each study area (Fig. 4).

Verification

The timing of the beginning and maximum years of growth decline for the known outbreak periods (post-1920) closely matched the documented occurrence and peak years of budworm outbreaks (from Forest service records) within the different study areas. Statistical evidence that the host tree-ring indices were good indicators of budworm activity was also provided in a regression analysis using budworm population and defoliation data that was recorded for individual sampled trees in the New Mexico plots from 1978 to 1981 (Swetnam 1986).

Figure 4. Corrected growth index series from Douglas-fir. Vertical dotted lines show timing and synchrony of outbreaks that have occurred since the late 1800s. Open arrows indicate timing of outbreak periods verified by Forest service records. Closed arrows indicate timing of inferred outbreaks.



Empirical exponential models indicated that average host growth indices were closely associated with cumulative plot defoliation (sum of defoliation estimates in each successive year, where defoliation is loss of current years needle growth) (R^2 = 0.584, n = 28, F = 11.07, p < 0.01), and with the number of egg masses per M^2 of foliage in the previous year (R^2 = 0.670, n = 21, F = 5.01, p < 0.005). These observations verified that the corrected tree-ring series were a good measure of the occurrence and radial growth effects of past budworm outbreaks.

Current and Past Budworm Incidence

The corrected series (Fig. 4) were used to identify the timing (dates) of outbreaks, the duration of budworm induced low growth periods, and the maximum annual and periodic radial growth losses. The latter two measures were derived by subtracting the corrected indices during outbreaks from the potential growth value (1.0) and multiplying by 100. Thus, the radial growth reduction measures are expressed in relative terms as a percentage of the expected growth.

Table 2 lists statistics for these data, including the results of t-tests for differences in means for pre-1910 and post-1910 outbreaks. The means test was conducted to determined if there were significant differences in budworm incidence in the twentieth century relative to previous periods. The year 1910 was chosen as the dividing year because a late nineteenth century outbreak apparently continued in several of the study areas until approximately this year (Fig. 4). This analysis indicated that the average duration of budworm induced low growth periods was somewhat shorter during the twentieth century than during earlier periods, but periodic growth losses were significantly greater. There were no significant differences between the mean intervals for pre- and post-1910 periods.

A number of forest ecologists have suggested that the severity, extent, and frequency of budworm outbreaks may have increased in the twentieth century, because of forest management practices, such as fire control and selective harvesting that have led to dense, multiple-storied forests, with a greater proportion of budworm host species (Carlson et al. 1983; Schmidt 1985). It is argued that forests with these characteristics are more susceptible and vulnerable to budworm outbreaks. The reconstructed budworm history for the four New Mexico stands reported here does not provide any clear confirmation of an increasing trend in severity of budworm outbreaks. A high rate of occurrence of absent rings in Douglas-fir trees during the recent outbreak suggests that it may be relatively more severe than earlier outbreaks. However, some pre-1900 outbreaks were evidently quite severe. For example, analysis of growth trends in ring-width series and age class data suggest that the 1890's-1900's outbreak (Fig. 4) was followed by mortality of some host trees, growth release in survivors (note the high positive

Table 2. Mean duration and growth reduction estimates for budworm outbreaks in New Mexico mixed conifer stands. T-statistic is from a two-sample t test, and probability levels are one sided. Interval A is the period in years between reduced growth periods, Interval B is the period between the initial years of successive reduced growth periods.

	Pre-1910		Post-1910			Prob.	1700-1983	
	Mean	S.Dev.	Mean	S.Dev.	t-Stat.	Level	Mean	S.Dev.
Duration (years)	15.2	6.4	11.1	3.9	1.981	0.029	14.0	6.0
Interval A (years)	19.9	9.1	19.4	12.5	0.115	>0.250	19.7	10.5
Interval B (years)	34.3	10.8	30.8	15.5	0.623	>0.250	33.8	13.0
Maximum Growth Loss (percent)	41.4	11.4	45.2	8.1	-0.975	0.164	42.5	10.5
Periodic Growth Loss (percent)	17.3	5.0	22.7	2.2	-3.848	<0.001	19.0	5.0

indices following this period in some study areas in Fig. 4), and establishment of a younger age class of trees (Swetnam 1986).

A number of limitations in the tree-ring data make interpretations of changes in budworm incidence through time very difficult. It must be recognized that the sampled trees were necessarily survivors. Thus, the most extreme impact of budworm defoliation - mortality, was only indirectly observed as growth releases in competing trees.

Also, ring-width reductions in the lower bole may underestimate growth reduction throughout the stem, and lag the actual defoliation of the crown by one or more years (Mott et al . 1957). Recent work by Alfaro et al (1985), however, has shown that volume reduction in Douglas-fir due to budworm defoliation is fairly uniform throughout the stem. A number of uncertainties indicate there is a need for a re-evaluation of the effects of environmental stress on growth throughout the stems of trees: (1) Previous observations from stem analysis of lag effects and differential growth reduction between the upper and lower bole of defoliated trees have often ignored the recovery period, which is typically more rapid in the upper crown than in the lower bole, thus, possibly offsetting greater growth reduction in the crown. (2) Absolute growth (eg., ring widths) has also usually been compared, rather than relative (eg., growth indices). Ring widths are typically wider in the juvenile wood of upper stems, and absolute decreases in ring widths due to stress may be greater than in the lower bole, but volume reduction may be not be as great, because of the lower overall proportion of volume in the upper stems. (3) Crossdating has generally not been utilized in stem analysis studies, thus the lag effects that have been reported may be due to undetected missing rings.

Application of stem analysis in combination with dendrochronology techniques offers a promising new approach for extracting environmental information from tree-rings (LeBlanc *et al.* this volume). Combined analysis of tree-ring reconstructions of budworm history and climatic changes may also reveal relationships that have eluded forest entomologists and ecologists for many years.

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