EXECUTIVE SUMMARY

Tree-ring Research in an Integrated Watershed Study of Acid Deposition Effects

Air Resources Board

Contract No. A3-098-32

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EXECUTIVE SUMMARY

A tree-ring study was conducted in conjunction with the integrated watershed study of acid deposition effects at Emerald Lake in Sequoia National Park. The objectives were 1) to develop two chronologies (series of indices of radial growth occurring within a stand of trees), 2) to determine if these chronologies contain any evidence of current or historical declines (extended periods of reduced growth), and 3) to determine if further analyses of these data are warranted.

Tree cores were collected from one stand each of western white pine (Pinus monticola) and lodgepole pine (P. contorta var. murrayana. These cores were mounted on wooden backing, sanded to clarify ring structure, and crossdated to assign exact calendar years to each tree ring. Each ring was then measured to the nearest 0.01 mm using an electronic measuring machine. Age trends were removed from each ring-width series by fitting empirically determined curves, and then the sets of transformed series were combined into chronologies for each species using a robust mean value function.

Chronology statistics revealed that all trees were not synchronized, but rather that some exhibited different growth patterns, which might have resulted from microsite variation, disturbance, or an age distribution that was too broad. This had little effect on the conclusions of this study because the mean value function effectively reduces the influence of outliers. Chronologies for western white pine and lodgepole pine were quite similar suggesting that radial growth in both species was limited by a common set of environmental factors.

Both chronologies exhibited historical periods of reduced growth within the last four centuries, but they were more pronounced in western white pine. Correspondence of a recent decline in both species with low snowpack suggested that the declines were climatically induced. There is no evidence of an obvious decline currently occurring; however, subtle air pollution effects may have been masked by the more limiting influence of climate.

This study was proposed to be exploratory in nature, with additional tree-ring research dependent upon successful development of chronologies. Hence, we recommend that additional analyses of these data be undertaken.

The first objective of these analyses should be to increase the signal-to-noise ratios of these chronologies. This may be as simple as limiting the age range of the trees used or it may require autoregressive standardization (Cook 1985) to minimize the unique variance (noise) in the tree-ring series. This is really only important if the chronologies are to be used in the statistical modeling to be described because the major features of the chronology plots are not likely to change.

The second objective should be to determine if subtle effects of air pollution can be detected that may have been obscured by climatic influences. This can be done by relating

variation in the chronologies to the climatic information contained in the snow survey data. This model would be calibrated during the prepollution period (say, 1925-1950), verified on independent data also from the prepollution period (say, 1951-1963), and then used to predict the chronology values during the putative pollution period. Differences between the observed and predicted chronology values may be attributable to air pollution. Regardless of whether or not these analyses detect any air pollution effects, they will be beneficial as demonstrations of a rational methodology for this purpose.

We also recommend that a chronology for foxtail pine (*P. balfouriana*) be developed and analyzed. Tree cores from this species have been collected and prepared, but the significant tasks of crossdating and measurement remain. The similarities between the chronologies already developed suggest that these high elevation pine species are similarly limited by climate. Hence, they may serve as better predictors of growth for each other than we could ever hope to get from snow survey data. Furthermore, if we could identify one species as being resistant to air pollution, then it could be used as a climatic control for the sensitive species in an analysis similar to that just described. An additional chronology from foxtail pine would increase our chances of having a resistant species. Moreover, the great longevity (median age, 478 years) would significantly increase our historical record of tree decline.

FINAL REPORT

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ABSTRACT

A tree-ring study was conducted in conjunction with the integrated watershed study of acid deposition effects at Emerald Lake. Tree cores were collected from western white pine and lodgepole pine. Age trends were removed from crossdated ring-width series, which were then combined into chronologies. Both chronologies revealed historical periods of reduced growth within the last four centuries, but no evidence of an obvious decline currently occurring. However, it is possible that there are subtle effects of air pollution present that are masked by the currently more limiting influence of climate. Recommendations for further study were made.

ACKNOWLEDGEMENTS

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SUMMARY AND CONCLUSIONS

A tree-ring study was conducted in conjunction with the integrated watershed study of acid deposition effects at Emerald Lake in Sequoia National Park. The objectives were 1) to develop two chronologies (series of indices of radial growth occurring within a stand of trees), 2) to determine if these chronologies contain any evidence of current or historical declines (extended periods of reduced growth), and 3) to determine if further analyses of these data are warranted.

Tree cores were collected from one stand each of western white pine (*Pinus monticola*) and lodgepole pine (*P. contorta* var. *murrayana*. These cores were mounted on wooden backing, sanded to clarify ring structure, and crossdated to assign exact calendar years to each tree ring. Each ring was then measured to the nearest 0.01 mm using an electronic measuring machine. Age trends were removed from each ring-width series by fitting empirically determined curves, and then the sets of transformed series were combined into chronologies for each species using a robust mean value function.

Chronology statistics revealed that all trees were not synchronized, but rather that some exhibited different growth patterns, which might have resulted from microsite variation, disturbance, or an age distribution that was too broad. This had little effect on the conclusions of this study because the mean value function effectively reduces the influence of outliers. Chronologies for western white pine and lodgepole pine were quite similar suggesting that radial growth in both species was limited by a common set of environmental factors.

Both chronologies exhibited historical periods of reduced growth within the last four centuries, but they were more pronounced in western white pine. Correspondence of a recent decline in both species with low snowpack suggested that the declines were climatically induced. There is no evidence of an obvious decline currently occurring. However, it is still possible that air pollution affected growth within the last decade or so, but that its effects were masked by the more limiting influence of climate.

RECOMMENDATIONS

This study was proposed to be exploratory in nature, with additional tree-ring research dependent upon successful development of chronologies. Hence, we recommend that additional analyses of these data be undertaken.

The first objective of these analyses should be to increase the signal-to-noise ratios of these chronologies. This may be as simple as limiting the age range of the trees used or it may require autoregressive standardization (Cook 1985) to minimize the unique variance (noise) in the tree-ring series. This is really only important if the chronologies are to be used in the statistical modeling to be described because the major features of the chronology plots are not likely to change.

The second objective should be to determine if subtle effects of air pollution can be detected that may have been masked by the more limiting influence of climate. Although no long-term climatic records exist for this area, we may be able to relate variation in the chronologies to variation in snow pack, which is known for a site within 3 km of Emerald Lake. This approach assumes that the climatic information reflected by the snow survey data also limits tree growth. The model would be calibrated during the prepollution period (say, 1925-1950), verified on independent data also from the prepollution period (say, 1951-1963), and then used to predict the chronology values during the putative pollution period. Differences between the observed and predicted chronology values may be attributable to air pollution. Regardless of whether or not these analyses detect any air pollution effects, they will be beneficial as demonstrations of a rational methodology for this purpose.

We also recommend that a chronology for foxtail pine (*P. balfouriana*) be developed and analyzed. Tree cores from this species have been collected and prepared, but the significant tasks of crossdating and measurement remain. The similarities between the chronologies already developed suggest that these high elevation pine species are similarly limited by climate. Hence, they may serve as better predictors of growth for each other than we could ever hope to get from snow survey data. Furthermore, if we could identify one species as being resistant to air pollution, then it could be used as a climatic control for the sensitive species in an analysis similar to that just described. An additional chronology from foxtail pine would increase our chances of having a resistant species. Moreover, the great longevity (median age, 478 years) would significantly increase our historical record of tree decline.

INTRODUCTION

The high Sierra Nevada are an area potentially susceptible to acid deposition effects. Although this area is known to receive significant acid deposition (Roth et al. 1985), we are not aware of any reports of direct effects on forests. Hence, this research was designed to detect potential forest impacts using tree-ring analysis in an integrated watershed study of acid deposition effects conducted at Emerald Lake in Sequoia National Park.

Dendrochronological studies are based upon the distinctive banding patterns resulting from seasonal variation in tree growth rates. These tree rings provide a long-term record of tree growth that can be related to a number of causal factors. Deviations from long-term growth trends can be identified and used to produce hypotheses of significant environmental impacts. For example, Johnson and Siccama (1983) found a widespread decrease in ring widths of red spruce that may be attributable to acid deposition. However, a pollution effect can not be inferred until all natural causes have been considered.

As a component of an integrated watershed study, tree-ring analysis can serve many other useful functions. Climate reconstruction has long been a important application of tree-ring analysis. This procedure uses a sequence of known climatic conditions to calibrate a climatic model of tree-ring variation, which then can be used to estimate past climatic variation. A similar approach can be used to estimate historic patterns of snowpack. This may be particularly valuable in a high elevation watershed study.

Our research was somewhat exploratory in nature because we did not know _a priori_ whether the trees available for sampling would be datable and therefore suitable for chronology development. Given this uncertainty, our proposed research was limited in scope to development of chronologies for two species, _P. monticola_ (western white pine) and _Pinus contorta_ var. murrayana (lodgepole pine), and assessments thereof.

Specific phases of the project included: (i) location and sampling of suitable stands in the Emerald Lake area of Sequoia National Park, (ii) preparation of tree cores including mounting and sanding to clarify ring structure, (iii) crossdating and dating verification, (iv) measurement and error analysis, (v) chronology development including modeling of growth trends, and (vi) assessment of chronologies and determination of their adequacy for further research.

METHODS

Fieldwork was conducted during August 1984. The selection of tree species and sampling sites was limited by the restriction that they be within or near the Emerald Lake watershed. Three species were present in sufficient numbers: western white pine, lodgepole pine, and foxtail pine (P. balfouriana). Of these only western white pine was actually within the Emerald Lake basin.

Tree cores were collected from each of these species using a 5mm Haglof increment borer with a teflon coated bit. All trees of suitable age were sampled except those showing signs of lightning damage or heartrot or those growing immediately adjacent to each other. The latter were excluded because they often show growth reduction from competitive interactions. At least two cores were collected from each tree at breast height (1.5m) to allow comparison of within and among tree variation in radial growth. Sampled trees were marked with metal tags allowing relocation if necessary. Cores were collected on opposite sides of the tree and perpendicular to the aspect of the site thus avoiding the asymmetric growth that typically occurs on the up- and down-slope sides of a tree. Two additional cores were collected from a subset of each stand for trace element analysis by Dr. P.W. Rundel at UCLA. All holes from tree coring were plugged with wooden dowels. Approximate locations of sample sites are shown in Appendix B.

Western white pine was collected above the lake on the NE side at approximately 2925m (9600'). The area sampled overlaps a NPS reference stand. The site had an average slope of about 50° and a generally SW aspect (ca. 220°). A total of 27 trees were sampled.

Lodgepole pine was collected outside the watershed, approximately 1 km north of Emerald Lake. A high percentage (ca. 40%) of this species showed evidence of lightning damage or heartrot. Trees showing such damage were avoided, resulting in a larger collection area. This stand was somewhat below Emerald Lake at approximately 2700m (8900'). The site had a 35° slope and a generally NW aspect (ca. 220°). Twenty lodgepole pine were sampled.

Foxtail pine was also collected outside the watershed on the ridge immediately east of Emerald Lake. The ridge has a generally northern aspect, slope of 25°, and elevation of approximately 3100m. A total of 20 foxtail pine were sampled.

The cores were air dried, mounted on a wooden backing, and sanded to clarify the ring structure. Inspection of the cores revealed increased variation in ring width of western white pine and lodgepole pine relative to foxtail pine. This variation should facilitate crossdating. Hence, we decided to concentrate on western white and lodgepole pines for this study. This is not to say that foxtail pine is unsuitable for dendrochronological study. The median age of our sample was 478 years, and this great longevity would be highly advantageous for many applications.

Tree cores from western white pine and lodgepole pine were then examined under a binocular microscope to identify crossdatable sequences of rings. Crossdating involves matching of 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 has been a major criticism of a number of air pollution studies (Thompson 1981). To ensure reliability and accuracy of the dates assigned, an independent verification of the dating was performed by senior personnel in our laboratory.

Crossdated ring widths were then measured to the nearest 0.01mm using an electronic microcaliper (Henson Full Range Measuring Machine). The measuring machine was interfaced with a microcomputer. Using software developed by Robinson and Evans (1980), the measurements were collated and stored directly on floppy disks. Our microcomputer was also interfaced with a mainframe computer on which the data were permanently stored for later processing. Measurement accuracy was verified by remeasuring a random sample of 25% of each tree core. Criteria developed by Fritts (1976) were used to determine if the measurement error was acceptable.

Additional quality control for both dating and measurement was performed using software (Holmes 1985), which identifies data that should be reexamined for possible error. This is accomplished by comparing measurements from short segments of each core with a master series that is essentially an average of all other cores in the sample. Each segment is checked to ensure that its correlation with the master series is positive and highly significant and that it is higher when matched as dated than when shifted forward or backward by up to 10 years. Suspect cores are then checked for dating or measurement errors.

Sequences of ring widths characteristically decrease in size in later years from effects of tree age and ring geometry. Hence, it would be invalid to combine measurements from different aged trees into a chronology without accounting for this age trend. Our chronologies were produced using a time series analysis approach to tree-ring standardization (Cook 1985a, Cook and Holmes 1985). This methodology is state-of-the-art in dendrochronlogy and should eventually replace the methods that have been in use for over two decades (Fritts 1976).

The first step in this methodology was to remove the age trend from each ring-width series. A double-detrending procedure was employed, which corrects for inadequacies found in most other procedures. Ring widths are typically large near the center of the bole and decrease rapidly with distance from the center to a more or less constant value about which they fluctuate until the latest year's growth. This behavior was modeled with a negative exponential curve, which was very effective during the rapid decline phase but which had no effect during later years when the curve is essentially a horizontal line. The fluctuations during later years may result from competition or disturbances within the stand. Because they are biological in nature, they must be removed from each tree-ring series before the final chronology can be used to study abiotic phenomena. Hence, a second detrending was performed using a cubic smoothing spline (Cook and Peters 1981). The flexibility of the spline was constrained to have a 50% frequency response (25% variance reduction) at a frequency of

1/N (where N is the series length, Cook 1985a). A frequency of 1/N corresponds to a wavelength with period equal to N. The spline will remove increasingly larger amounts of variance at frequencies lower than 1/N and smaller amounts at higher frequencies. Thus, the smoothing spline will result in a relatively constant mean throughout the length of the time series. In both detrending steps, the measured ring widths were divided by the corresponding value of the fitted curves. This results in indices with mean equal to 1.0 and stabilized variance throughout each index series.

The tree ring indices were then combined into chronologies using a biweight robust mean value function (Cook 1985a, Mosteller and Tukey 1977). This function was used because the arithmetic mean is especially sensitive to outliers, which can greatly affect estimates of location. Outliers frequently occur when one or a few trees are affected by some disturbance that alters its growth. An effort was made to remove such asynchronous variation under the assumption that useful climate or pollution signals will be synchronous effects over the entire stand. (If variation in sensitivity or exposure within the stand were suspected, then the sample should have been stratified.) The biweight robust mean value function reduces the influence of outliers by inversely weighting each variate by a function of the median absolute deviation, which is a robust measure of variance or spread.

The chronologies were characterized by calculating several statistics: mean sensitivity, first-order autocorrelation, standard deviation, and the signal-to-noise ratio. Mean sensitivity is a measure of the relative change between adjacent ring widths and reflects the proportion of high frequency variance (short period) in the tree-ring series. It was calculated as the average of the absolute values of twice the difference between adjacent indices divided by the sum of the two indices (Fritts 1976). Autocorrelation is an estimate of the of the dependence of successive values commonly present in tree-ring series. It is a measure of nonrandomness and reflects the proportion of low frequency (long period) variance in the tree-ring series for which the radial growth for a particular year is correlated to the condition or growth of a previous year (Fritts 1976). Standard deviation, which includes both high and low frequency components measured by mean sensitivity and autocorrelation, was calculated in the usual manner. The signal-to-noise ratio compares the variance in common to all index series (signal) to that which is unique to each series (noise). As formulated by Cook (1985a), autocorrelation is accounted for in estimates of both signal and noise components.

RESULTS

Crossdating was successful for 48 of the 54 cores collected from western white pine. This included 23 trees with replicate

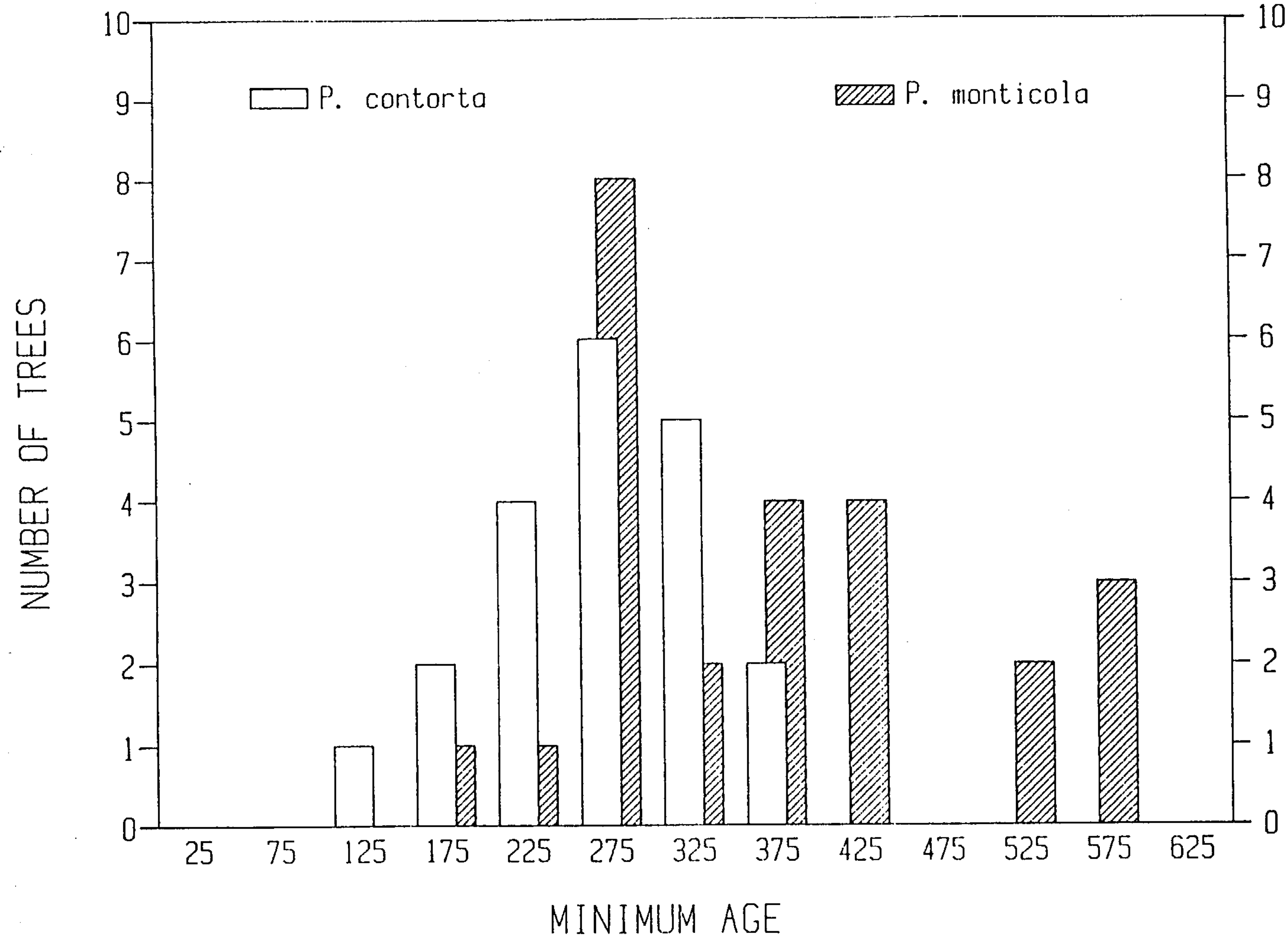

Fig. 1. Age distributions for trees sampled.

cores and 2 trees with one core each. For lodgepole pine, 37 cores were datable including 17 trees with replicates and three without replicates.

Minimum age distributions for the two samples are given in Fig. 1. These are minimum ages because we did not in all cases reach the center of the tree; hence, each of the trees could have been considerably older than indicated by our cores. The oldest western white pine we sampled was at least 596 years old, and five trees were older than 500 years. The median age was 364 years; however, the modal age class was that with limits of 250 and 300 years. Only two trees had a minimum age less than 250 years.

The minimum age distribution for lodgepole pine was much tighter than for western white pine, but the modal age class was the same (Fig. 1). The oldest lodgepole tree ring sampled was 368 years old, and the median age was 292 years. The youngest tree was 116 years old. Hence, for both lodgepole and western white pine, there was a three-fold difference in age between the oldest and youngest trees sampled.

Raw ring-width measurements for Pinus monticola and P. contorta will be made available in tabular form and on magnetic tape (nearly 27,000 measurements). A quality control analysis of these data was performed as described in the Methods (Holmes 1985). A number of trees of each species were flagged as having potential dating and/or measurement problems. Each of these cores were reexamined. A few were found with dating errors and corrected. However, most of the flagged cores were found to be correctly dated and measured. We concluded that the problems were the result of real differences in radial growth and left them unchanged. This resulted in some low correlations of individual cores with the master dating series (minimum 0.39), although the average correlations of western white pine and lodgepole pine with their master dating series were 0.55 and 0.62, respectively.

Raw ring-width series were then double-detrended as described in the Methods, and a comparison of these tree-ring index series was undertaken for the time period for which all series had values. The common period for western white pine was 1822-1984 (163 years was the length of the shortest core) and for lodgepole pine was 1870-1982 (113 years). Cross-correlations among the index series gave results similar to the quality control analysis previously described. That is, the radial growth patterns displayed in the index series were not consistent among all of the trees in the samples. The average correlation of individual series with the average series was 0.38 for western white pine and 0.53 for lodgepole pine. Certain types of analyses might warrant the exclusion of inconsistent trees; however, for this preliminary assessment they were retained.

Index series were combined into site chronologies for each species using the biweight robust mean value function described in the Methods and Cook (1985a). The chronologies obtained are shown graphically in Fig. 2 and in tabular form in Appendix A. The western white pine chronology extends from 1388-1984. However, the

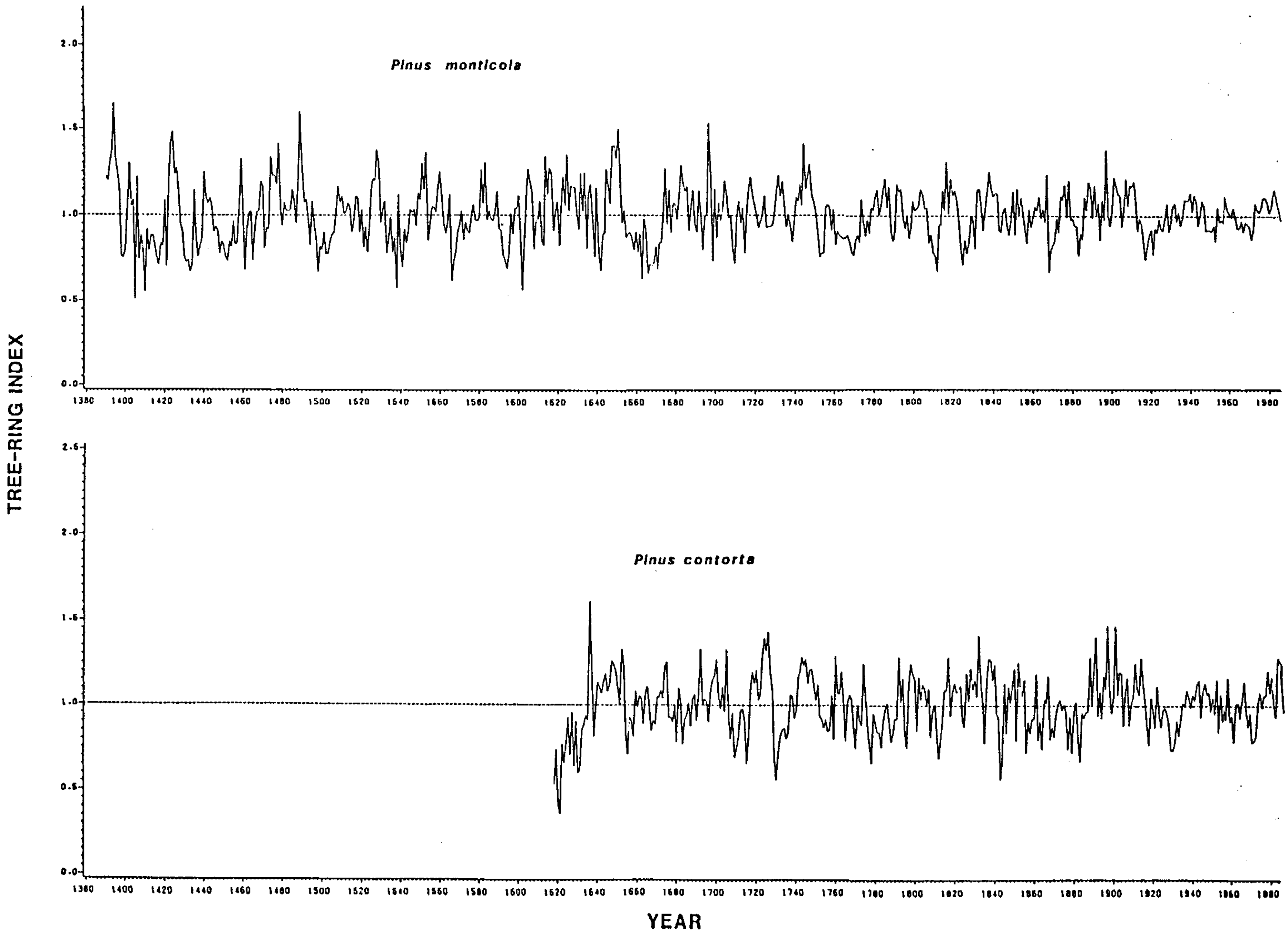

Fig. 2. Tree-ring chronologies.

sample sizes (given in Appendix A) for the first two centuries are so small that they may not reliably estimate the common signal in the tree ring series. A reasonable sample size of 10 was obtained in 1567. Similarly, the lodgepole chronology extends to 1616, but a sample size of 10 is not obtained until 1668 (Appendix A). Increasing sample size may be responsible for the apparently diminished variability of the chronologies in later years (Fig. 2).

Mean sensitivity of the western white pine chronology was 0.132, which indicates that a relatively low proportion of high frequency variance is present. The first-order autocorrelation of this chronology was 0.475. The value of the chronology for a given year is dependent upon the value of the previous year. However, this dependence is not as great as has been observed in other species (e.g., Fox et al. 1986). Similarly, the standard deviation of the chronology, 0.169, was relatively low suggesting there was relatively little total variation in this species. The signal-to-noise ratio was 3.239. The common signal in the tree-ring indices may have been greater than indicated by this statistic, but it was diminished by the inconsistency of the growth patterns among trees.

Chronology statistics for lodgepole pine reveal that this species had slightly more variance of each type than western white pine. Mean sensitivity was 0.149, autocorrelation was 0.552, and standard deviation was 0.195. In addition, the signal-to-noise ratio was about twice as large at 6.486. The latter value is still relatively low reflecting the extra noise introduced by the differences in growth pattern observed in some trees. However, the mean value function employed should have produced robust estimates of the chronology values because of the diminished weights given to outliers.

Chronology plots for both species illustrate historical variation in radial growth (Fig. 2). Over their common period (after 1650), they exhibit very similar patterns of radial growth. In particular, most years with reduced growth in one species are matched in the other species. Years in which this type of matching occur include 1655, 1663, 1687, 1709, 1715, 1739, 1752, 1770, 1795, 1808, 1812, 1824, 1835, 1843, 1851, 1856, 1868, 1883, 1894, 1899, 1905, 1916, 1921, 1929, 1944, 1954, and 1970. Correspondence between the species was good enough that most ring-width series of each species crossdated to the master dating series of the other species.

Both chronologies exhibit periods in which reduced growth was sustained for a decade or more. In western white pine the were 5 such periods of tree decline: 1650-1670, 1760-1774, 1822-1832, 1912-1927, and 1962-1972. In lodgepole pine, tree decline was evident during 1867-1887 and 1922-1935. Neither tree species shows any evidence that a tree decline is currently occurring. However, this examination would not detect a subtle effect of air pollution, which may have been masked by the influence of climate.

DISCUSSION

The objectives of this research project were 1) to develop tree-ring chronologies for two species in the Emerald Lake area, 2) to determine if there is any evidence of current or historical decline in these series, and 3) to determine if further analyses of these data are warranted to detect current or future declines that may be attributable to air pollution.

Chronologies for western white pine and lodgepole pine were successfully developed. Tree cores from foxtail pine were also collected, prepared, and ring-counted, but the other species were selected for initial study because they appeared to be the easiest with which to work. Foxtail pine may be useful; with more work, it may even be a better species for dendroecological studies because of its great longevity. Furthermore, although it appeared less variable in time, it may have a smaller among tree noise component masking that temporal variance.

Analyses of western white pine and lodgepole pine (including quality control, cross-correlation, and chronology statistics) suggested that growth patterns differed among some of the trees sampled. This was especially evident in the former species. Reexamination of the cores revealed that this was not from dating or measurement errors, but that they represented real differences in the growth patterns of some trees in each species. Three possible causes for these differences include microsite variation, historical disturbance, and age differences.

Variation in site conditions within a stand can always be a problem ,but these sites were very homogeneous in appearance. The slope, aspect, and elevation were very consistent. Moreover, the stands were open-canopied, so competition effects were not likely. However, microsite conditions can vary in ways not readily apparent such as soil type, soil moisture, or even snow accumulation. We have no data to eliminate any of these possibilities.

Historical disturbances can produce differences among trees in growth patterns, especially if they differentially affect individual trees. When sampling, we excluded obviously disturbed trees (e.g., lightning or heartrot); only normal appearing individuals growing on open sites were selected. Disturbances that might be more difficult to detect include avalanches and rock slides (from earthquakes, etc).

Large differences in the ages of trees sampled can introduce artificial differences among the index series. Detrending is designed to remove age trends, but, when the trees vary greatly in age, it can alter their variance structure. Recall that the stiffness of the smoothing spline fit to the data is determined by the length of the series. Hence, younger trees will have less low frequency variance because they will have more flexible curves fit to them. The trees we sampled varied 3-fold between the maximum and minimum ages. In future analyses, it will be necessary to investigate the effects of this age variation.

The term decline in forestry refers to a widespread decrease in health and vigor of forests, frequently leading to death of many individuals. If only a single tree species is involved, the term tree decline is appropriate. A forest decline involves more than one species. Decreased radial growth is the most frequently cited symptom of tree or forest decline. In fact, it is sometimes the only symptom. Possible causes for declines include a wide variety of predisposing, inducing, and/or contributing stress factors of which air pollution has been receiving a great deal of recent attention (Schutt and Cowling 1985).

Although neither western white pine nor lodgepole pine appear to be currently experiencing a decline (but see below), several have occurred in the last four centuries. Within the 20th century, a major decline occurred in both species that was centered around the 1920's. Snow survey data indicate that these were consistently low snowfall years. Therefore, this decline was probably climate related. A second decline occurred in 1962-1972 in western white pine and in 1966-1972 in lodgepole pine. Some years in this period had low snowfall, but a direct relationship to snowfall was not apparent from cursory examination. Most of the variation in these chronologies is probably related to climate, but careful analysis would be necessary to establish this. Because of the controlling influence of climate, it is impossible to say conclusively that air pollution is not affecting growth in these species.

Air pollution is widely believed to be responsible for or at least contributing to the observed declines in Europe and the eastern United States. The tree-ring studies leading to these conclusions are not all scientifically defensible. Many have not even used proper dating control, but beyond that radial growth is determined by many natural factors that must be accounted for before inferring a pollution effect. This can be a difficult task. In an attempt to lend credibility and acceptability to these studies, Cook (1985b) outlined a rational approach for applying dendroecology to pollution problems.

This approach is based upon an heuristic model of ring-width variation that includes effects of age trend, climate, endogenous and exogenous disturbances, pollution, and error. We will outline this approach as it might be applied to the data of this study to determine if air pollution was contributing to the behavior of the chronologies during the last decade.

We have previously discussed the age trend and how it can be removed from a ring-width series. Additionally, it would be advisable to stratify the sample with respect to age or limit the analysis to a subset of the age range for reasons discussed previously. Exogenous disturbances are those caused by natural environmental forces such as fire, disease, and insect infestation that have stand-wide impact. Such a disturbance could present a problem in differentiating a pollution effect because the latter is also assumed to be a stand-wide impact. However, their recent history has generally been documented, and, therefore, they are avoidable. That is, stands with known history of exogenous disturbances should not be considered for air pollution studies.

The above are not dramatically different from what has already been done in the present study. Cook's approach differs most in his innovative application of time series analysis to remove the effects of endogenous disturbances, which are those that uniquely affect a small subset of the stand. Multivariate and univariate autoregressive modeling are used to minimize the unique variance in each to the tree-ring index series and amplify the common signal attributable to climate and potential pollution effects. The biweight robust mean value function (see Methods) is also instrumental for this purpose. This procedure was developed to deal with the growth pulse often seen with release from competition in closed-canopy forests. Its efficacy for the present study is uncertain; stratification by age may be sufficient to enhance the common signal in these open-canopy trees. We are currently investigating the benefits of the procedure in our studies of western larch exposed to sulfur dioxide.

The final stage of Cook's approach is one which has been used very successfully in dendroclimatology (Fritts 1976). The transformed chronology is regressed upon a set of climate variables for the time period prior to the hypothesized pollution effect. The regression model obtained is then used to predict the tree-ring indices for the pollution period. Differences between the observed and predicted tree-ring indices may be attributable to a pollution effect.

Application of this final stage in the high Sierra Nevada is limited by the availability of climate data. Normally, long series of monthly temperature and precipitation data are used. However, snow survey data are available for the high Sierra Nevada with a site with one of the longest records (1925-present) within 3 km of Emerald Lake. Data included are monthly snow depth and water equivalent for January through April. The potential significance of these data for tree growth is supported by the previously described correspondence of a synchronous decline in both western white pine and lodgepole pine with low snowpack during the late 1920's and 1930's.

We would calibrate a snow (climate) model for radial growth using years from 1925-1950. This model would then be verified during the prepollution period of 1951-1963. Verification during a prepollution period allows us to assess the confidence we should have in our predictions for the pollution period. Finally, the snow model would be verified during the suspected pollution period of 1975-1984. Again, differences between the observed and predicted tree-ring indices may be attributable to pollution effects.

An alternate approach may be possible if the tree species present can be identified as sensitive and resistant species. If so, then the resistant species could be used as a predictor of ring-width variation in the sensitive species with the assumption that they have similar climatic responses and the analysis carried out as above. This may be some additional motivation for completing the chronology development for foxtail pine.

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APPENDIX A

Chronology listings. First 4 columns give the beginning year or decade of the row. The next ten fields with format (F4.3,I3) give the chronology values and the sample sizes, respectively, for the years of the indicated decade.

Western White Pine (*Pinus monticola*)

```
1388                                                                     1233  11439  1
13901229  11198  11282  11341  11606  11266  11152  11077  11420  21504  2
14001229  21130  31081  31045  31046  3 496  31321  3 849  3 812  3 806  3
1410 555  3 936  3 842  31014  3 910  3 856  3 769  3 685  3 807  3 863  3
1420 776  3 597  31223  31453  31467  31186  31023  31006  3 820  3 837  3
1430 653  3 670  3 705  3 641  3 746  31186  3 961  3 752  3 795  3 992  3
14401195  41082  41075  41066  41067  4 840  4 900  4 896  4 762  4 907  4
1450 871  4 738  4 780  4 915  4 806  4 996  4 998  5 723  5 997  51399  5
1460 923  5 598  5 870  51008  51028  5 733  5 901  51028  5 977  51171  5
14701082  5 862  5 926  5 816  51292  51267  51237  51196  51397  51030  5
1480 856  61121  61111  61046  61028  61152  61089  6 987  61276  61613  6
14901244  61064  6 969  61007  6 810  61064  6 907  6 851  6 603  6 854  6
1500 995  6 775  6 844  6 830  6 901  6 897  6 894  7 912  71181  71077  7
15101109  71016  7 966  71031  71077  7 924  7 965  71146  71098  7 903  7
15201076  7 814  7 941  7 776  7 977  71180  71181  71168  71434  71344  7
1530 986  71041  71078  7 782  7 867  7 988  7 786  7 863  7 590  71088  8
1540 887  8 724  8 939  8 850  8 925  81042  8 913  81079  8 984  81136  8
15501099  81395  81178  81350  8 947  8 942  91055  9 944  9 996  91155  9
15601270  91099  9 962  9 876  9 954  91007  9 715  9 775 10 854 10 920 10
1570 954 101053 11 891 12 913 12 913 12 919 121045 13 981 13 941 13 944 13
1580 964 131248 131057 131300 13 874 141003 14 893 14 987 141044 141141 14
1590 937 14 918 14 764 14 752 14 725 14 782 151004 15 891 151046 151047 15
16001132 15 876 16 575 16 857 161131 171192 181144 181069 18 760 18 980 18
1610 969 181122 18 835 18 821 181351 181128 181263 181238 18 888 181005 18
16201079 19 828 191067 191207 191041 191357 191025 191157 191173 191155 19
1630 946 19 884 191229 19 988 211205 21 802 211093 211160 21 928 21 726 21
16401142 21 780 21 669 21 886 22 934 231308 231197 241066 241402 241420 24
16501292 241472 241186 24 916 24 996 24 845 24 871 24 915 25 872 25 793 25
1660 893 25 767 25 885 25 636 25 979 25 926 25 651 25 694 25 704 25 713 25
1670 866 25 723 25 816 25 883 251044 251306 25 983 261130 26 903 271043 27
16801073 27 963 271114 271307 271167 271124 281175 28 920 291065 291167 29
1690 950 30 906 301120 301018 30 764 30 981 30 992 311515 311242 31 692 32
17001128 33 858 351087 35 979 351024 351202 351113 36 950 36 998 36 780 36
1710 714 361014 361101 36 966 361063 36 786 361011 361206 361228 361103 36
17201041 361001 36 939 39 938 391006 391127 40 942 40 923 40 936 40 948 40
1730 999 401127 401225 411101 411177 411043 41 922 411019 41 934 41 833 41
1740 958 411126 411079 411167 411037 421416 421149 421226 421295 421106 42
17501063 431016 43 900 43 752 43 779 43 786 431061 431051 431027 43 904 43
17601028 45 821 45 889 45 905 45 877 45 862 45 867 45 879 45 843 45 774 45
1770 759 45 872 45 891 45 863 451104 45 972 45 882 45 965 46 883 461066 46
17801032 461116 461144 46 981 461025 461124 461206 461030 461133 46 884 46
1790 817 46 917 461179 461139 461144 46 977 46 906 46 972 46 905 46 957 46
18001111 461040 461053 461070 461156 461143 461039 471040 47 844 47 882 47
1810 779 47 761 47 652 47 939 47 958 471164 471051 471328 47 998 471195 47
18201121 481131 481093 48 977 48 801 48 693 48 842 48 770 48 824 48 994 48
1830 973 48 793 481141 481179 481058 48 904 481032 481142 481261 481150 48
18401101 481134 481132 48 918 48 898 481025 481060 48 933 48 877 48 969 48
18501136 48 879 481129 481002 481090 481015 48 904 48 810 481025 48 946 48
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1860 978 481052 481024 481098 48 991 481022 48 958 481228 48 663 48 770 48
1870 828 48 846 48 976 48 896 481116 481085 481177 48 981 481193 48 971 48
1880 970 48 929 48 932 48 757 48 879 48 852 481106 481039 481195 481154 48
1890 980 481179 48 971 481070 48 839 481084 48 980 481397 48 975 48 913 48
19001007 481223 481193 481115 481116 48 930 481026 481207 481058 481183 48
19101186 481214 481092 48 909 48 974 48 954 48 849 48 718 48 839 48 901 48
1920 928 48 773 48 923 48 917 48 986 48 915 48 918 48 989 481064 48 878 48
1930 932 481049 481061 48 952 481028 48 942 48 982 481099 481078 481078 48
19401124 481027 481093 481108 48 951 481003 481085 481059 48 892 48 904 48
1950 914 48 910 48 927 48 837 481032 48 964 48 958 48 952 481107 481050 48
19601007 48 981 481025 48 980 48 903 48 900 48 960 48 897 48 963 48 949 48
1970 945 48 871 48 917 481062 481030 481032 481057 481099 481095 481074 48
19801020 481089 481108 481080 48 984 48
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Lodgepole Pine (<u>Pinus contorta</u>)

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1616                                             751  1 548  1 533  1 736  1
1620 393  1 260  1 638  1 570  1 658  1 836  1 638  3 867  3 596  3 738  3
1630 668  3 562  3 668  3 761  3 934  3 839  31607  31173  4 697  4 794  4
16401068  41170  41110  41254  41221  51172  51133  51329  51314  61335  6
16501083  61121  61446  61362  6 794  6 608  6 902  6 947  6 829  61074  6
1660 984  61034  71041  7 886  71046  71220  81094  8 871  9 885 10 885 10
16701029 101052 111082 111047 111228 111290 11 925 11 921 12 881 12 971 12
1680 772 121137 121103 12 821 12 913 12 934 12 996 14 873 141002 141111 14
1690 958 141078 151360 151068 151031 161026 16 909 161071 161171 161205 16
17001270 161102 16 988 161065 16 928 161278 161032 17 849 17 967 17 706 17
1710 717 17 825 17 940 17 995 17 934 17 680 18 704 181045 181187 181105 18
17201231 181058 181102 181353 181478 181417 181542 191304 191156 19 702 19
1730 536 20 654 20 857 20 855 20 857 20 774 21 811 211028 211023 21 918 22
1740 931 221153 221284 231302 231264 231312 231204 231260 231246 241160 24
17501077 261156 26 965 26 937 26 887 26 938 26 861 26 843 261052 26 798 26
17601283 261094 261069 261185 261007 26 760 26 959 261064 261046 26 886 26
1770 740 26 982 26 899 26 859 261246 261093 26 891 26 774 26 635 27 910 27
1780 893 27 829 27 825 27 737 27 848 27 976 271019 28 902 28 815 28 824 28
1790 923 30 920 301273 311066 311188 31 873 34 741 341094 341271 341211 34
18001181 34 871 341151 351048 351126 351122 351006 351097 35 822 35 947 35
18101009 35 808 35 672 35 784 35 940 351086 351083 351278 35 955 351059 35
18201140 351092 351102 351131 35 935 35 862 351188 351073 351245 351130 35
18301174 351089 351419 351164 351035 35 791 351135 351299 351302 351172 35
18401263 35 972 35 944 36 569 36 656 361130 36 847 361053 361008 361104 36
18501223 36 810 361224 361147 361050 361167 36 744 36 880 36 838 36 920 36
1860 932 361187 36 810 36 885 36 748 361035 361022 361186 36 821 38 867 38
1870 802 38 965 381015 381013 38 960 38 990 38 998 38 749 38 930 38 732 38
1880 969 381033 38 842 38 676 38 957 38 947 38 975 38 975 381292 381006 38
18901179 381412 38 989 381083 38 952 381187 381138 381496 381147 38 958 38
19001055 381492 381111 381223 381226 38 898 381075 381186 38 910 381002 38
19101072 381282 381111 381068 381305 381159 381014 38 871 38 741 381044 38
1920 986 38 868 381102 38 964 38 857 38 941 38 985 38 939 38 855 38 747 38
1930 719 38 788 38 907 38 819 38 915 381032 38 993 381084 381058 38 984 38
19401048 381060 381130 381168 38 932 381084 381147 381085 381084 38 968 38
19501049 38 956 381165 38 871 381091 38 921 38 976 38 902 381173 38 908 38
1960 938 38 792 38 980 381041 38 901 381037 381173 38 996 38 872 38 968 38
1970 786 38 787 38 804 381015 381090 381005 381051 381041 381210 381093 38
19801167 38 956 381230 381213 37 972 37
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APPENDIX B

Map showing approximate sampling locations for three tree species near Emerald Lake in Sequoia National Park.