CLIMATE: A FACTOR IN THE ORIGIN OF THE POLE BLIGHT DISEASE OF *PINUS MONTICOLA* DOUGL.[1]

Charles D. Leaphart and Albert R. Stage[2]
U. S. Department of Agriculture, Forest Service
Intermountain Forest and Range Experiment Station, Ogden, Utah

Abstract. Measurements of cores or disc samples representing slightly more than 76,000 annual rings from 336 western white pine trees were compiled to obtain a set of deviations from normal growth of healthy trees that would express the response of these trees to variation in the environment during the last 280 years. Their growth was demonstrated to be a function of temperature and available moisture for the period of climatic record from 1912 to 1958. Extrapolating the relation of growth to weather to the long tree ring record of western white pine, we find that the period 1916–40 represents the most adverse growth conditions with regard to intensity and duration in the last 280 years. This drought, superimposed on sites having severe moisture-stress characteristics, triggered the chain of events which ultimately resulted in pole blight. If the unfavorable conditions for growth during 1916–40 do not represent a shift to a new climatic mean and if western white pine is regenerated only on sites with low moisture-stress characteristics, the probability is high that pole blight will not reoccur for many centuries in stands regenerated from this date on.

Introduction

Climate, in its many ramifications, profoundly influences the growth of forest trees. Likewise, climate influences the inception and intensification of tree diseases through physiological responses of the trees and their pathogens. Unfortunately, for many forested areas few weather records cover much more than the past 50 years; for example, weather in the western white pine type has been recorded instrumentally only since 1911. However, the integrated effects of weather as recorded in the growth rings of trees permit us to extend by several hundred years our knowledge of the distribution in time of the environmental factors that influence ring width.

Long records of fluctuations in the growth rates of trees have been analyzed chiefly for archeological purposes by dendrochronologists (Glock 1955, Studhalter 1955, Schulman 1956). Shorter sequences of growth rates have provided insight into those aspects of climate to which trees respond (Fritts 1966, Zahner and Stage 1966). We applied both of these types of analyses to the growth history of western white pine (*Pinus monticola* Dougl.) to answer the following: Do the correlations of growth with climate and the history of white pine growth support the hypothesis that the pole blight disease of western white pine is the result of an adversely dry climatic epoch? And, if the disease is climatically induced, what does the historical record tell us of the probability that the disease will cause recurrent losses?

[1] Received September 1, 1969; accepted April 14, 1970.
[2] The authors are stationed at the Forestry Sciences Laboratory, Moscow, Idaho, maintained in cooperation with the University of Idaho.

Pole Blight—Its Host and Environment

Western white pine is one of the most desirable species for management on approximately 3½ million acres in northern Idaho, northeastern Washington, and western Montana (Fig. 1). Here it is a seral species in nine habitat types (Daubenmire and Daubenmire 1968) that are occupied by climax vegetation characterized by grand fir (*Abies grandis* (Dougl.) Lindl.), subalpine fir (*A. lasiocarpa* (Hook.) Nutt.), western redcedar (*Thuja plicata* Donn), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and mountain hemlock (*T. mertensiana* (Bong.) Sarg.) In the southern part of this area, western white pine forests occur rather extensively in somewhat broad river valleys and often to the ridgetops on all slopes. Further north to the Canadian border, the species is largely restricted to moist creek bottoms, lower benches and flats, and northerly slopes. Pole blight has occurred only to the north of the Clearwater drainage (Fig. 1).

Pole blight was first observed in 1929. It is restricted to sites with shallow soils or soils of low available moisture storage capacity in the upper 3-ft mantle unless these conditions are mitigated by some subsurface source of moisture (Leaphart 1958). Root deterioration and rootlet mortality are higher in healthy stands on these sites than on sites where storage capacities exceed 5 inches (12.7 cm) in the 3-ft (0.91-m) mantle. Furthermore, as the trees on the droughty sites develop external symptoms of pole blight, the root decline becomes much more prevalent. In severely diseased trees much of the functional root system is almost devoid of absorbing rootlets. Rootlet mortality is higher in dry than in moist summers.

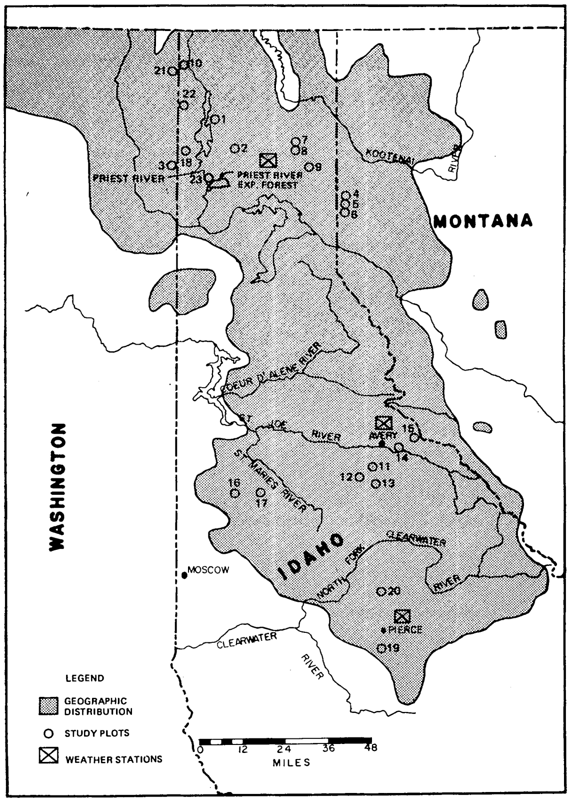

FIG. 1. Location of study plots and the geographic distribution of the western white pine type.

Under stressed conditions western white pine appears unable to keep pace in regenerating rootlets to replace those lost for any cause from its absorbing system. Crown decline is probably a secondary reaction following decline of the root system. Concurrent research on the disease in British Columbia has supported these conclusions (Wellington 1954, Molnar and McMinn 1958, McMinn and Molnar 1959, McMinn 1965). For further detail supporting these conclusions, the reader is referred to the following: Pole Blight Committee 1952, McMinn 1956, Foster 1957, Leaphart 1957, Leaphart and Copeland 1957, Graham 1958*a,* 1958*b,* and Leaphart and Wicker 1966.

Aside from the impact of pole blight (Graham 1958*b*), current management of western white pine has also been severely curtailed by an introduced rust disease caused by *Cronartium ribicola* J. C. Fisch. ex Rabenh. (Ketcham, Wellner, and Evans 1968). By itself, this resulting shift in emphasis to management of other species, or eventually of species mixtures including western white pine, would undoubtedly lessen the future impact of pole blight.

The climate of the nine habitat types in which western white pine occurs is characterized by short summer seasons with scant precipitation, low humidity, and a high proportion of clear, warm days and by winters with heavy snowfall and fairly low temperatures. The existing weather records describe only the recent climate—the oldest records started in 1911 at the Priest River Experimental Forest. To extend our knowledge of climate to past epochs through analysis of growth rings, we can only focus on those factors of the environment to which tree growth rates are sensitive. Such a study would most likely miss the critical factors for a specific pathogen. However, growth-ring analysis does provide insight into past conditions of moisture stress (Zahner and Stage 1966). Hence, it should also provide insight into the same aspects of the tree's physiology affected by the site characteristics and root decline already associated with pole blight.

If we can assume that the climatic variations experienced during the last two centuries can be represented by the fluctuations of a random variable having a constant mean and variance, then the probability with which pole blight will occur in a particular stand should be the product of the conditional probability for the site times the probability that at least as severe a climatic epoch will be experienced during the critical period in the life of the stand. Leaphart (1958) has estimated the relative frequency with which pole blight might occur in pole stands with a component of this species. The probability increased on soils of low moisture-storage capacity and low recharge potential. However, the survey from which these estimates were obtained sampled only one point in time. Corresponding probabilities of occurrence should be much lower following climatic periods when critical moisture stress would prevail only on soils of exceptionally low moisture-storage capacity. Our limited knowledge of the conditional probability distribution with respect to site conditions precludes a complete management analysis. However, study of the time series of variations in ring widths should provide the approximate probability distribution of climatic fluctuations to answer the questions we have posed.

COLLECTION OF DATA

Western white pine was selected for this analysis for several reasons. We were primarily interested in the fluctuations of those growth conditions that affect this species even though it is not ideal for dendroclimatological analysis per se. Furthermore, a comparison of the growth patterns of healthy trees and diseased trees of the same age might provide insight supplemental to Marshall's (1927) into conditions antecedent to the development of pole blight. Even if growth-climate correlations were not strong, mensurational treatment might show differences between the growth pattern during the first 50 years of growth in several categories: old stands, young healthy stands, and young stands currently affected by the disease.

One plot was established in each of 23 stands (Fig. 1). Most plots were in the vicinity of the Priest River Experimental Forest on the Kaniksu National Forest and the Avery Ranger Station on the St. Joe National Forest because the longest weather records in the western white pine type were available at these two locations. In addition, two plots in stands between 50 and 100 years old were selected near Pierce, Idaho, on the Clearwater National Forest.

The 23 plots were selected from stands grouped into four broad age classes: 50–100, 100–150, 150–200, and 250–400 years. Except for five plots in the older age groups, all stands were uniform in age; that is, the age spread in a plot was less than 20 years (Table 1). Although the age spans of plots 2, 6, 10, 13, and 21 were greater than 20 years, these stands had an even-aged appearance. The oldest stand, in which only two trees (379 and 384 years) were sampled, was located in an uneven-sized stand that had a history of at least two burns, the last of which occurred about 1890.

Plots were selected to represent stands of average density. Nearly all were located on soils with good internal drainage and on moderate to steep slopes. Severe exposures were avoided, except for one plot in the 250- to 400-year age class. Most of the more accessible and suitable stands of that age class had been harvested or partially cut in past years.

Of the 336 western white pine trees sampled all were dominant with respect to their immediate neighbors. Except for 52 trees in four plots in the 50- to 100-year age class, all were healthy and of good vigor. The 52 trees were diseased with pole blight and were used in analyses separate from the climate-growth-correlation analyses.

Two cores, approximately 4.5 mm in diameter, were taken to the pith with an increment borer at 4.5 ft (1.37 m) above mean ground level. Cores were taken on the opposite sides of nonleaning trees; on leaning trees they were taken at right angles to each other from the two quadrants opposite the zone of greatest compression. Abnormal depressions or swellings were avoided when securing core samples. In four of the older plots, sample trees were felled and a section at 4.5 ft (1.37 m) was removed. Two radial strips from the bark to the pith were cut at right angles from this section; each represented the average radius insofar as possible.

Cores were air-dried and smoothed to facilitate accurate readings of each annual ring. A sliding micrometer stage device under ×45 magnification was used to measure width to the nearest one-hundredth of a millimeter. Slightly more than 76,000 annual rings were recorded, nearly all of which were used in one or more analyses.

The two cores or strips from each tree were cross-dated to assure correct annual measurements from the year 1958 to the age of the tree at the pith. Trees within each plot were then cross-dated so that for any year within the age represented by the plot an accurate average annual growth for each tree in a plot would be obtained.

Analysis of Core and Weather Measurements

Normal growth vs. age curves

Our objective for the compilation of the annual ring data was to obtain a set of deviations from normal growth of healthy trees that would express the response of the trees to the environment. The form of growth expression had to be such that the deviations from it would show relatively great variation between years and low variation among trees within years. In addition, the deviation had to have constant variance with respect to tree size and age.

Duff and Nolan (1953) found that data from widths of annual rings taken in vertical sequence (a constant number of rings from pith) were superior to those from widths taken in horizontal sequence for demonstrating environmental effects on growth. However, the physical job of sampling the vertical sequence precluded its use on large trees.

Basal area increment has long been recognized as a measure of growth that is fairly constant over a considerable period in the life of a tree growing under uniform conditions. However, basal area increment varies widely between trees in the same stand. The larger trees with better crowns and root systems grow consistently faster than do their less favorably situated neighbors. Relative basal area growth rate (basal area increment divided by basal area) is less sensitive to this source of variation.

Both basal area increment and relative basal area increment change with increasing tree age. To remove this trend with age all the data from healthy plots were averaged by age. The two age sequences of average growth rates thus obtained will be referred to as the normal growth trend for the logarithm of relative basal area increment ($\ln R$) and basal area increment (BAI), respectively.

The distribution of plots in several age classes was such that certain dates tend to cluster about

TABLE 1. Distribution of plots by age class

50–100 years			100–170 years			170–250 years			250+ years		
Plot number	Number of trees	Age range	Plot number	Number of trees	Age range	Plot number	Number of trees	Age range	Plot number	Number of trees	Age range
19	15	50–58	14	10	114–128	02	5	152–167	06	14	264–295
16	27[a]	57–64	02	8	116–134	01	10	179–194	13	10	254–296
08	15	58–64	09	15	118–125	10	15	183–211	12	10	269–278
07	34[b]	58–64	11	10	124–141				21	10	270–303
05	30[c]	58–68							22	2	380–384
20	15	59–64									
17	12	60–63									
03	11	60–67									
18	21[d]	60–81									
04	15	61–67									
15	12	74–83									
23	10	83–92									
Total	217			43			30			46	

[a]Includes 12 diseased trees.
[b]Includes 14 diseased trees.
[c]Includes 15 diseased trees.
[d]Includes 11 diseased trees.

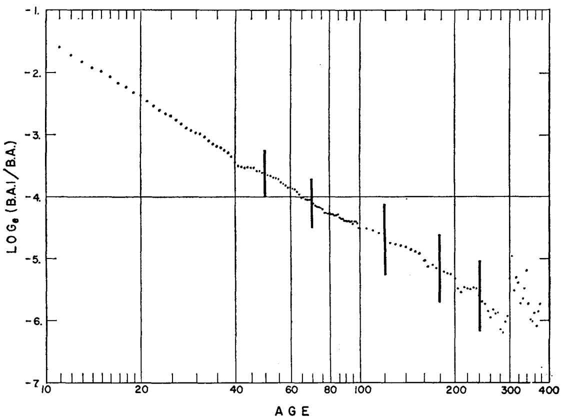

FIG. 2. Normal trend of adjusted ln R with tree age. Vertical bars show standard deviation.

certain ages. If these particular dates are characterized by abnormal growth rates, the normal growth trends would be warped at the corresponding ages. To overcome this possibility, a second set of adjusted normal growth trends was prepared. The trees were divided into 14 age classes, with division points as near as possible to discontinuities in the age-class distribution. For each of these age classes, a scaling factor was calculated in such a manner that the product of the scaling factor times the average growth rate would be equal for all age classes (as of 1958) for the years corresponding to 36–50 years of age. The adjusted average growth rate for each year of age was then computed as the mean over all trees of the growth rate times the scaling factor appropriate to each tree (Fig. 2). This adjustment process reduced the large departure from linearity in the data at an age of about 70 years. Vertical bars in Fig. 2 indicate average values of the standard deviations about the means for several portions of the curve.

Deviations from normal growth

Differences between the measured annual increments and the corresponding normal growth curve were computed for each tree according to the age of the trees when the increment was formed. These deviations were averaged within years for trees in all healthy plots. In this analysis, 283 trees with a total of 34,728 annual rings were represented. Comparison of these deviations for two expressions of growth showed that the ratio of variance between years to variance within years was 123.0:1 for ln R and 1.72:1 for BAI. The advantage of the former measure for studying growth response is obvious. Hereafter, all growth analyses used deviations of the logarithm of relative basal area increment.

A curve of the form:

$$\ln R = a + b \ln (age) + c\, [\ln (age)]^2$$

was fitted to the sequence of averages for ages greater than 10 years. Each average was weighted in the least-squares solution by the number of rings in the average; hence, the weighting was inversely proportional to the variance. Although the data were predominantly linear, the coefficient for the square of the logarithm of age was significant at the 1/10% level.

The deviations from this smoothed normal growth curve of individual annual rings from healthy trees greater than 10 years of age were collated by age and their averages calculated. The history of these average deviations for all healthy trees is shown in Fig. 3A for the period from 1680 to 1958. Slow growth is indicated in this historical sequence by negative deviations. Al-

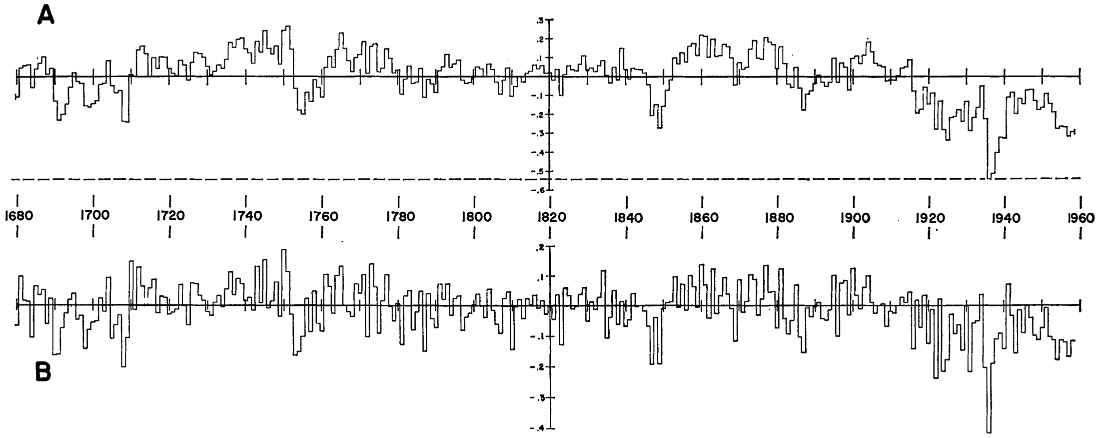

FIG. 3. (A) Average deviations from the adjusted normal relative growth trend sorted by date. Periods above the solid line correspond to periods of better than average growth. (B) Sequence of deviations after removing effect of serial correlation. Vertical scale has been expanded to achieve a standard deviation equal to the A series.

though records of the oldest trees in the study started in 1574, at least 10 trees older than 10 years of age at breast height were deemed necessary to obtain a stable average; hence, 1680 is the earliest date in this sequence.

The sequence of negative departures, beginning about 1916 and continuing to the end of the record, clearly represents the most unfavorable growth for western white pine in the 280-year sequence. The decline beginning in 1905 also is evident in Marshall's (1927) data. Conversely, the periods from 1853 to 1882 and 1900 to 1908—when many of our blighted stands germinated—were characterized by unusually consistent, rapid growth rates.

The serial correlation coefficient of this sequence is +0.81. With a lag of 15 years, the serial correlation coefficient of +0.3 is still fairly high.

Climatic connections

Regional weather summaries.—Weather records from the three stations used in this study in the western white pine type indicate similarity in deviations from mean annual precipitation for the water year (October 1 through September 30) (Fig. 4). Average daily mean and maximum temperature curves for the months of April through August also indicate a generally uniform climatic pattern within the timber type. Nonpole blight areas (Pierce station) annually receive much more precipitation than do most pole blight areas typified by Priest River and Avery. From 1916 to 1940, a period of critical stress for growth (Fig. 3A), annual precipitation at Priest River was below the 46-year mean of the three stations (Fig. 4) in all but three of the 24 years, whereas at

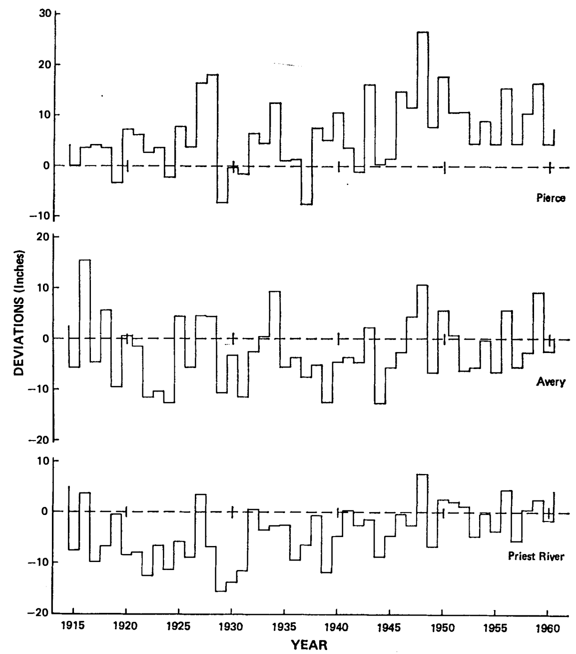

FIG. 4. Deviations from mean annual precipitation for three weather stations. Year extends from October 1 to September 30. Zero ordinate of each panel corresponds to the grand mean of the three stations (34.15 inches/year (86.78 cm/year)).

Pierce it dropped below the mean in only six of them; three were consecutive, 1929–31.

Precipitation was higher during the water year and also higher during the growing season (April through September) at the Pierce station. Pierce averages about 2.5 and 3.4 inches (6.35 and 8.64 cm) higher than Avery and Priest River, respectively, during the growing period. More favorable conditions for tree growth outside the pole

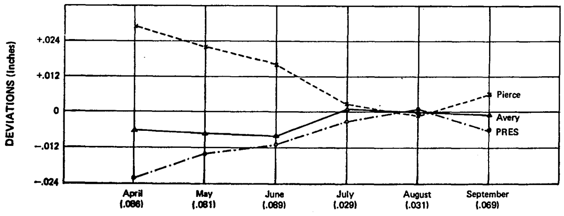

FIG. 5. Deviations from monthly mean daily precipitation for the years 1922–60 at the three weather stations (monthly means in parentheses). The higher level of annual precipitation at Pierce extends well into the growing season.

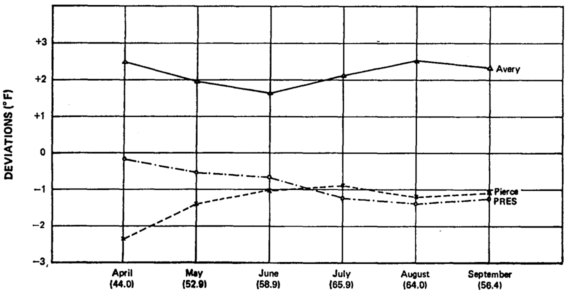

FIG. 6. Deviation from monthly mean daily temperature for the years 1922–60 at the three weather stations (monthly means in parentheses). Priest River Experiment Station is warmer in the spring than Pierce; temperatures are higher throughout at Avery.

blight areas are also shown by the deviations from the monthly means of the three stations from 1922 through 1960 for average daily precipitation and mean temperatures (Fig. 5 and 6). The mean daily temperatures are significantly lower and daily precipitation higher through June for the Pierce station than for the other two stations. The stations differ little in July and August, but by September Pierce again exhibits a more moist environment. The high temperature regimes at Avery predominate throughout the season.

Correlation of growth with weather.—A correlation between fluctuations in tree growth rates and changes in weather has been almost axiomatic in ecology and forestry. However, to define weather and growth rate so as to demonstrate statistically that such a correlation exists has not always been easy. Hence, a careful analysis of the relation of ring width of western white pine to climatic factors was a necessary inferential base to attribute the history of growth fluctuation to climatic variation. Zahner and Stage (1966) describe in detail the conclusions based upon the analysis of the data used in this study. However, a brief summary is appropriate here to support the hypothesis that climate is a factor in the origin of the pole blight disease.

The weather records at the Priest River Experimental Forest were used for this analysis because they are the longest available for the western white pine type. Data from six of the plots closest to the Priest River Experimental Forest were compiled for the years 1912–58. The climatic factors considered on a daily basis were temperature, precipitation, and moisture stress.

Daily values of mean temperature and precipitation, as measured at the Priest River Experimental Forest, were approximated by fifth degree orthogonal polynomials for the period April 1 to October 24. In addition, an estimate of evapotranspiration was obtained by means of a day-by-day water-balance program that used soil-moisture storage and depletion curves specific to each plot. The difference between Thornthwaite's potential evapotranspiration and the estimated evapotranspiration, which we have called moisture stress (Zahner and Stage 1966), was included in the analysis in terms of the coefficients of the orthogonal polynomials.

The dependent variable in this regression analysis was the average of the difference between the logarithm of relative basal area increment (annual basal area increment/basal area) for the trees in one plot and the corresponding trend with age. From the six plots with 46 years of records, 276 observations were obtained upon which to base the regression.

Climatic variables for both current and preceding seasons and the dependent variable for the preceding season were included as independent variables, along with linear and quadratic time-trend variables that were unique to each plot. In all, there were 49 variables in the regression. For this mixed autoregressive-regressive system, the usual least-squares solution has been shown to be the best unbiased linear estimating procedure (Durbin 1960).

The complete model accounted for 78% of the variance in the deviations from normal basal area growth. Moisture stress, temperature, and precipitation together accounted for 56% of the variance remaining after the effect of the lagged dependent variable was removed. Moisture stress, which depends on the moisture-storage capacity of the soil and the seasonal patterns of precipitation and evapotranspiration, accounted for 28% of the variance remaining after direct temperature and precipitation effects were removed.

The variation accounted for is sufficient to support the hypothesis that the sequence of deviations from normal relative basal area growth substantially reflects the sequence of climatic factors affecting western white pine growth. In particular, moisture stress is one of the more important aspects of climate to which western white pine responds. However, no one aspect of climate taken alone is sufficient to explain variations in tree growth. Consideration of day-by-day variations in climatic factors is also required.

An additional important aspect of this regression analysis was the estimate of the autoregression coefficient. The coefficient represents the serial correlation with a lag of 1 year between successive deviations from normal growth. Because it is estimated in a multiple regression including the preceding year's weather, it does not include the effect of persistence in weather that may occur from year to year. Thus, the value for the autoregression coefficient of +0.602 estimated in this regression is less than the serial correlation of the growth deviations themselves (+0.70 for the period 1911–58 or +0.81 for the longer period starting in 1680), but it illustrates the significant effect of previous year's growth on the current year's growth.

Comparison of growth patterns within age and health classes.—The relative growth of the various-aged trees in different time periods further illustrates the adverse effect of the last 50 years' climate on tree growth. All age classes shown in Table 2 grew more slowly during the last 50-year period (1909–58) than in the preceding 50-year period (1855–1904).

TABLE 2. Differences between average decadal relative growth 1909–58 and the 50-year average of the same trees for the period 1855–1904

Tree age in 1958	1909–18	1919–28	1929–38	1939–48	1949–58	Average difference 1909–58
200+	0.121	–0.081	–0.079	–0.069	–0.136	–0.049
150–199	– .080	– .287	– .338	– .185	– .215	– .221
100–149	.057	– .022	– .037	.037	– .052	– .003

Early growth patterns of trees in several age classes provide insight into the conditions these trees experienced prior to and during the time they would have been susceptible to pole blight. Time periods were selected to represent the 50 years starting when all trees in the age class were at least 10 years old. Average deviations from normal growth for each age were calculated for 5 succeeding decades (Table 3). It is clear that the 1909–58 period (represented by "all healthy" trees in the 50- to 99-year-old class) was less favorable for growth than the first 50-year period in the lives of trees represented in any of the three other age classes. The mean relative growth of the first 50 years has decreased in succession for each of the three age classes originating since 1714 (last column, Table 3).

Within the 50- to 99-year-old class, average growth of trees for the 5 decades from stands outside pole blight areas, i.e., stands within the Clearwater drainage or in areas physiographically or geologically different and separated from the diseased and their adjacent healthy stands, differed significantly from the above age-class trend and from the average for other healthy trees in the class (Table 3). However, even these trees show a consistently declining trend through the 5 decades. Thus, even though the climate of these stands represented by Pierce is more favorable for tree growth than the climate of diseased and adjacent healthy stands represented by the other stations (Fig. 4, 5, and 6), some adverse environmental influence is indicated since the decreasing growth pattern is contrary to normal growth expectations.

The marked negative departure from normal for 50- to 99-year-old healthy trees adjacent to and within pole blight areas is particularly noticeable (Table 3). Although the diseased trees had a pattern similar to their healthy counterparts for their first 3 decades, they apparently never recovered sufficiently from the most critical decade (1929–38) to maintain comparable growth. Once they became diseased, their growth drastically dropped off as indicated by the fifth decade (1949–58).

STOCHASTIC INTERPRETATIONS

We have answered the first of our two introductory questions. Specifically, we have shown that the pole blight disease apparently is a consequence of adverse climate interacting with site factors at a critical stage in the development of the tree or stand. The manager's interest in our second question concerning the probability of pole blight recurrence can be considered from two aspects: (1) Is there evidence for a cyclic occurrence of such adverse climate? and (2) What is the probability that a year as unfavorable to growth as 1936 occurs during the critical pole stage of a stand's development?

Answers to these questions were sought through spectral analysis of the 283 deviations shown in Fig. 3A. The spectrum shown in Fig. 7 can be considered as an analysis of variance testing for periodicity in the time series of deviations. The total area covered by all bars represents the total variance of the deviations. Thus, the area of each bar represents the portion of the total variance associated with the periodicity over which each is plotted. Peaks in this diagram would indicate a tendency for sequences of adverse (and likewise, intervening favorable) conditions to appear periodically with an interval indicated by the abscissa.

TABLE 3. Comparison of early growth patterns of four age classes of healthy and diseased trees growing in differing proximity to pole-blighted (PB) stands

Time period	Age class in 1958	Disease proximity class[a]	No. trees	Decades in time period[b]					Average deviation for 5 decades
				1	2	3	4	5	
				(Average deviation)					
1714–1763............	200+	Adjacent PB stands	44	0.183	0.192	0.278	0.284	0.071	0.201
1790–1839............	150–199	Adjacent PB stands	25	–.124	–.071	–.070	–.032	–.071	–.074
1855–1904............	100–149	Adjacent PB stands	35	–.036	–.156	–.177	–.236	–.139	–.149
1909–1958............	50–99	Outside PB area	42	.137[c]	.117	.087	.021	–.097	.053[c]
		Adjacent PB stands	73	–.064[c]	–.248	–.408	–.189	–.265	–.235[c]
		In PB stands	50	–.096	–.271	–.485	–.262	–.256	–.274
		All healthy	165	–.033[c]	–.162	–.305	–.157	–.219	–.175[c]
		Diseased trees	52	–.089	–.311	–.471	–.323	–.597	–.358

[a]All trees healthy except the 52 comprising the last line.
[b]First group beginning with all trees in the age class at least 10 years old.
[c]Adjusted because tree number varied from start to end of decade.

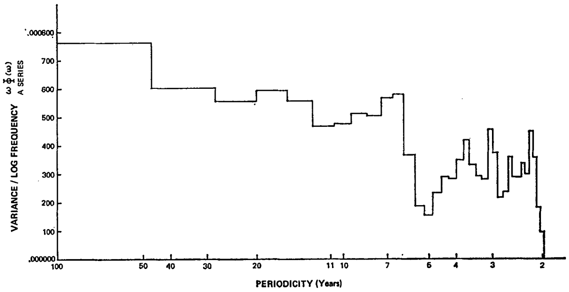

FIG. 7. Power spectrum of the series of deviations drawn in Fig. 3A. Vertical scale is the product of power times frequency. Horizontal scale is logarithm of frequency. Hence, areas under the spectrum are proportional to variance.

Several studies of tree rings have been analyzed in this way, looking for evidence of a periodicity associated with the 11-year cycle in sunspots (e.g., Bryson and Dutton 1961, Matalas 1962). No peak occurs at 11 years in the spectrum of these western white pine trees to indicate a response to the sunspot cycle. Rather, the variance seems to increase fairly steadily with increasing period length. The trend of variance is approximately proportional to the one-fourth power of the periodicity. For comparison, Bryson and Dutton (1961) report that somewhat greater proportion of the variance of their sequoia series is associated with shorter periodicities.

To answer the question concerning the probability distribution of climatic fluctuations from year to year, the data were transformed so that the model and results of Gringorten (1966) could be used. First, the serial correlation coefficient that is attributable to stored foods, enhanced foliage development, and other physiological bases was removed from the sequence of deviations. Accordingly, a new series of deviations (Fig. 3B) was computed from the original series (Fig. 3A) by using the serial correlation coefficient in the formula:

$$b_i = a_i - 0.602\, a_{i-1}\,.$$

The vertical scale of the B series has been expanded so that both the A series and the B series have the same apparent standard deviation.

The next step of the analysis transformed the B series into a series of normally distributed deviations having zero mean and unit variance. This step was accomplished by plotting the ordered deviations of the B series against their cumulative probability on normal probability paper (Fig. 8). Then, a straight line was drawn on this graph to represent the desired normal distribution. For each element of the B series, the normal deviate having the same ordinate was read off the upper scale of Fig. 8 as indicated by the arrows for one example. The unbiased estimate of the serial correlation (for a lag of 1 year) of the normalized series was 0.19. The probability distribution of 60-year minima from a normal distribution characterized by serial correlation of 0.19 was derived from Gringorten's Fig. 2. This distribution, transformed back to growth deviates, is drawn on an extreme-value probability scale in Fig. 9.

This probability distribution indicates that a deviation of the B series as low as or lower than that of 1936 occurs at least once in 60 years with an estimated probability of less than 0.01. The corresponding probability for the 1922 low is 0.10; and for the 1931 low, 0.14.

If pole blight could be triggered on a particular site by a climatically extreme year, such as 1922, during a critical stage of 60 years in the life of a stand, then the probability of 0.10 indicates that about one-tenth of the stands regenerated in the course of managing a forest with an even distribution of age classes would be affected with this disease. For a forest managed on 120-year rotation such an event would affect half (60/120) the forest characterized by the particular site quality.

On a better site, perhaps a deviation as great as that experienced in 1936 would be required, and

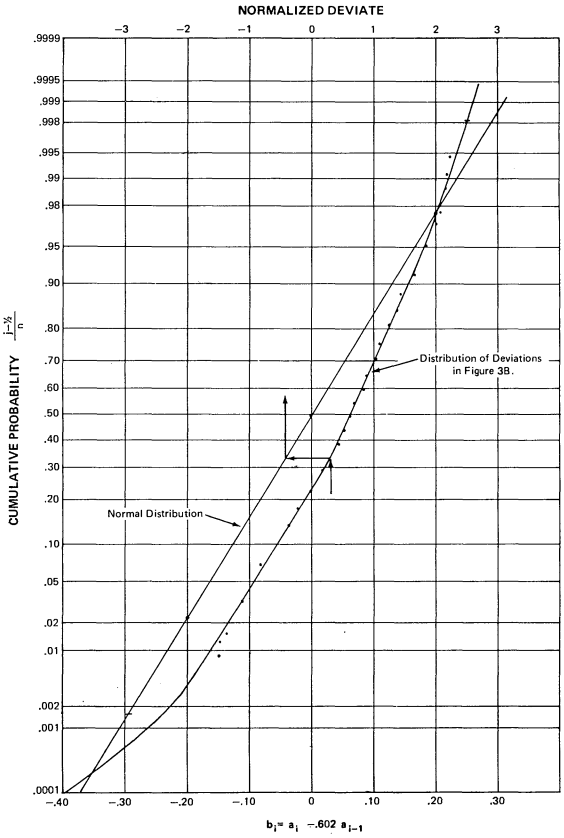

FIG. 8. Diagram used to transform the series in Fig. 3B to normality.

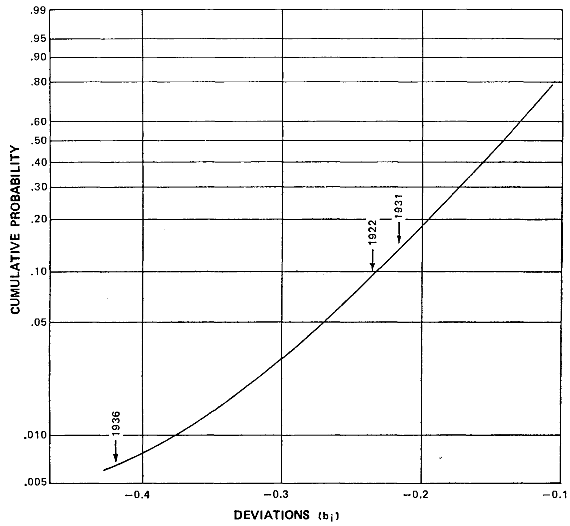

FIG. 9. Probability of a minimum deviation (as drawn in Fig. 3B) occurring within a 60-year interval. The probability is plotted on an extreme-value distribution scale.

then less than 1% of the stands regenerated might be afflicted. However, if all age classes up to 120 were equally represented on the site, those in the hypothesized critical 60-year age span would be affected when the event occurs. Thus, half the forest area in that site class would be damaged.

Obviously, a single adverse year does not trigger pole blight. More likely, a series of adverse years occurring in close proximity in time is required. Therefore, the probability of occurrence of the disease is greatly reduced. For example, if 6 consecutive years at least as bad as 1935 to 1940 or 1952–1957 ($b_i \ldots b_{i+5} \leqq -0.5$) define the critical event, then the probability of this event occurring in a 24-year period is reduced to less than 0.025, or about one in 40.

The relatively large proportion of variance associated with components of the long period displayed in the spectral analysis may indicate that extreme deviations are likely to be clustered in time to a somewhat greater degree than would characterize the model used by Gringorten. The period 1916–40 exemplifies such a cluster in which only 4 of the 25 years reached the overall average level of growth (Fig. 3B). There is a chance that similar clusters will occur in the future with pole blight as a consequence, but our records are inadequate to establish estimates of their frequency. Thus, the above probability statements should be considered as first approximations to be revised as current weather becomes climate.

DISCUSSION

Western white pine regenerates readily on most sites (within its range) denuded by fire, man, or other natural catastrophes. Consequently, under circumstances favorable for germination and growth in years past (1853–82, Fig. 3A), our current pole stands originated on a wide variety of sites. When these stands reached an age of 40–80 years on some of these sites, especially those with low moisture-storage capacity, exceptionally adverse circumstances induced critical physiological stresses. The result was not only reduced growth of trees, but abnormal mortality as well. Our interpretation of the pole blight disease in western white pine is based on an analysis of the growth rings of the trees, on analysis of studies of the root system (Leaphart 1957, Leaphart and Wicker 1966, and McMinn 1956) in relation to tree growth, and on the correlation of tree growth with climate, predominantly temperature and available moisture. Since we are also convinced that the tree-ring record of western white pine reflects the relative severity of its climate, we have singled out one period (1916–40) that represents the most adverse growth conditions with regard to intensity and duration in the last 280 years.

We find no evidence from tree-ring patterns to indicate that present-day mature (200 ± 70 years) stands suffered growth depression in their early life, nor do we find from present stand structure and composition that these stands experienced an abnormal amount of mortality, such as would be represented by an epidemic of pole blight. For example, Deception Creek Experimental Forest in northern Idaho and the Hiatt Creek drainage of northwest Montana contain fully stocked, mature western white pine stands adjacent to pole-sized stands in which most western white pine trees were killed or affected by pole blight. Elsewhere in the western white pine type, one finds the remnants of what probably were relatively dense stands of western white pine, but they are near-climax stands of cedar, grand fir, or hemlock with a few stately 200+-year-old western white pine trees per acre.

Our knowledge of the histories of these latter stands is conjectural. Even though our tree-ring records to 1680 suggest that no severe drought was experienced in early life of mature western white pine stands, we have not ruled out the possibility that pole blight may have started such stands toward their present low number of stems per acre. On the other hand, those stands could have started with a low density of western white pine or could have been decimated by a bark beetle epidemic such as occurred in the late 1930's and 1940's or occurs today in mature stands on the St. Joe and Clearwater National Forests.

Growth in all age classes, though tending to recover in the late 1940's and early 1950's, still was below normal in 1958. In that year also, Leaphart (1959) reported drought damage in young western white pine stands in the Priest River valley, and some of these same areas suffered similar drought symptoms again in 1967. Pole blight still manifests itself in the pole stands surveyed in the early 1950's (Graham 1958*b*). Some stands found in 1956 to be very lightly blighted (e.g., Hiatt Creek) with no mortality had by 1967 experienced considerable spread of the disease and had suffered moderate damage and mortality from it. Still, some blighted stands of the late 1940's (e.g., at Priest River Experimental Forest) seem to have passed the stage of disease expression. Although most affected trees have died, a few survived; these, along with those that did not develop symptoms, now appear healthy, but show the reduced growth pattern of trees within pole blight areas (Table 3). These trees, like the older trees of mature stands, apparently are past the susceptible stage now.

The one known epidemic of pole blight was coincident with and followed the drought period identified in our tree-ring patterns. This drought, superimposed on those sites with characteristics that predispose trees to moisture stress, triggered the chain of events which ultimately resulted in pole blight. Although the hazard rating of these sites for the occurrence of pole blight will always be high (Leaphart 1958), the probability of disease reoccurrence appears to be low from our calculations. If the climate of the period from 1916 to 1940 does not represent a permanent shift to less favorable growth conditions and if western white pine is favored for regeneration only on sites of low moisture-stress characteristics, then chances are very favorable that pole blight will not reoccur for many centuries.

Conversely, a continuing adverse climatic pattern would drastically increase the predicted probabilities of pole blight occurrence, since clusters of dry years would be both more frequent and more severe. Evidence of even warmer and drier periods than ours of 1916–40 is recorded from studies of glaciation (Mathews 1951, Heusser 1956, Goldthwait 1966), of sea levels (Jelgersma 1966, Milliman and Emery 1968), and of vegetational successions (Hansen 1947, Heusser 1956). As experienced in the British Isles (Lamb 1965), these periods drastically affected agricultural activities, and one lasting about 200 years occurred around 1100 A.D., a relatively recent event. Although our tree-ring record and a similar though longer one of Keen's (1937) show no such long periods, such events could nevertheless be meaningful in terms of the long life of most forest trees. Lamb (1965) aptly states, "A table of statistics can never be substituted for a forecast," but the probability of recurrence of even the short adverse periods predicted from our records provides management with its most plausible base for assessing the hazard of pole blight to western white pine.

Acknowledgment

The authors sincerely appreciate the assistance of Dr. Ed F. Wicker, Forestry Sciences Laboratory, Moscow, Idaho, who helped collect the core and disc samples and measured all annual rings (76,000+) used in this study.

Literature Cited

Bryson, R. A., and J. A. Dutton. 1961. Some aspects of the variance spectra of the tree rings and varves. Ann. N.Y. Acad. Sci. **95**: 580–604.

Daubenmire, R. F., and Jean B. Daubenmire. 1968. Forest vegetation of eastern Washington and northern Idaho. Wash. Agr. Exp. Sta. Tech. Bull. 60. 104 p.

Duff, G. H., and Norah J. Nolan. 1953. Growth and morphogenesis in the Canadian forest species. I. The controls of cambial and apical activity in *Pinus resinosa* Ait. Can. J. Bot. **31**: 471–513.

Durbin, J. 1960. Estimation of parameters in time-series regression models. J. Roy. Statist. Soc. Ser. B, **22**: 139–153.

Foster, R. E. 1957. Pole blight of western white pine. Timber of Canada **18**(9): 60, 62, 63, 65, 66, 100.

Fritts, Harold C. 1966. Growth rings of trees: their correlation with climate. Science **154**: 973–979.

Glock, W. S. 1955. Tree growth. II. Growth rings and climate. Bot. Rev. **21**: 73–188.

Goldthwait, R. P. 1966. Evidence from Alaskan glaciers of major climatic changes, p. 40–53. *In* Int. Symp. on World Climate, 8000 to 0 B.C. Proc., 1966.

Graham, Donald P. 1958*a*. Results of some silvicultural tests in pole blight diseased white pine stands. J. Forest. **56**: 284–287.

———. 1958*b*. Results of pole blight damage surveys in the western white pine type. J. Forest. **56**: 652–655.

Gringorten, Irving I. 1966. A stochastic model of the frequency and duration of weather events. J. Appl. Meteorol. **5**: 606–624.

Hansen, Henry P. 1947. Postglacial forest succession, climate, and chronology in the Pacific Northwest. Amer. Phil. Soc. Trans., N. S. **37**: 1–130.

Heusser, Calvin J. 1956. Postglacial environments in the Canadian Rocky Mountains. Ecol. Monogr. **26**: 263–302.

Jelgersma, S. 1966. Sea-level changes during the last 10,000 years, p. 54–71. *In* Int. Symp. on World Climate, 8000 to 0 B.C. Proc., 1966.

Keen, F. P. 1937. Climatic cycles in eastern Oregon as indicated by tree rings. Mon. Weather Rev. **65**: 175–188.

Ketcham, David E., Charles A. Wellner, and Samuel S. Evans, Jr. 1968. Western white pine management programs realigned on northern Rocky Mountain national forests. J. Forest. **66**: 329–332.

Lamb, H. H. 1965. Britain's changing climate, p. 3–31. *In* C. G. Johnson and L. P. Smith [ed.] The biological significance of climatic changes in Britain. Academic Press, London.

Leaphart, Charles D. 1957. Root characteristics of western white pine and associated species in a stand affected by pole blight of white pine. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta. Res. Pap. 52. 11 p.

———. 1958. Pole blight—how it may influence western white pine management in light of current knowledge. J. Forest. **56**: 746–751.

———. 1959. Drought damage to western white pine and associated tree species. Plant Dis. Rep. **43**: 809–813.

Leaphart, Charles D., and Otis L. Copeland, Jr. 1957. Root and soil relationships associated with the pole blight disease of western white pine. Soil Sci. Soc. Amer. Proc. **21**: 551–554.

Leaphart, Charles D., and Ed F. Wicker. 1966. Explanation of pole blight from responses of seedlings grown in modified environments. Can. J. Bot. **44**: 121–137.

Marshall, Robert. 1927. Influence of precipitation cycles on forestry. J. Forest. **25**: 415–429.

Matalas, Nicholas C. 1962. Statistical properties of tree ring data. Int. Ass. Sci. Hydrol. Bull. **7**(2): 39–47.

Mathews, W. H. 1951. Historic and prehistoric fluctuations of alpine glaciers in the Mount Garibaldi map area—southwestern British Columbia. J. Geol. **59**: 357–380.

McMinn, R. G. 1956. Studies on the root ecology of healthy and pole blight affected white pine. Can. Dep. Agr., Forest Biol. Div., Sci. Serv. Bimonthly Progr. Rep. 12(6): 3.

———. 1965. Further observations on pole blight of white pine. Can. Dep. Agr., Forest Biol. Div., Sci. Serv. Bimonthly Progr. Rep. 21(6): 3.

McMinn, R. G., and A. C. Molnar. 1959. Further observations on pole blight and climate. Can. Dep. Agr., Forest Biol. Div., Sci. Serv. Bimonthly Progr. Rep. 15(1): 2–3.

Milliman, John D., and K. O. Emery. 1968. Sea-levels during the past 35,000 years. Science **162**: 1121–1123.

Molnar, A. C., and R. G. McMinn. 1958. The current status of pole blight in British Columbia. Can. Dep. Agr., Forest Biol. Div., Sci. Serv. Bimonthly Progr. Rep. 14(3): 3–4.

Pole Blight Investigations Steering Committee. 1952. Pole blight—what is known about it? U.S. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta. Misc. Publ. 4. 17 p.

Schulman, Edmund. 1956. Dendroclimatic changes in semiarid America. Univ. Arizona Press, Tucson, Ariz. 142 p.

Studhalter, R. A. 1955. Tree growth. I. Some historical chapters. Bot. Rev. **21**: 1–72.

Wellington, W. G. 1954. Pole blight and climate. Can. Dep. Agr., Forest Biol. Div., Sci. Serv. Bimonthly Progr. Rep. 10(6): 2–4.

Zahner, Robert, and Albert R. Stage. 1966. A procedure for calculating daily moisture stress and its utility in regressions of tree growth on weather. Ecology **47**: 64–74.