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CLIMATIC CYCLES IN EASTERN OREGON AS INDICATED BY TREE RINGS[1]

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[Division of Forest Insect Investigations, Bureau of Entomology and Plant Quarantine, U. S. Department of Agriculture, May 1937].

During the past two decades the ponderosa pine forests of eastern Oregon and northeastern California have been seriously depleted by drought and bark beetles. Billions of board feet of merchantable timber have been killed, and there has been a gradual encroachment of desert conditions into what were once thriving pine stands.

The question naturally arose in the minds of foresters and timber owners as to whether this trend toward dryness and retreat of the forest was to continue over any long period of time or was merely a short cycle in a variable climate which would soon reverse the trend and give some hope for forest perpetuation in threatened sites. Since this problem was intimately tied in with increasing timber mortality due to bark beetle activity, we, as entomologists, were concerned to know whether we could expect any eventual aid from Nature in holding beetle damage in check.

Weather records, because of the relatively short period of time covered by them, were obviously inadequate to give an answer as to long-period climatic fluctuations. Records as to fluctuations in lake levels were also either too recent or too indefinite as to dates to be of much help. Tree rings, on the other hand, carried a very old and precise record of climatic fluctuations, provided they could be interpreted.

EARLY WORK ON CLIMATE AND TREE GROWTH

The influence of climate on tree growth has been recognized by scientists for centuries. Even Leonardo Da Vinci realized this relationship when, in the fifteenth century, he explained to his pupil "how to arrive at the years of a split tree trunk by the number of its rings; and by the thickness of these rings, at the degree of moisture of the corresponding year."

In more recent times, Huntington (7), (8), Antevs (1), Douglass (3), (4), and many others have contributed to our knowledge of this subject and have demonstrated that tree rings not only show the age of a tree but record all of the vicissitudes throughout its life. Particularly prominent in the tree-ring record are such events as severe forest fires, insect defoliations, and droughts. The ancient history thus recorded gives a particularly valuable record of long-period climatic sequences, provided the other influences which have affected growth can be eliminated.

Recently the Library of the Forest Service, United States Department of Agriculture, in Washington, D. C., issued a 7-page leaflet in which the present tree-ring bibliography was compiled (12). The subject is, therefore, not a new one but has become well established as a method of analyzing ancient climatic history.

The only new phase of the present study is the application of the tree-ring method of analysis to the interpretation of growth and climatic cycles in eastern Oregon. The only previous work of this character in the Pacific Northwest is that reported by Robert Marshall (9) in the vicinity of Priest River, Idaho, and a general analysis of growth cycles by Walter H. Meyer (10). Douglass (4) has also reported the analysis of a few tree-ring samples from this region.

METHODS OF STUDY

The present study was begun in 1923 at Klamath Falls, Oreg., and has been continued somewhat intermittently ever since. Only in the last few years, however, has it been possible to give it sufficient attention to bring definite results. During the last year, the assistance of two W. P. A. helpers loaned by the Pacific Northwest Forest Experiment Station has materially aided me in completing measurements and computations. Measuring by micrometer hundreds of trees involving thousands of rings has been a very tedious and laborious process, and I am gratefully indebted to a number of assistants who have strained their eyesight over this phase of the work.

The methodology of tree-ring studies such as the present one has been very fully described by Huntington (7), Antevs (1), and Douglass (3), and does not need to be discussed here except to indicate briefly such variations as were made in these methods for certain steps.

Tree selection.—Since we were most concerned with bark beetle damage to ponderosa pine (*Pinus ponderosa*) in eastern Oregon, it was only natural that this tree should have been selected for the tree-ring study. Moreover, it is a tree admirably adapted to this purpose, and is the one first selected by Douglass (3) for his comprehensive tree-ring studies in the Southwest.

In the ponderosa pine stands of eastern Oregon, moisture is a limiting factor in tree growth. Given adequate soil moisture and suitable temperatures, ponderosa pine makes rapid annual growth. When soil moisture drops below the wilting coefficient, the tree suffers; foliage is lost, roots dry up, and diameter growth diminishes, sometimes almost to the vanishing point. Following severe droughts, once adequate moisture conditions are restored, it may take several years for trees to recuperate. Ring width thus tends to measure more or less the cumulative effect of moisture deficiency. Such a study would not be possible in western Oregon and Washington, where moisture is rarely, if ever, a limiting factor in tree growth. A few comparisons of the rings of Douglas fir from western Oregon showed such uniformity in growth as to indicate clearly the difficulties involved in using a humid-zone tree for a climatic study.

[1] This paper is a preliminary report on a study not yet completed, the results of which will probably be given in more detail in a later publication. It was presented at the Meeting of the American Meteorological Society held at Seattle, Wash. July 17, 1936.

In the first selection of trees for ring study, only those growing on well-drained slopes were chosen. A brief analysis was sufficient to show that the ring patterns of trees growing along swales or creeks or on rocky ridges were not suitable for climatic comparisons. Those along streams were growing at a fairly uniform rate and only showed fluctuation in the very driest years. Trees growing on very rocky ridges were likely to be stunted and of such slow growth as to give very inconsistent patterns.

In the course of the study, tree-ring sections have been taken from 1,240 ponderosa pines in 44 different localities of eastern Oregon and northeastern California, and on different pine sites ranging from site III (stands in which trees reach an average height of 142 feet) to poor site VI along the desert edge (stands in which the average height of trees is 64 feet). A comparison of the growth fluctuations on different sites showed that the poor sites along the desert edge were much more sensitive to drought conditions than the moister sites at higher elevations. On these moister sites, tree growth was likely to be complacent except in very dry years. Trees growing on the desert edge, however, showed marked fluctuations from year to year and hence were best adapted for the tree-ring study.

From most plots a radial section or increment core was secured by means of a Swedish increment borer. For this purpose dominant trees between the ages of 100 and 250 years were selected. Trees of these ages are making fairly rapid diameter growth and respond readily to climatic changes. They give ring patterns which are easily measured and compared for the purpose of determining short, recent-period fluctuations. From 12 to 15 cores of this type were taken at random from each plot and 10 of the more uniform ones were selected for measurements. It was found that 10 cores, selected in this manner, gave a pattern of ring-growth fluctuations which represented with considerable accuracy the average ring pattern for that plot—a pattern which could be duplicated by any other random sample similarly taken.

For the long-period fluctuations, five areas were selected in widely separated sections of eastern Oregon, where logging operations were in progress. These were the Clover Station area west of Klamath Falls, the Bly Mountain area south of Beatty, the Horsefly Mountain area south of Bly, the Pringle Falls area west of La Pine, and the Watkins Butte area north of Fort Rock, Oreg. The first three areas in Klamath County were approximately 50 miles apart, while the last two areas in Deschutes County were over 100 miles north of these and 50 miles from each other. The differences in topography, forest type, site, and distance apart of these five areas served to eliminate the chance of any one factor other than climate affecting growth patterns in exactly the same manner in any given period of years.

From each area V-shaped radial sections were sawed from freshly cut stumps so as to include the center and the most uniform radius. From 30 to 90 stump sections were obtained from each area, so selected as to give a balanced overlapping of age classes.

From the Clover Station area a group of 31 stump sections from trees of various ages was obtained from the Weyerhaeuser Timber Co.'s logging operation. The timber was of Site quality III, and the oldest tree was 530 years of age. It was possible with this group to carry the record back to the year 1500, but satisfactory cross identification was not established beyond 1700.

From the Horsefly Mountain area a group of 46 stump sections was taken on the Pelican Bay Lumber Co.'s operation. The stand was of Site quality III and showed the same average growth rate as the Clover Station group. The oldest tree was 710 years of age and the record was carried back to 1500, but, as with the Clover Station group, there were too few trees in the older age groups to establish satisfactory cross identification beyond 1700.

The Bly Mountain group of 52 stump sections was obtained on the Crater Lake Lumber Co.'s operation south of Beatty, Oreg. The area represented a Site V stand, with a marked fluctuation in growth pattern between good and poor years. The oldest tree was 600 years of age and the pattern was carried back to the year 1480 with fairly satisfactory across identification.

The Pringle Falls group consisted of 46 stump sections taken adjacent to the Pringle Falls Experimental Forest near La Pine, Oreg., in the logging operation of the Shevlin-Hixon Lumber Co. The stand was a good Site IV, and the growth rate was quite uniform. Apparently, climatic changes had affected this stand only slightly and only the outstandingly poor years were marked in the pattern. However, the group showed an interesting history of fires and insect defoliations which caused cessation of growth at periodic intervals.

The Watkins Butte group consisted of 90 stump sections taken on the Brooks-Scanlon Lumber Co.'s operation on the edge of the desert north of Fort Rock, Oreg. This was the most complete group with a uniform overlapping of age classes throughout and a record going back to the year 1268. The oldest tree was approximately 755 years of age with about 100 years of growth missing at the center, due to decay. With a great deal of painstaking work, cross identification was accurately established throughout a full 650 years. This was difficult to do, as many of the samples showed missing rings, following years that were evidently those of severe defoliation. A few distant trees, less severely affected and having a full complement of rings, served to bridge the gaps and establish accurate dating.

Cross identification.—The first task, after reaching the laboratory, was to cross identify and accurately date the rings on each core. This was done by counting back from the outer ring of known date and, at the same time, matching the pattern with other cores from the same locality to avoid mistakes in the count. The sequence of small and large rings is usually so uniform for any one locality that there is no difficulty in deciding as to the correct year for any given ring, once the typical pattern has been determined. Figure 1 shows how closely two cores from the Watkins Butte area match for certain key years.

Because of fires, insect defoliations, frosts, and other injuries, the possibility of finding false rings or missing rings in the growth pattern of individual trees had to be considered. False rings were extremely rare, but missing rings were not uncommon, especially following abrupt stoppages of growth. Matching patterns before and after such catastrophes showed how many years were missing. In very few cores were more than one to three rings lost at such times. The pattern on each area was in this way independently determined, and then compared with the pattern of other areas. Since, as will be presently shown, there was found to be general agreement in key years between all areas, it seems reasonable to conclude that the dating was accurately done.

Measurements.—A smooth radial section was prepared on each core with a razor blade, and once the correct dates had been determined, the decadal intervals were marked on each core with indelible pencil.

Decadal measurements then were made to the nearest one-tenth millimeter with a millimeter rule. Measurements of annual growth were made with a microscope and

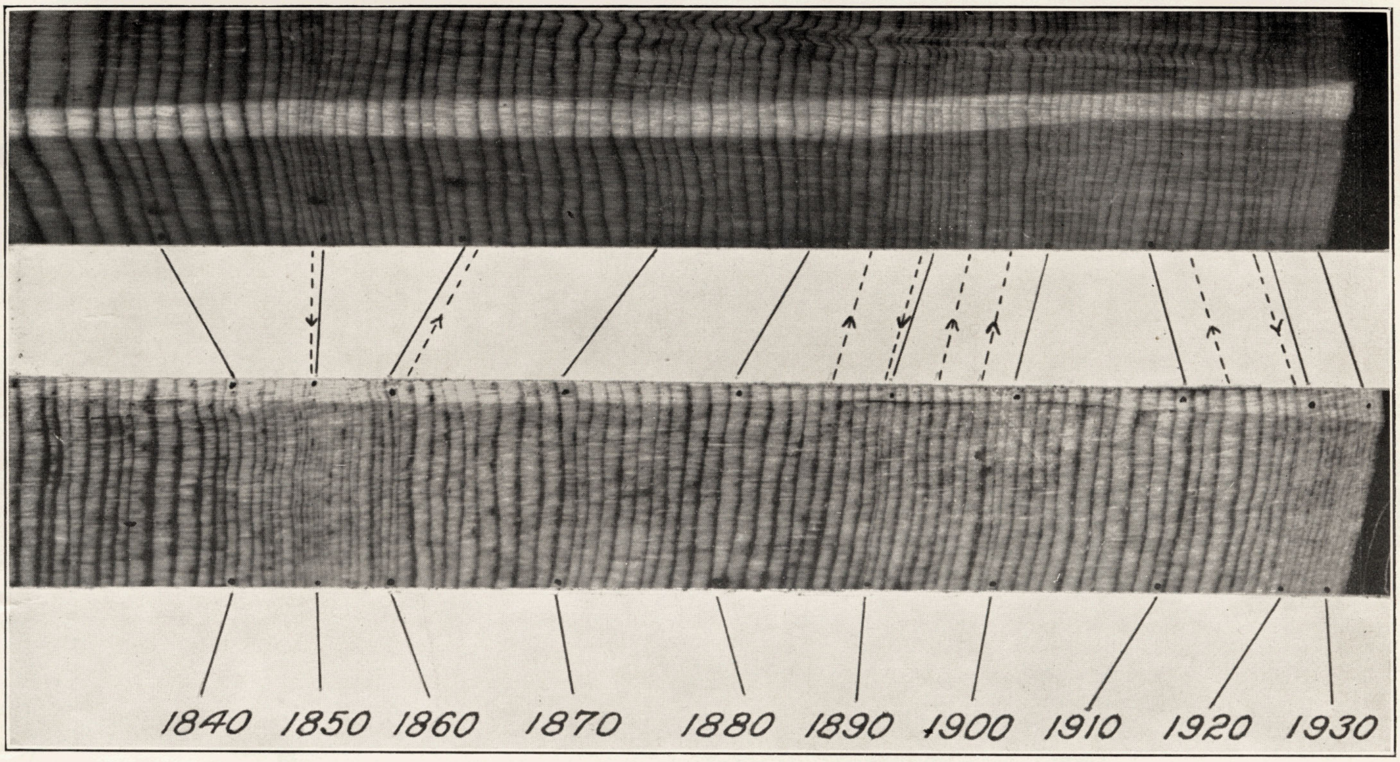


FIGURE 1.—Radial sections from two trees on the Watkins Butte area illustrating cross identification of ring patterns. Dotted lines connect certain key years which show consistently large or small growth and which have been useful for cross identification purposes.

sliding micrometer stage which recorded ring width to the nearest one-hundredth millimeter. This increment core measuring device was constructed in the Washington shops of the Bureau of Standards. A more complicated device has recently been constructed for the T. V. A., and is called a dendroheliomicrometer.

Plotting.—Decadal measurements were plotted on a fairly large scale so as to permit fitting through the points a smoothed average growth-trend curve from which values for normal growth could be read. Measurements of the annual rings were recorded and plotted on long, narrow strips of profile paper mounted on cardboard so that they could be shifted to provide for totalling by either age of tree or year dates.

THE GROWTH PATTERN

One of the first things noted about ponderosa pine growth in eastern Oregon was the similarity in fluctuations of annual growth, not only as between neighboring trees but also between trees throughout a wide area. This similarity in pattern gave encouragement to the theory that no factor other than climate could cause such a widespread and consistent response. Practically every increment core or radial section, wherever taken in eastern Oregon, showed a sudden drop in growth between the 1916 and 1917 rings; the years 1921, 1923, and 1928 stood out above their neighbors; and the years 1924 and 1929 showed the smallest growth in that decade.

Even when trees of different growth and vigor characteristics were compared, this same pattern of relative fluctuations was found. Figure 2 shows the annual radial growth by tree classes from one local area of the Ochoco National Forest. The actual millimeter growth of these different tree classes is vastly different in amount, as one would naturally expect when comparing young, vigorous trees with old, overmature veterans. But when this growth is reduced to a percentage of the general average for each class, then it is apparent that the proportional fluctuations in growth have been practically the same for all classes of trees. Only the rapid juvenile growth of young trees and the slow complacent growth of overmature or suppressed trees are likely to show erratic or negligible response.

By comparing the growth pattern, similarly determined, from different areas in southern and central Oregon and northeastern California, it was found that the same pattern of growth extended over a wide area. (See fig. 3.) Evidently there exists a broad climatic zone which influences and has dominated the growth pattern over a large region east of the Cascade Range.

At present the boundaries of this climatic zone are not clearly defined. Pinehurst, Oreg., at the summit of the southern Cascades, is the most westerly point examined which clearly shows the typical growth pattern. To the south the same pattern extends through the Modoc National Forest to Lookout and Alturas, Calif., and may extend on south to Susanville. All of the Fremont and Deschutes National Forests from Lakeview north to Bend, Oreg., show the same influence which extends on eastward to the Ochoco National Forest east of Prineville, Oreg. Detailed measurements have not been made from other portions of the region in the present study, but Meyer (**10**) has shown similar tendencies extending throughout the Blue Mountains and north throughout eastern Washington. It is evident that in its major phases we are dealing with climatic influences which are more or less general throughout the northern Great Basin region, and are only slightly modified by more local weather conditions.

In comparing the eastern Oregon pattern of ring growth with that of the big tree from the west slope of the Sierras, Huntington (**7**) and Antevs (**1**), very little similarity was found in the annual fluctuations or even in the decadal growth. The big tree record shows very uniform or complacent growth as compared with the marked fluctuations found in the ponderosa pine rings. This is undoubtedly due to the great differences in moisture conditions in the two localities. The big trees and the pines do, however, show a marked similarity in the long-swing fluctuations, and agree in this respect.

Agreement between the patterns of annual growth fluctuations of ponderosa pines in Arizona (Douglass (**4**))and those from eastern Oregon, for the period 1840 to 1918, was not evident from inspection, but did give a correlation ratio of $+0.41\pm0.09$ which may be considered as significant.

Normal tree growth.—Since there are large differences in the growth rates of individual trees according to age, diameter, tree class, position in the stand, and local influences, it is useless to compare yearly fluctuations in growth between different trees without first reducing these fluctuations to a common base. In other words, we must first determine a value for normal tree growth in order to have a base upon which fluctuations due to climate may be measured.

Reducing yearly growth to a percentage of the mean, as is shown in figure 2, is only accurate for relatively short periods of time, of less than 50 years, for it does not take into account the normal growth cycle of the tree, nor does it compensate for other factors which may influence growth rates over a long period of time.

A normal curve of radial growth for each area was determined by summating and taking the average growth according to age of all trees used in the study regardless of years during which such growth occurred. The rate of annual radial or diameter increment, for ponderosa pines used in this study, gradually increases up to about 75 years of age. By that time trees have reached an average diameter of 8 inches (100 mm radius) on poor sites and about 12 inches on good sites. From that point on, the rate of diameter growth gradually decreases until the trees are about 300 years of age. The growth curve then flattens out and diameter growth after 300 years becomes practically constant. (See fig. 4.)

Individual tree variation.—On comparing the growth curve of any individual tree against the general average or normal curve of growth, it was evident that this correction alone failed to compensate for large differences in growth rates due to differences in individual tree vigor, dominance, crowding, or sudden release due to fire or windthrow of neighboring trees. Therefore, individual tree variation was compensated for by plotting the decadal growth and then fitting a smooth trend line. This process was the same as making the assumption that the trend of average growth which a tree maintained during a period of 100 years or more was normal for that tree, and that deviations from this trend line were due to outside influences, including climate.

The smoothed growth-trend curves fitted to each tree's pattern tended to obscure any long-swing climatic changes of more than a century in length. To determine whether any such long-swing changes existed, the smoothed growth curve for each tree, which had been assumed to the normal for that tree, was then compared with the general average curve of growth according to age, and the deviations for each decade noted. Separate comparisons were made for trees between the ages of 75 and 150 years, between 150

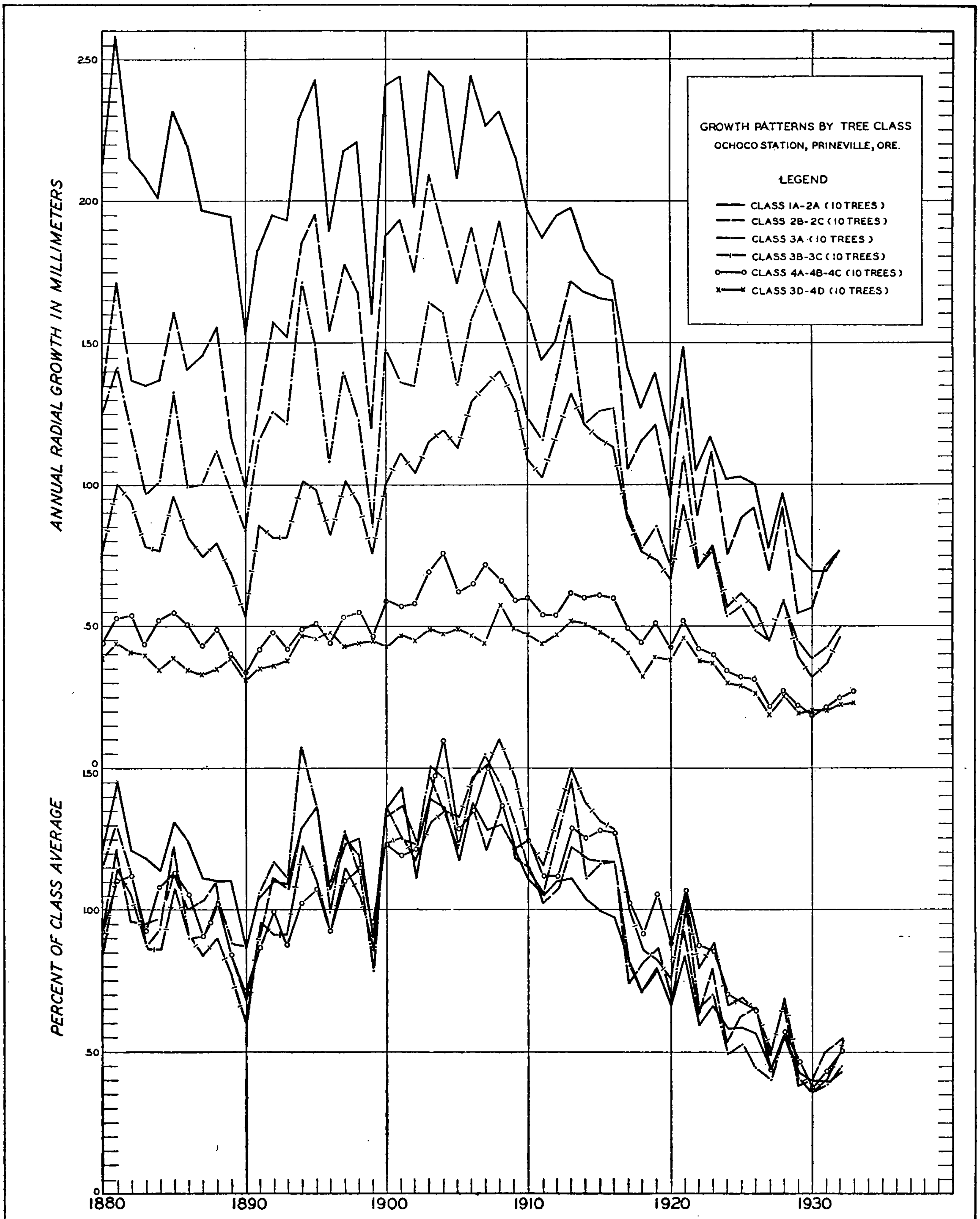
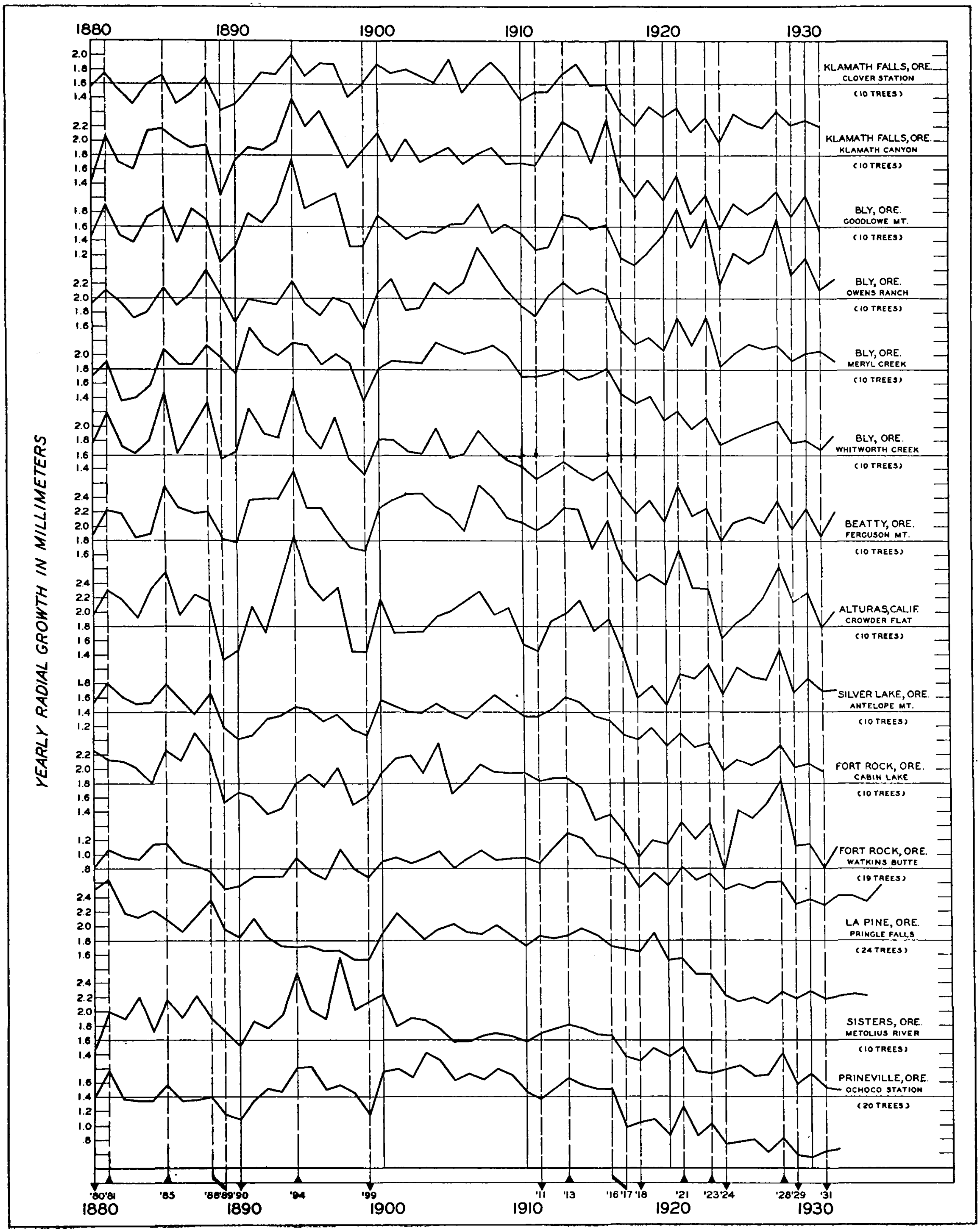

GROWTH PATTERNS BY TREE CLASS
OCHOCO STATION, PRINEVILLE, ORE.
LEGEND
CLASS 1A-2A (10 TREES)
CLASS 2B-2C (10 TREES)
CLASS 3A (10 TREES)
CLASS 3B-3C (10 TREES)
CLASS 4A-4B-4C (10 TREES)
CLASS 3D-4D (10 TREES)
ANNUAL RADIAL GROWTH IN MILLIMETERS
PERCENT OF CLASS AVERAGE
2.50
2.00
1.50
1.00
.50
0
150
100
50
0
1880
1890
1900
1910
1920
1930

FIGURE 2.



YEARLY RADIAL GROWTH IN MILLIMETERS
KLAMATH FALLS, ORE. CLOVER STATION (10 TREES)
KLAMATH FALLS, ORE. KLAMATH CANYON (10 TREES)
BLY, ORE. GOODLOWE MT. (10 TREES)
BLY, ORE. OWENS RANCH (10 TREES)
BLY, ORE. MERYL CREEK (10 TREES)
BLY, ORE. WHITWORTH CREEK (10 TREES)
BEATTY, ORE. FERGUSON MT. (10 TREES)
ALTURAS, CALIF. CROWDER FLAT (10 TREES)
SILVER LAKE, ORE. ANTELOPE MT. (10 TREES)
FORT ROCK, ORE. CABIN LAKE (10 TREES)
FORT ROCK, ORE. WATKINS BUTTE (19 TREES)
LA PINE, ORE. PRINGLE FALLS (24 TREES)
SISTERS, ORE. METOLIUS RIVER (10 TREES)
PRINEVILLE, ORE. OCHOCO STATION (20 TREES)
1880 1890 1900 1910 1920 1930
'80 '81 '85 '88 '89 '90 '94 '99 '11 '13 '16 '17 '18 '21 '23 '24 '28 '29 '31

Figure 3.

and 300 years, and over 300 years. If it was found that in any decade, growth of trees in all three age groups showed the same significant deviation in growth either above or below the general average, than it was concluded that this displacement represented a real climatic effect. However, it so happened that the average of the assumed normals as represented by the smoothed curves did not deviate from the general average growth curve by more than 10 percent for any century. The smoothed curves had concealed an average decline of about 6 percent during the period 1430 to 1630, had underestimated the good growth period of 1630 to 1830 by 7 percent, and had underestimated the poor growth since 1830 by about 4 percent.

In order to eliminate the erratic growth of youth and extreme old-age measurements were started at 100 mm from the center and stopped at age 450. The portion of the record most consistent with climatic fluctuations was found in rings between the one hundredth and two hundred and fiftieth years. In very old cores measurements were extended to the center rather than lose this ancient record. The oldest ring measured was that of the year 1268, just 668 years ago.

Disturbing influences.—While the smoothed curve of growth eliminated the factor of tree dominance and position in the stand it did not fully compensate for sudden fluctuations due to fires, defoliation by insects, or released

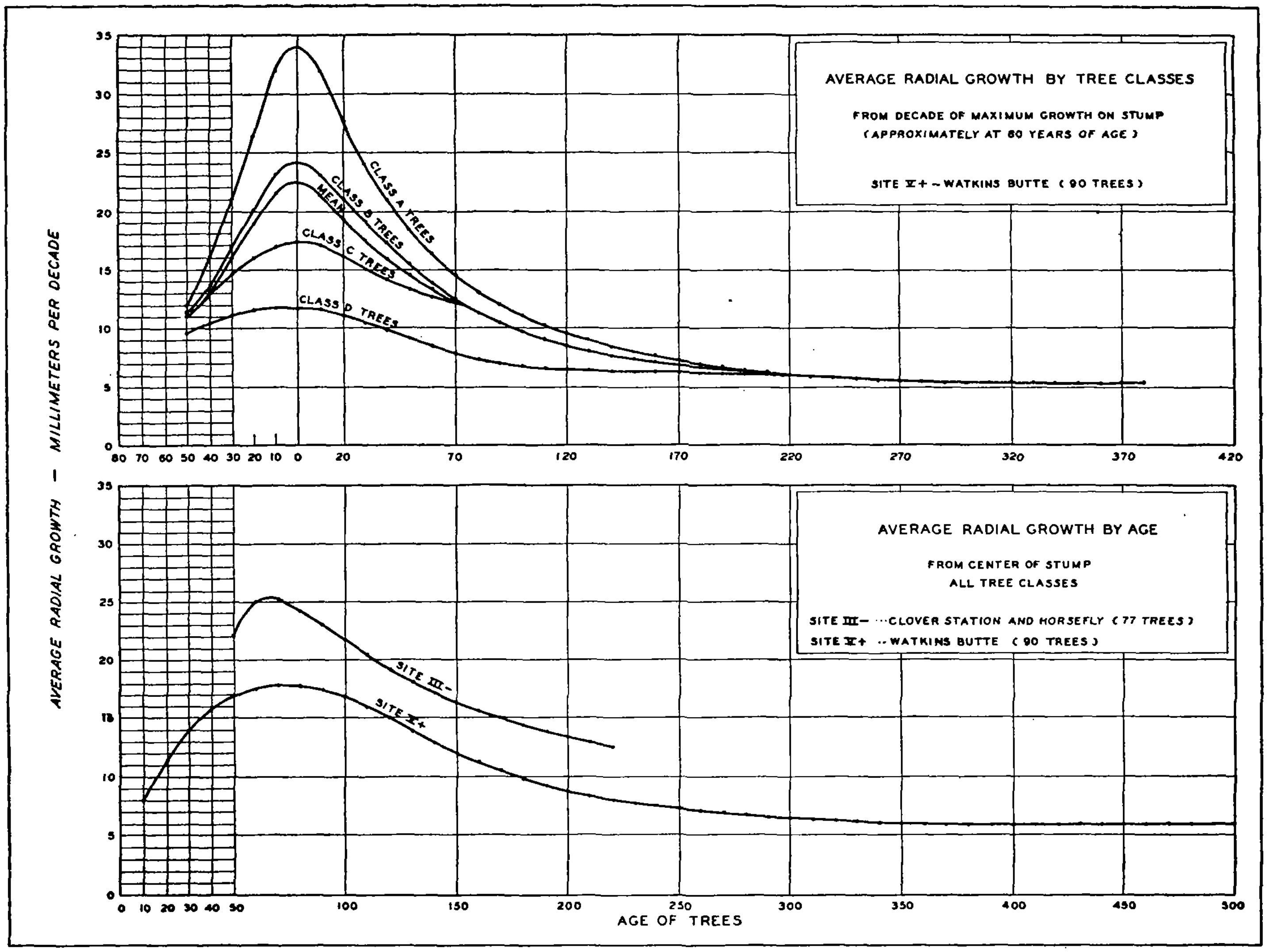


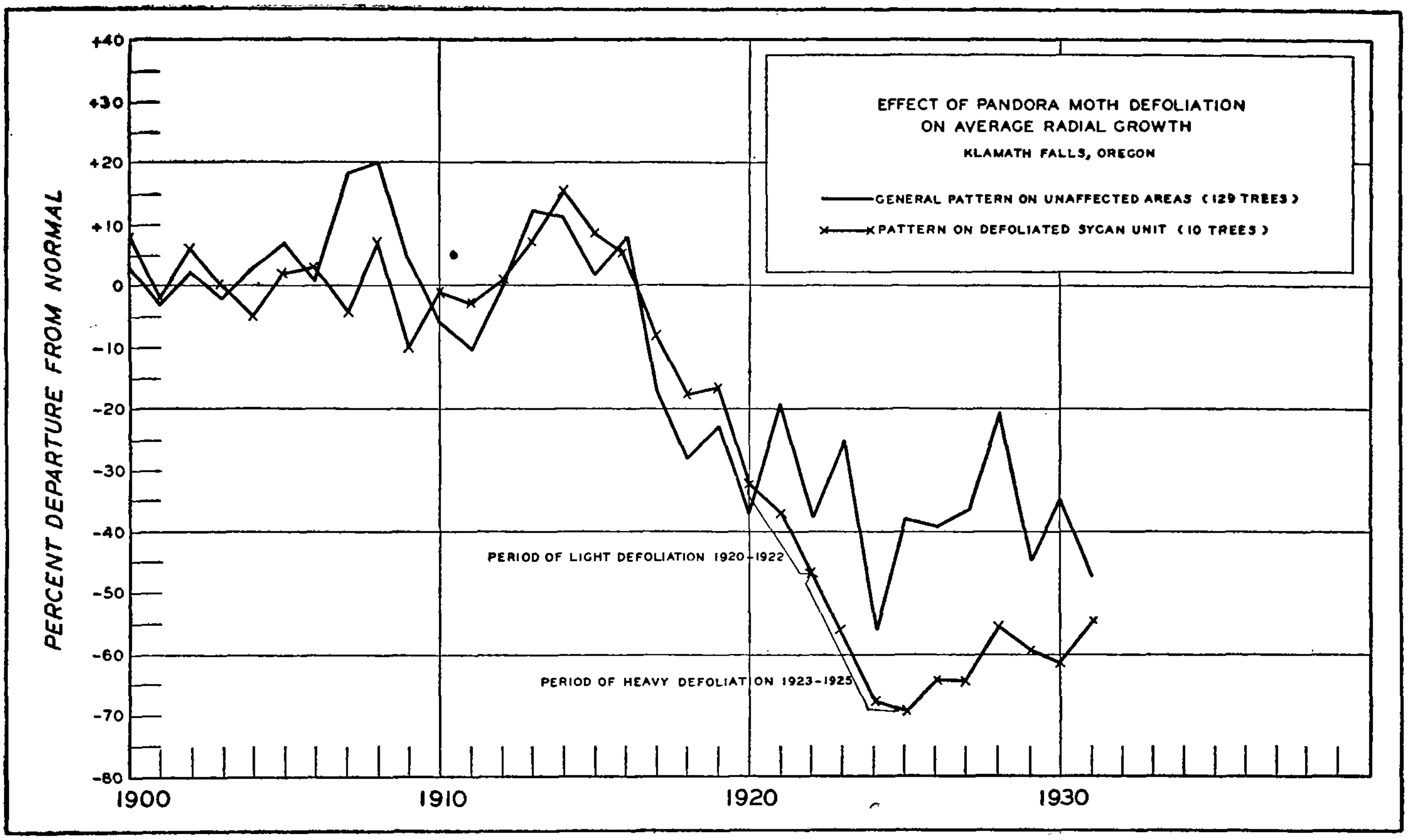
FIGURE 4.

These small differences were well within the limits of accuracy of the study.

Many trees showed an early period of suppressed growth at their center. Apparently, while in the seedling stage, these trees had stagnated owing to competition for a period of 50 to 75 years and in some cases for 150 years. Then, with a release from competition, probably as a result of forest fires, they suddenly began to grow at normal rates and their subsequent growth varied, not with age, but more in accordance with their diameters. For this reason the early period of suppression was eliminated from the computations and the peak of growth was used as a point of origin. (See fig. 4.)

growth due to neighboring trees being killed or blown over. Some of these factors are very important and give all outward indications of important climatic changes.

(1) Fire: Fires often have an important influence upon ring patterns and growth rates. If a fire is severe enough to cause heavy defoliation without killing the tree, rings at the base will show a sudden cessation of growth, a period of very slow growth, often missing rings (Craighead (**2**)), and then gradual recovery, usually followed by a period of stimulated growth. (See fig. 5.) Surface or ground fires, which do not result in defoliation, usually cause little change in the growth pattern, except a subsequent increase in growth due to elimination of competing


EFFECT OF PANDORA MOTH DEFOLIATION
ON AVERAGE RADIAL GROWTH
KLAMATH FALLS, OREGON
GENERAL PATTERN ON UNAFFECTED AREAS (129 TREES)
PATTERN ON DEFOLIATED SYCAN UNIT (10 TREES)
PERIOD OF LIGHT DEFOLIATION 1920-1922
PERIOD OF HEAVY DEFOLIATION 1923-1925
PERCENT DEPARTURE FROM NORMAL
1900
1910
1920
1930

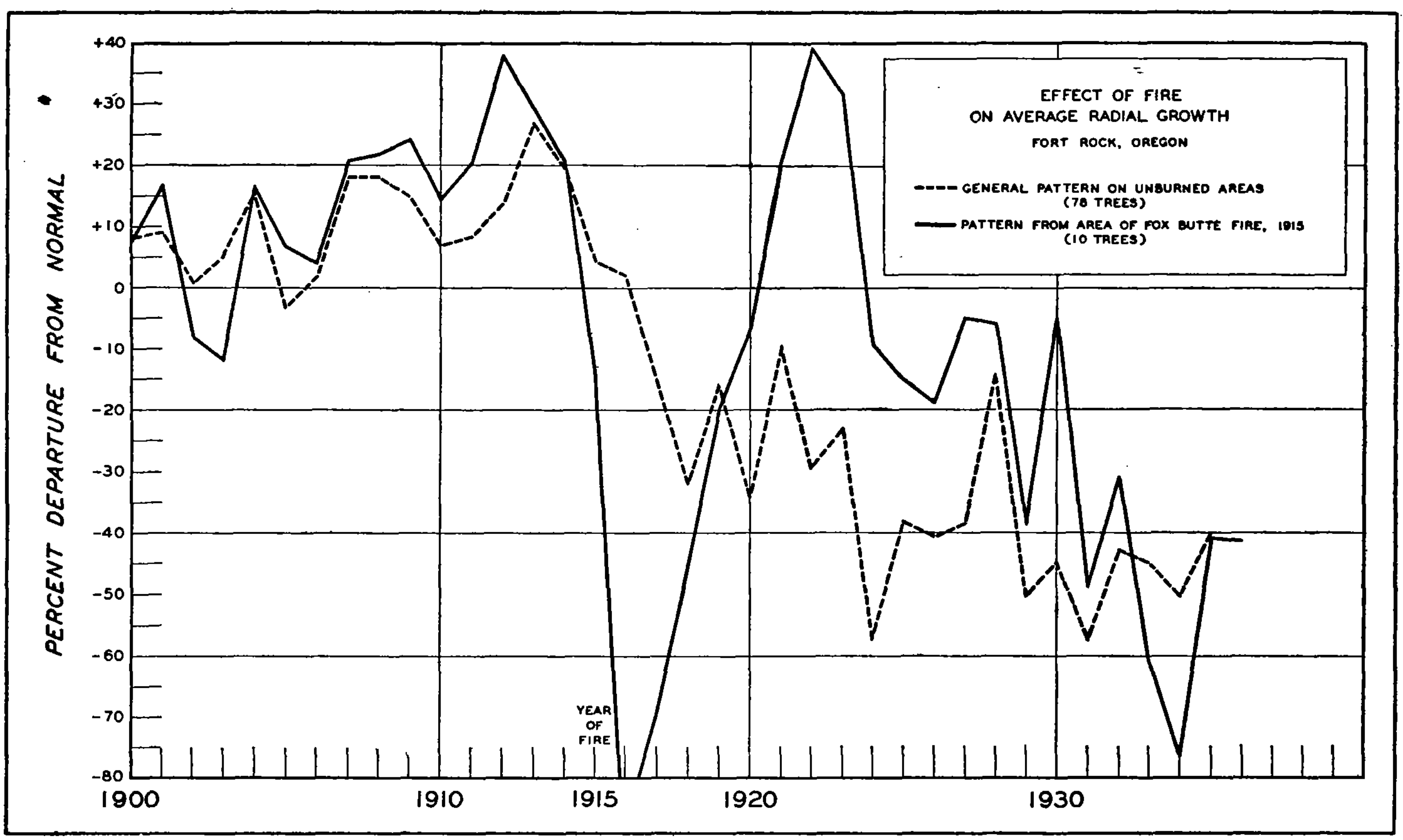

EFFECT OF FIRE
ON AVERAGE RADIAL GROWTH
FORT ROCK, OREGON
GENERAL PATTERN ON UNBURNED AREAS (78 TREES)
PATTERN FROM AREA OF FOX BUTTE FIRE, 1915 (10 TREES)
YEAR OF FIRE
PERCENT DEPARTURE FROM NORMAL
1900
1910
1915
1920
1930

FIGURE 5.

trees and other vegetation. Young trees often show sharp declines in growth following fires, while older trees give little indication of a disturbance. Apparently the effect upon ring patterns depends upon the amount of defoliation which the trees suffer. Tall trees which escape foliage injury naturally show less effect than the smaller trees which are hit severely.

Fires have been of such frequent occurrence in the pine region during the past centuries that it might be supposed that their effects would completely obscure the influence of climate, and they do inject an element of uncertainty into ring interpretation as far as any one area is concerned. For instance, fire scars at the base of trees on the Watkins Butte area showed that during the nineteenth century fire swept the area in 1824, 1838, 1843, 1863, 1883, and again in 1888. Other centuries showed similar fire frequencies. In spite of these frequent fires, the ring pattern on this area was not greatly disturbed by them. Referring to the radial sections shown in figure 1, it will be noted that the ring immediately following each fire was usually small with subsequent larger rings. This was particularly true of the fires of 1838, 1843, and 1888, but the fires of 1863 and 1883 caused no noticeable effect.

(2) Insect defoliation: Defoliation by needle-feeding insects must also be taken into account. In the ponderosa pine region of eastern Oregon at least two important defoliators, the Pandora moth (*Coloradia pandora* Blake) and the pine butterfly (*Neophasis menapia* Felder), may cause such damage. The effect of a Pandora outbreak of 1920–25 on the average growth pattern of trees on the Klamath Indian Reservation is shown in figure 5.

In general the effect of insect defoliation is similar to that of fire. There is likely to be a sudden cessation of growth, frequently missing rings, and then gradual recovery. About the only difference is that following insect defoliations there is no subsequent period of stimulated growth due to release of trees from competition, and, as a consequence, the reduced period of growth may be more extended than in the case of fire. Furthermore, both young and old trees will show the injury, the greatest effect being registered in the growth of the older trees. Swaine, Craighead and Bailey (**11**) have shown that defoliations also cause an enlargement or normal growth of the annual ring in the lower trunk and a reduction in the upper trunk for the first year of the defoliation, so that by sectioning trees both at the top and base it should be possible definitely to determine the defoliation periods.

While the effects of fires and defoliations on the growth pattern can usually be recognized, the only way to eliminate these and to determine what the growth would have been in spite of such disturbing influences is to take the average of a number of widely separated areas on the assumption that the same catastrophe would not be likely to occur in the same year over an entire region. Even fires are not likely to be so widespread, and we know that defoliations in this pine type are localized.

CORRELATION OF TREE GROWTH WITH PRECIPITATION

Tree growth is the product of many factors, such as the inherent characteristics of the tree species, the age and size of the tree, the amount of available food and moisture, and the action of heat and light. Annual-growth response of a tree summates the effect of all of these factors, and the width of each annual ring reflects the net result. It is, therefore, a better measure of good and poor growth periods than can be obtained by any number of direct measurements of each independent factor.

Of all the factors affecting tree growth, those relating to climate are the most variable. The inherent growth characteristics of the tree species and the tree's age, size, dominance, and position in relation to its food supply change not at all or only slightly from year to year. The greatest variables are the climatic factors of precipitation and temperature. In the semiarid ponderosa pine region of eastern Oregon mean annual temperatures fluctuate within a narrow range. Precipitation, however, is extremely variable and, since soil moisture is so essential to tree growth, this one factor becomes the dominating influence in determining annual fluctuations in tree-ring width in this region.

The normal distribution of ponderosa pine is limited to the zone where annual precipitation is in excess of 12 inches. This appears to be the tree's minimum requirement. According to Weather Bureau records, the eastern division of Oregon has an average annual precipitation which fluctuates between 9.32 and 19.14 inches, and shows a mean of 13.75 inches for the period 1890 to 1935, inclusive. The precipitation at individual stations may vary between 4 and 65 inches. It is evident, therefore, that in some localities and in certain years the minimum moisture requirement for ponderosa pine growth is not met. The ground moisture drops below the wilting point, the trees suffer, and bark beetles take their toll. In other years, with precipitation above normal, conditions are favorable for rapid tree growth. Thus along the desert edge we find the most sensitive response to conditions of adequate or deficient moisture reflected in tree growth.

While it is evident, even from casual observation, that ponderosa pines do respond to differences in available moisture, we should hardly expect to find a perfect correlation between precipitation and ring width. The optimum requirements for trees are met when the soil moisture lies between the wilting point and field-carrying capacity. If the soil moisture drops below the wilting point, trees respond accordingly and their growth is either retarded or they die. On the other hand, if moisture increases beyond the field-carrying capacity, the soil becomes waterlogged and any further increase in growth is inhibited. Undoubtedly the best conditions for optimum growth are reached when an adequate soil-moisture supply is maintained throughout the year and when warm, humid weather conditions prevail through a long growing season. Wet, cold years are just as likely to result in poor tree growth as hot, dry ones.

In the ponderosa pine region extreme conditions of total lack of soil moisture or complete saturation of the soil rarely, if ever, occur for more than short periods of time, and seasonal precipitation varies within a range which is not greatly different from the limits of possible tree response. For this reason it is not surprising to find a high degree of positive correlation between fluctuations in annual ring width and differences in seasonal precipitation.

Douglass (**4**) reports finding an 82 percent correlation between rainfall and ponderosa pine radial growth at Prescott, Ariz., and has even developed a formula by which rainfall of past centuries could be computed from tree-ring measurements with an accuracy of 70 percent. He also found that the tree rings were not merely proportional to the rainfall of the current year but showed the cumulative effect of excesses and deficiencies from the preceding years.

In the present study the average departures of ring growth from normal have been compared with the yearly departures of precipitation in eastern Oregon. This relationship is shown graphically in figure 6. A certain degree of correlation is evident simply upon inspection. Applying the methods of statistical analysis, the coefficient of correlation between current growth and current seasonal rainfall (Sept. 1 to Sept. 1) was found to be $+0.50\pm0.09$.

Examination of the seasonal precipitation and tree-ring curves in figure 6 shows that in most cases the peaks and depressions coincide. In other cases there appears to be a lag of 1 year in the response of growth. This lag usually coincides with a similar 1-year lag in water run-off. For instance, the increased rainfall of 1926–27 was followed by the heaviest run-off and a peak of tree growth in 1928. decades lake levels in eastern Oregon have receded. In 1926 Goose Lake and many others dried up completely. Springs which have been depended upon for watering stock for many years have dried up, streams have dwindled and dust-swept deserts have taken the place of once fertile farm lands. Judging from the rainfall record alone we should hardly expect such catastrophes, but the tree rings accentuate this long-swing deficiency.

This cumulative moisture deficiency is also shown in the record of the annual mean discharge of the Columbia River. Records of the United States Geological Survey give this information for The Dalles, Oreg., back to 1879

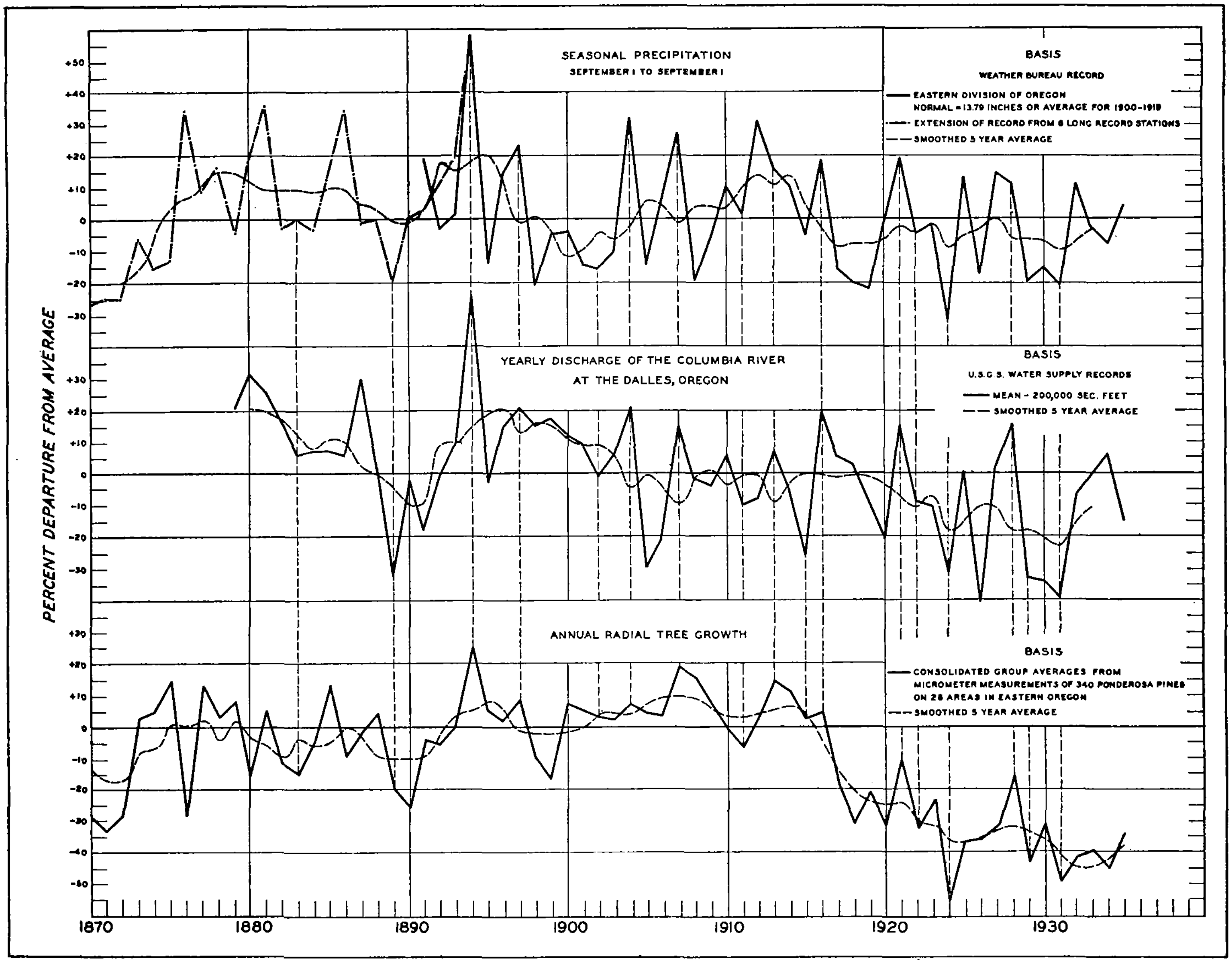


FIGURE 6.

The same was true of increased precipitation in 1911–12, which was followed by increased run-off and tree growth in 1913. Comparing growth deviations with a 2-year cumulative departure of precipitation, a coefficient of correlation of $+0.82\pm0.04$ was found. Thus, the tree rings show some effect of water conservation, and, in most cases, a lag of 1 year in full growth response.

It is evident that the marked reduction in growth following 1917 is due in large part to a cumulative deficiency of moisture, to a lowering of water tables, and to a physiological drought condition that is not strikingly evident in the yearly precipitation records. During the past two

(6). The percent departures from a mean of 200,000 second feet is shown in figure 6. The correlation with the tree-ring record is most striking and statistical analysis shows a coefficient of correlation of $+0.56\pm0.09$.

The correlation between tree rings and climatic factors might be improved by taking into account several of the less important factors. For instance, the distribution of precipitation throughout the year has been found to be of importance. Rainfall in the spring and early summer during the growing period was found to be much more important than an excess of precipitation during the winter months. Variations in temperature and the length of the growing season undoubtedly play a part. Multiple correlations including all of these minor factors have not as yet been determined.

THE TREE-RING CALENDAR

The combined pattern of growth from all areas in terms of percent departure from normal growth is shown in figure 7. In this chart the effects of fires and other agencies have been largely eliminated back to 1,500 by combining the averages.

The ancient history of eastern Oregon, as recorded in this tree-ring calendar, makes very interesting reading. The successions of fires, droughts, floods, and insect epidemics are all written in this record only awaiting a complete deciphering. So far only some of the more outstanding events have been interpreted.

Going back over the record, we find that the recent drought started in 1917, reached a low in 1924 and a second low in 1931, and now shows a trend toward recovery. Growth during the period 1912 to 1916 was much better than average, and reflects the abundant precipitation which fell during those years.

During the period 1900 to 1919 average conditions prevailed, and we find by summating the departures that the average growth during this period is equal to the general average of the past 650 years. This is of great importance in indicating what can be expected as normal weather conditions in the future. The average rainfall during this period (1900–1919) was 13.79 inches for the eastern division of Oregon, which is only slightly more than the general mean of 13.75 inches for the total period 1890 to 1932, for which the Weather Bureau has summarized records for this half of the State.

The great flood of 1893–94 is clearly marked in the tree-ring calendar. As will be remembered, during this flood the Columbia River rose to its highest recorded stage of 33.0 feet, and the Willamette River flooded the business section of Portland. That such flood conditions were not unusual in early history is indicated in the tree-ring calendar, when peaks such as occurred in 1861, 1814, 1791, 1775, 1752, 1702, and 1673 greatly exceeded the peak of 1894.

Except for three short depressions in the years 1871, 1880, and 1889, the period from 1860 to 1900 was above average in growth rate.

In 1861 we find an outstanding peak of growth which marks a high point in the ring pattern throughout eastern Oregon. This was a winter of heavy snows which was followed by one of the worst floods in the history of the State. Mr. E. L. Wells, of the Portland office of the Weather Bureau, has uncovered some interesting old records of this flood year.

The tree record shows that between 1839 and 1854, when the emigrant trains were trekking into Oregon, the country was suffering from a severe drought. Evidently Goose Lake, Harney Lake, and many other lakes in the region were dry at that time, for when Goose Lake dried up in 1925 for the first time in the memory of present settlers the ruts of a wagon road were clearly seen crossing the bed of the lake, indicating that in the 1840's there was no water in this lake to impede the progress of the early settlers. The tree-ring record indicates that this was undoubtedly the case, for the depression of growth rate during the 1840's and early 1850's was almost as severe as the present one.

From the year of discovery of Oregon in 1805, through the Lewis and Clark Expedition, during the period of early settlement and until the coming of the emigrants in 1840, the country was relatively wet according to the tree-ring record.

Carrying the record back for the previous five centuries, we can only speculate upon conditions through analogy. It seems fairly certain that the decade 1670 to 1680 was the wettest within the life span of the present living pine forests. The Seventeenth century was above normal in growth, the Sixteenth century as dry as the recent one, and the Fifteenth century was wet.

GROWTH CYCLES

So far the present study has been devoted mainly to obtaining an accurate measure of normal growth rates of the past centuries, and a measure of deviations from this normal, both as to amplitude and period of time covered by above-normal or below-normal departures. The pattern and amplitude of these growth fluctuations in the eastern Oregon pine region have now been determined back to 1500, with at least partial elimination of the effect of defoliations and fires, and back to 1268 on one area, without elimination of such effects.

It now becomes possible to analyze these fluctuations in terms of rhythmic harmonic cycles or as simple chance fluctuations. While this step in the analysis has been only briefly examined, as yet no evidence either for or against the existence of predictable cycles has been found. References to figures 7 and 8 indicate conclusively that over the 668-year period represented by the tree-ring record there has been so consistently downward trend of growth but rather a series of fluctuations above and below a constant average.

In analyzing the California precipitation record from 1850 to 1933 Gray (5) found a downward trend amounting to about 8 inches in 80 years. For the same period the tree-ring record shows close agreement with the precipitation record and shows a similar downward trend. But when the tree-ring record is extended back into earlier times this trend is reversed and finally becomes a straight line, representing a constant average.

Referring to figure 7 it is apparent that there have been alternate periods of good and poor growth. Some of the poor-growth periods are of short duration but of great intensity; others are long periods in which growth is only slightly below normal. The duration and intensity of good- and poor-growth periods are shown in table 1. Good-growth periods have ranged in length from 4 to 50 years, with an average of 13.6. Poor-growth periods have ranged from 3 to 28 years, with an average of 12.9 years. It is interesting to note that the cumulative deficiency of 627 percent for the period 1917 to 1936 greatly exceeds that of any other period. The fact that the cumulative deficiencies of growth are greater than the cumulative increases is probably due to the abnormal effect of frequent forest fires and defoliations, and the inherent potentialities of tree growth, for there is a much smaller range in the possible increase of tree growth above normal than in its possible decrease.

Combining duration and intensity, it is possible roughly to divide the more outstanding good- and poor-growth periods into three magnitudes, or degrees of importance. All important peaks of good growth are listed in table 2 and outstanding depressions in table 3. Taking into account the intervals between all the peaks tabulated, we find an average interval of 9.4 years between years of good growth and 7.8 years between years of poor growth. The range is from 2 to 33 years. Taking the intervals between peaks of second-degree magnitude, and between

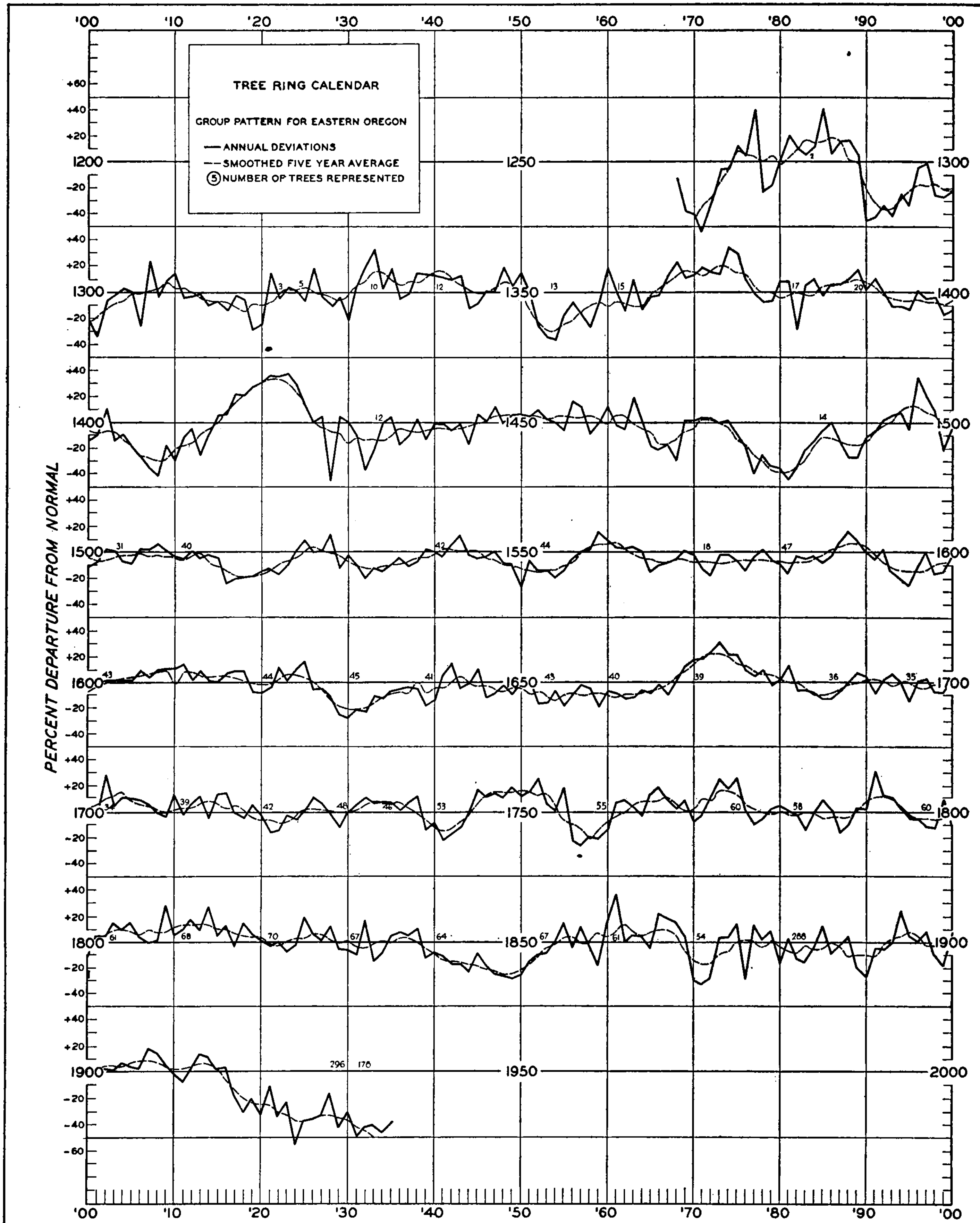

TREE RING CALENDAR
GROUP PATTERN FOR EASTERN OREGON
ANNUAL DEVIATIONS
SMOOTHED FIVE YEAR AVERAGE
NUMBER OF TREES REPRESENTED
PERCENT DEPARTURE FROM NORMAL
'00 '10 '20 '30 '40 '50 '60 '70 '80 '90 '00
1200 1250 1300
1300 1350 1400
1400 1450 1500
1500 1550 1600
1600 1650 1700
1700 1750 1800
1800 1850 1900
1900 1950 2000

FIGURE 7.

those of first and second degree, we find an average interval of 29.2 years between these peaks of good growth, and 15.0 years between the corresponding depressions. On comparing only the major peaks and depressions, we find an average interval of 55.4 years between years of best growth and 82.5 years between years of the worst depressions. However, the range of these intervals is from 19 to 219 years, so the regularity of occurrence is certainly not significant.

If cycles are of uniform length, a moving average equal in length to the length of the cycle or a multiple of it will produce a straight line. This method of analysis is applied in figure 8.[4] It will be noted that of the shorter cycles none tend to efface the fluctuations until we get to one of 45 years in length. With a 91-year period certain fluctuations are still evident, showing that the cyclic phenomena presented by tree rings are far from simple.

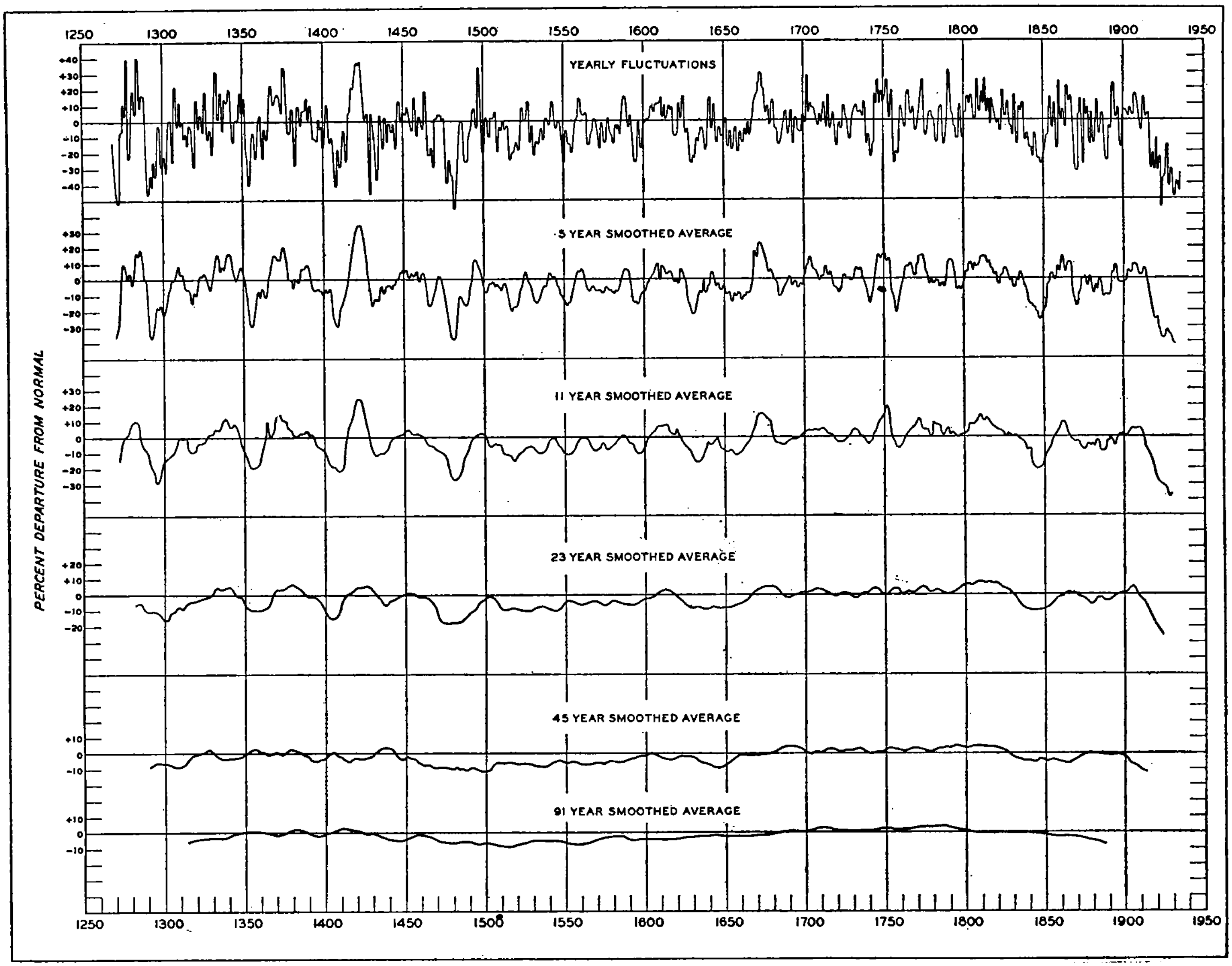


FIGURE 8.

As far as can be determined at the present time, there is nothing to indicate that the apparent cycles of growth are anything more than chance variations.

[4] The portion of these curves representing the earlier tree-ring record, particularly the period from 1268 to 1500, is not as yet based upon a sufficiently large number of trees to be conclusive.

TABLE 1.—*Durations of good and poor growth periods in eastern Oregon climatic zone as shown by annual growth of rings of Ponderosa pine*

Above normal				Below normal			
Dates	Duration	Cumulative increase	Best year	Dates	Duration	Cumulative deficiency	Worst year
	Years	*Percent*			*Years*	*Percent*	
1275–89	14	137	*1285*	1268–74	6	184	*1271*
1305–10	5	18	1307	1290–1304	14	343	*1290*
1321–26	5	13	1326	1311–20	9	93	1319
1331–51	20	161	*1333*	1327–30	3	36	1330
1367–77	10	155	*1374*	1352–66	14	210	*1353*
1386–92	6	45	1389	1378–85	7	11	1382
1415–27	12	*267*	1423	1393–1414	21	298	*1408*
1445–63	18	81	1463	1428–44	16	126	*1428*
1493–98	5	67	1496	1464–92	28	450	*1481*
1524–28	4	10	1528	1499–1523	24	210	*1516*
1540–47	7	3	1543	1529–39	10	109	1532
1557–64	7	37	1559	1548–56	8	119	1550
1587–92	5	95	1588	1565–86	21	148	1572
1602–25	23	128	*1611*	1593–1601	8	93	1595
1641–45	4	18	1642	1646–68	22	198	1659
1669–81	12	*180*	*1673*	1626–40	14	199	*1630*
1688–1738	50	111	*1702*	1682–87	5	47	1686
1745–55	10	*160*	*1752*	1739–44	5	76	1741
1761–76	15	145	1775	1756–60	4	102	1757
1789–94	5	•62	1791	1777–88	11	35	1787
1800–1838	38	*212*	*1814*	1795–99	4	22	1798
1854–69	15	111	1861	1839–53	14	254	*1849*
1984–1916	22	109	1894	1870–93	23	138	1890
				1917–36	19	627	*1931*
Average	13.6	101		Average	12.9	172	

TABLE 2.—*Important peaks of good growth in eastern Oregon climatic zone*

Date	Magnitude	Interval (in years) between: All peaks	Intermediate peaks[1] (and major peaks)	Major peaks only
1913	3d			
1907	3d	6		
1894	1st	13		
1885	3d	9		
1877	3d	8		
1875	3d	2		
1868	3d	7		
1866	2d	2	28	
1861	1st	5	5	33
1857	3d	4		
1855	3d	2		
1838	3d	17		
1832	3d	6		
1828	3d	4		
1825	3d	3		
1818	3d	7		
1814	1st	4	47	47
1809	2d	5	5	
1805	3d	4		
1803	3d	2		
1799	3d	4		
1791	2d	8	18	
1775	1st	16	16	39
1773	2d	2	2	
1766	3d	7		
1755	3d	11		
1752	1st	3	21	23
1749	3d	3		
1747	2d	2	5	
1745	3d	2		
1738	3d	7		
1732	3d	6		
1726	3d	6		
1716	3d	10		
1713	3d	3		
1702	1st	11	45	50

[1] In this column peaks of 3d degree magnitude are ignored and only the longer intervals between peaks of either first or second degree magnitude are listed.

TABLE 2.—*Important peaks of good growth in eastern Oregon climatic zone*—Continued

Date	Magnitude	Interval (in years) between: All peaks	Intermediate peaks[1] (and major peaks)	Major peaks only
1681	3d	21		
1673	1st	8	29	29
1645	3d	28		
1642	3d	3		
1625	3d	17		
1622	3d	3		
1611	2d	11	62	
1588	3d	23		
1559	3d	29		
1543	3d	16		
1528	3d	15		
1496	1st	32	115	177
1463	3d	33		
1460	3d	3		
1456	3d	4		
1447	3d	9		
1423	1st	24	73	73
1402	3d	21		
1389	3d	13		
1374	1st	15	49	49
1371	3d	3		
1368	2d	3	6	
1350	3d	18		
1348	3d	2		
1341	2d	7	27	
1335	3d	6		
1333	1st	2	8	41
1326	3d	7		
1321	3d	5		
1307	2d	14	26	
1285	1st	22	22	48
1281	2d	4	4	
1277	2d	4		
	Average	9.4	29.2	55.4

TABLE 3.—*Important depressions of poor growth in eastern Oregon climatic zone*

Date	Magnitude	Interval (in years) between: All depressions	Intermediate depressions[1] (and major depressions)	Major depressions only
1931	1st			
1929	2d	2	2	
1924	2d	5	5	
1918	3d	6		
1899	3d	19		
1890	2d	9	34	
1883	3d	7		
1880	3d	3		
1876	2d	4	14	
1871	2d	5	5	
1859	3d	12		
1849	1st	10	22	82
1844	2d	5		
1839	3d	5		
1833	3d	6		
1831	3d	2		
1800	3d	31		
1798	2d	2	51	
1787	3d	11		
1783	3d	4		
1777	3d	6		
1757	2d	20	41	
1741	2d	16	16	
1739	3d	2		
1729	3d	10		
1721	3d	8		
1695	3d	26		
1686	2d	9	55	
1667	3d	19		
1659	2d	8	27	
1655	2d	4	4	
1652	3d	3		
1646	3d	6		
1639	3d	7		
1633	2d	6	22	
1630	1st	3	3	219

[1] In this column peaks of 3d degree magnitude are ignored and only the longer intervals between peaks of either first or second degree magnitude are listed.

TABLE 3.—*Important depressions of poor growth in eastern Oregon climatic zone*—Continued

Date	Magnitude	Interval (in years) between: All depressions	Interval (in years) between: Intermediate depressions [1] (and major depressions)	Interval (in years) between: Major depressions only
1598	3d	32		
1595	2d	3	35	
1581	3d	14		
1576	3d	5		
1572	2d	4	23	
1565	3d	7		
1554	3d	11		
1550	2d	4	22	
1537	3d	13		
1532	2d	5	18	
1529	3d	3		
1522	3d	7		
1519	3d	3		
1516	1st	3	16	114
1509	3d	7		
1505	3d	4		
1499	2d	6	17	
1489	2d	10	10	
1481	1st	8	8	35
1477	2d	4	4	
1468	2d	9	9	
1465	2d	3	3	
1444	3d	21		
1439	3d	5		
1436	3d	3		
1432	2d	4	33	
1428	2d	4	4	
1413	2d	15	15	

Date	Magnitude	Interval (in years) between: All depressions	Interval (in years) between: Intermediate depressions [1] (and major depressions)	Interval (in years) between: Major depressions only
1410	2d	3	3	
1408	1st	2	2	73
1399	3d	9		
1395	3d	4		
1382	2d	13	26	
1362	2d	20	20	
1358	2d	4	4	
1353	1st	5	5	55
1344	3d	9		
1330	2d	14	23	
1328	3d	2		
1319	2d	9	11	
1316	3d	3		
1314	3d	2		
1306	2d	8	13	
1301	2d	5	5	
1299	2d	2	2	
1295	2d	4	4	
1293	2d	2	2	
1290	1st	3	3	63
1278	2d	12	12	
1271	1st	7	7	19
	Average	7.8	15.0	82.5

[1] In this column depressions of 3rd degree magnitude are ignored and only the longer intervals between depressions of either first or second degree magnitude are listed.

SUMMARY

Through a study of tree rings in eastern Oregon it has been possible to arrive at an index of the ancient climatic history back to the year 1268. Micrometer measurements of annual radial growth of 1,240 ponderosa pines taken in 44 different localities of eastern Oregon have given a sound statistical basis for this study.

It was discovered that a broad climatic influence has uniformly dominated the growth pattern over a wide area of eastern Oregon and northern California. Any sample of ten selected trees was sufficient to show the same fluctuations of good and poor growth and outstandingly good and poor years, except for short periods where local influences such as fires, windfalls, or defoliations obscured the general pattern.

The boundaries of this climatic zone are not as yet well defined, but in its broader aspects it probably takes in all of the northern Great Basin region, from the Cascades to the Rocky Mountains, including the drainages of the Pitt, Klamath, Deschutes, Snake, and Columbia Rivers. Uniformity of tree-ring pattern has been found in this study from Alturas, Calif., north to the Metolius River, and from the summit of the Cascades eastward to the southern portion of the Blue Mountain Range. Meyer (**10**) has shown that the same general tendencies exist throughout the Blue Mountains and northward throughout eastern Washington. Since tree-ring patterns reflect such general agreement over broad regions, they are undoubtedly good indicators of such weather conditions as affect plant growth.

A significant correlation was found between seasonal precipitation and tree growth. On comparing the cumulative effect of 2 years of precipitation with tree-ring growth, a highly significant correlation ratio was found. By taking into account the distribution of rainfall through the year and the cumulative moisture through several seasons, an even higher degree of correlation may undoubtedly be found. The width of each annual ring represents a summation and net effect of all the factors influencing tree growth. Thus the tree rings become a better measure of good or poor periods for plant growth than can possibly be obtained through any number of weather-recording instruments.

The tree-ring record for eastern Oregon indicates that during the past 650 years there has been no general trend toward drier or wetter years. If such a trend exists, the change over a 650-year period is so slight that it is obscured by other fluctuations. Average growth for the 20-year period 1900 to 1919 was found to be identical with the average growth during the past 650 years. There have been important fluctuations in growth throughout the entire period, however, with alternate periods of good and poor growth.

All tree-ring measurements agree in showing that a very critical subnormal growth period has existed since 1917. This slowing down of the growth rate is undoubtedly the result of deficient precipitation and lowered water tables. As compared with other drought periods, the present one is the most severe and critical that the present forests have experienced in the last 650 years. Several other periods have exceeded the present one in duration of subnormal growth, but none has approached it for severity. Growth in 1931, the poorest year, was 68 percent below normal.

The tree-ring record indicates that the last period of 19 years of drought and poor tree growth represents a major fluctuation in a broad climatic cycle which eventually will be followed by a wet period of better than average growth. No rhythmic cycle has been found which would permit a prediction as to when this reversal in trend will occur.

LITERATURE CITED

(**1**) Antevs, Ernst. The Big Tree as a Climatic Measure. Quart. Climates, Carnegie Inst. Wash. Pub. No. 352, pp. 115–153, illus. 1925.

(**2**) Craighead, F. C. Abnormalities in Annual Rings Resulting from Fires. Jour. Forestry. 25 (7): 840–842, illus. 1927.

(**3**) Douglass, A. E. Climatic Cycles and Tree-Growth. Carnegie Inst. Wash. Pub. No. 289, vol. 1, 127 pp., illus. 1919.

(**4**) ——— Climatic Cycles and Tree-Growth. Carnegie Inst. Wash. Pub. 289, vol. 2, 166 pp., illus. 1928.

(**5**) Gray, Leslie G. Long-period Fluctuations of Some Meteorological Elements in Relation to California Forest-fire Problems. Monthly Weather Review 62 (7): 231–235, illus. 1934.

(**6**) Henshaw, F. F., and Dean, H. J. Surface Water Supply of Oregon 1878–1910. U. S. Geol. Surv. Water Supply Paper No. 370, 829 pp. 1915.

(**7**) Huntington, Ellsworth. The Climatic Factor as Illustrated in Arid America. Carnegie Inst. Wash., Pub. No. 192, 340 pp., illus. 1914.

(**8**) ——— Tree Growth and Climatic Interpretations. Carnegie Inst. Wash. Pub. No. 352, pp. 155–204, illus. 1925.

(**9**) Marshall, Robert. Influence of Precipitation Cycles on Forestry. Jour. Forestry. 25 (4): 415–429, illus. 1927.

(**10**) Meyer, Walter H. Growth in Selectively Cut Ponderosa Pine Forests of the Pacific Northwest. U. S. Dept. Agr. Tech. Bull. 407, 64 pp., illus. 1934.

(**11**) Swaine, J. M., Craighead, F. C., and Bailey, I. W. Studies on the Spruce Budworm (Cacoecia fumiferana Clem.). Canada Dept. Agr. Bull. 37, n. s., 91 pp., illus. 1924.

(**12**) U. S. Forest Service Library. Tree Rings, a Bibliography. U. S. Dept. Agr., For. Serv. Nov. 1, 1935.