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TREE GROWTH AND RAINFALL—A STUDY OF CORRELATION AND METHODS[1]

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The purpose of the present study is to test critically the covariation of tree growth and rainfall—tree growth as measured by the thicknesses of growth layers on increment cores. Three desiderata were the bases of the study. First, an altitudinal zone was to be selected above the region of violent fluctuations of soil moisture but below the region of excessive accumulation and possible carry-over from season to season. This would avoid the forest-border zone where temporary depletion of soil moisture during the growing season could bring growth to a halt temporarily and possibly cause multiplicity of growth layers during that season.

Second, the number of trees sampled was to be held to a minimum in order to avoid excessive duplication of record and to avoid inclusion of trees from habitats so diverse that the merged record would become blurred. The number, however, was to be sufficiently large to absorb any differences in relative growth-layer thicknesses from tree to tree due to slight variations in site factors local to the individual trees.

Third, the trees were to be selected *in the field* on the basis of ecologic principles, after which each core, unless marred by accident or disease, would enter into the group record whether or not the relative thicknesses of its growth layers closely agreed with those of the other cores.

The writer is aware[2] of the shortcomings and the possible misrepresentation inherent in the use of rain-gauge records taken some

[1] Grateful acknowledgment is made to Dr. A. Wetmore and to the Smithsonian Institution, which supported the entire project. To Dr. R. Sidwell gratitude is due for courtesies extended in the field. Herbert Gross, of Macalester College, was of much assistance not only in the preparation of the figures but also in the lively interest he evinced in the problem. Rainfall data from 1931 to 1946 were obligingly supplied by the Weather Bureau office in Albuquerque, N. Mex.

[2] Bot. Rev., vol. 7, pp. 649-713, 1941; Journ. Forestry, vol. 40, pp. 614-620, 1942.

miles from the site of the trees, in the use of a single radius to represent the entire volume growth of a tree, and in the emphasis on a single growth factor. However, if significant results can be obtained, in spite of handicaps, by proper selection of trees from the correct habitat, a critical test is highly worth while in view of the simplicity and directness of method. Heretofore, many of the correlations [3] between tree growth and rainfall have been discouraging unless the data were smoothed to an extent that direct responses were masked and only general trends revealed.

LOCATION AND TREE DESCRIPTION

The increment cores came from trees that grew near and on Holman Pass, in the Sangre de Cristo Range of north-central New Mexico, about 41 miles by road or about 35.5 miles airline north-northwest from Las Vegas (fig. 1). In so far as the life zones were concerned, the collection extended upward from mid-Transition into the lower portion of the Canadian.

All the trees sampled were dominant or codominant and in the timber stage of development.[4] On the whole, the ponderosa pines were slightly more mature than the other species. Neighboring trees not sampled were sufficiently distant to avoid undue competitive influence as far as site factors were concerned. Furthermore, the locations were chosen so that abnormal drainage toward or away from the trees was at a minimum. The soils were in no sense tight or lacking in aeration.

In all, nine trees were sampled and designated by the initials HPC, for Holman Pass Collection. The trees from which samples HPC 1 to 4 were taken grew on a nearly flat area a mile southeast of the Pass at an elevation of 9,000 feet. All four were within 150 yards of one another. The black soil contained numerous pebbles and boulders. Cores HPC 5 and 6 came from trees that grew on the Pass itself at an elevation of 9,450 feet. In spite of the fact that the site was on top of the actual pass, the trees stood in the middle of a broad, essentially flat area. The soil was derived from shale and sandstone bedrock, fragments of which remained. Between 7 and 8 miles west of the Pass and down Rio Pueblo Canyon the location of

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[3] Many of these are listed and discussed in Bot. Rev., vol. 7, pp. 687-698, 705-713, 1941.

[4] Following the classification of James W. Toumey and Clarence F. Korstian, Foundations of silviculture upon an ecological basis, p. 268, 1937. New York.

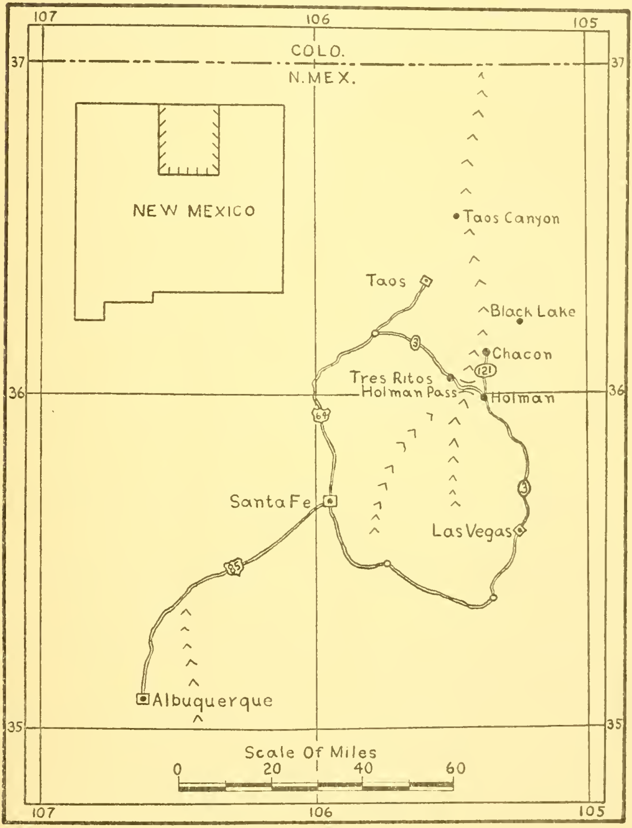

FIG. 1.—General location map for Holman Pass collection and rainfall stations.

the trees for HPC 7 to 9 was chosen at an elevation of approximately 8,000 feet. Here ponderosa pines were more mature and more dominant than at the other two sites. The trees grew on top of a very gently sloping terrace whose edge stood 20 feet above the stream channel. Toward the south the terrace top rose gently to a steeper, heavily wooded slope over 400 feet away. The soil, granitic in composition, contained numerous pebbles and boulders.

Individual tree and core descriptions are given below in concise form:

HPC 1. Ponderosa pine (*Pinus ponderosa*). 14 inches DBH. Average thickness of growth layers 1.61 mm. Range 1850-1946. Growth-layer sequence variable. Average departure from mean 0.58 mm., or 36 percent.

HPC 2. Ponderosa pine. 12 inches DBH. Distant 100 yards from HPC 1. Average thickness of growth layers 1.86 mm. Range 1850-1946. Growth-layer sequence variable. Average departure from the mean 0.54 mm., or 29 percent.

HPC 3. Foxtail pine (*P. aristata*). 24 inches DBH. Midway between HPC 1 and 2. Average width of growth layers 1.32 mm. Range 1770-1946. Growth-layer sequence variable. Average departure from mean 0.51 mm., or 39 percent.

HPC 4. White fir (*Abies concolor*). 15 inches DBH. Wettest location for group east of Pass; slight drainage toward tree. Average thickness of growth layers 2.93 mm., corrected to average 1.46 mm. Range 1880-1946. Growth-layer sequence only fairly variable. Average departure from mean 0.57 mm., or 39 percent.

HPC 5. Douglas fir (*Pseudotsuga taxifolia*). 15 inches DBH. Average width of growth layers 1.16 mm. Range 1810-1946. Growth-layer sequence variable. Average departure from mean 0.45 mm., or 39 percent.

HPC 6. Foxtail pine. 14 inches DBH. Distant 20 yards from HPC 5. Average width of growth layers 1.38 mm. Range 1820-1946. Growth-layer sequence uniform. Average departure from mean 0.36 mm., or 26 percent.

HPC 7. Ponderosa pine. 23 inches DBH. Distant 70 feet from edge of terrace above stream. Average thickness of growth layers 1.91 mm. Range 1830-1946. Growth-layer sequence uniform and rhythmic. Average departure from mean 0.52 mm., or 27 percent.

HPC 8. Ponderosa pine. 13 inches DBH. Distant 20 feet from edge of terrace above stream. Least mature. Ground-water relations make site better drained than that of HPC 7. Average thickness of growth layers 3.74 mm.; corrected to average 1.46 mm. Range 1897-1946. Growth-layer sequence only fairly variable. Average departure from mean 0.53 mm., or 36 percent.

HPC 9. Ponderosa pine. 19 inches DBH. Midway between terrace edge and base of steep slope. Wettest location for trees west of Pass. Average thickness of growth layers 2.71 mm.; corrected to average 1.46 mm. Range 1857-1946. Growth-layer sequence variable. Average departure from mean 0.44 mm., or 30 percent.

The designations variable, fairly variable, or uniform were assigned directly from the wood by visual judgment alone.

METHODS

Because all cores consisted of sound wood, none was discarded. Furthermore, because site factors such as light, drainage, slope, ground-water relations, and competition were evaluated on the spot as closely as possible, no reason existed immediately after the collection had been made for the rejection of any specimen. The collection was considered a normal representation of the site factors at the three chosen localities even though the sequences differed to a great extent in variability and average growth-layer thicknesses. At the time the cores were taken there seemed to be no reason why different species should show differences except those due to slight variations of site factors peculiar to each tree. Such a factor as soil aeration had to be judged by soil texture and composition and visible soil-water relations. There was no opportunity for analyses or measurements. Indeed, this problem of selection in the field, without measurements, was of great importance: could local site factors be judged with sufficient accuracy to demand the inclusion of each core as a representative specimen in the general collection? If so, choice in the field, based on ecologic principles, would be a dependable method of selection whose integrity could be questioned only on field evidence or its derivatives.

Treatment of the wood.—The cores and the growth layers they contained were subjected to the following procedure to prepare them for correlation among themselves and with rainfall.

1. The cores were glued in a groove sunk into the curved side of half-inch half-round and "shaved" by razor sufficiently to expose the growth layers clearly.[5]

2. Beginning with the increment for 1946, which was complete because of the time of sampling, October 5, 1946, the growth layers were counted inward and dated on the assumption that each sharply bounded layer represented a year.

3. Skeleton [6] plots were set up on coordinate paper, each ordinate representing a year. If a sharply bounded growth layer was decidedly thinner than its immediate neighbors an ink line was drawn on the ordinate appropriate to its date, the height of the line being inversely proportional to the thickness of the growth layer. The resultant skeleton plots and the master plot derived from them are shown on

[5] Principles and methods of tree-ring analysis. Carnegie Institution of Washington Publ. No. 486, p. 6, 1937.

[6] Ibid., pp. 14-16.

figure 2. Thus, the wood specimens were cross-dated with one another; that is, growth layers taken to be equivalent in time were set in line with one another.

4. The thicknesses of the growth layers were measured to hundredths of a millimeter by means of a measuring microscope. These measurements are called raw data in millimeters.

5. The average thicknesses of the growth layers on the sequences HPC 4, 8, and 9 were corrected downward to approximate the averages of the other sequences. Otherwise, if a sequence of high average thickness were one of several merged into a group, its high average would unduly influence the values in the group.

6. The raw data in millimeters of each sequence were changed into percentages of the sequence mean in order to establish an identity of units and an identity of base line between tree growth and rainfall.

7. The raw percentages were smoothed by the formula

$$\frac{a+2b+c}{4}.$$

8. Various sequences were merged into groups and smoothed.

Groups.—The nine sequences divided themselves geographically into three groups—east of the Pass, on the Pass, and west of the Pass. Nevertheless, other groupings were arranged in order to make the tests not only as critical but also as thorough as possible so far as comparison with rainfall was concerned.

The following groups were set up:

Group 1 (G 1). Trees 1-5, 8, and 9. Variable and fairly variable sequences only.

Group 2 (G 2). Trees 1-3, 5, and 9. Variable sequences only.

Group 3 (G 3). Trees 1-3, and 9. Most variable sequences based upon a visual study of the wood samples. Douglas fir omitted.

Group 4 (G 4). Trees 1-4. East of the Pass.

Group 5 (G 5). Trees 5 and 6. On the Pass.

Group 6 (G 6). Trees 8 and 9. West of the Pass, exclusive of the tree whose sequence is uniform.

Group 7 (G 7). Trees 1-9. All trees.

Group 8 (G 8). Trees 1, 2, and 9. Ponderosa pines with variable sequences.

Group 9 (G 9). Trees 7-9. West of Pass.

Group 10 (G 10). Trees 1-3, and 7. From the drier sites.

Group 11 (G 11). Trees 4-6, and 9. From the wetter sites.

The primary groups are numbers 4, 5, 9, 10, 11, and 7.

Selection of rainfall stations and the treatment of data.—A mountainous country permits little choice in the selection of rainfall stations. Fortunately, one station, Chacon, lies approximately 7 miles, airline

FIG. 2.—Skeleton plots of the nine trees, HPC 1 to 9, and their synthesis into a master plot. The longer the inked line is, the narrower the growth layer. "DBL" means double and "T" means thick. A wavy line includes a group of narrow growth layers. A dot inside of a circle rests on the central growth layer of the tree.

distance, north-northeast of Holman Pass. Unfortunately, its record is short compared with that of Santa Fe, distant 40 miles to the southwest from the Pass. Figure 1 shows the general relations.

Pertinent data in regard to the stations follow:

Chacon: 7 miles north-northeast, east of divide, in the mountains. Elevation 8,510 feet. Length of continuous record 1909-1941.

Black Lake: 19 miles north-northeast, east of the divide, in the mountains. Elevation 8,348 feet. Length of continuous record 1909-1946.

Taos: 24 miles north-northwest, west of mountains. Elevation 6,983 feet. Length of continuous record 1901-1945.

Taos Canyon: 32 miles north, west of divide, in the mountains. Elevation 8,959 feet. Length of continuous record 1909-1941.

Las Vegas: 35.5 miles southeast by south, east of mountains. Elevation 6,400 feet. Length of continuous record 1887-1943.

Santa Fe: 40 miles southwest, west of mountains. Elevation 7,013 feet. Length of continuous record 1850-1944.

Albuquerque: 101 miles southwest, west of Sandia Mountains. Elevation 5,196 feet. Length of continuous record 1892-1946; partial record 1850-1861, 1863-1867, 1878-1879, and 1889-1890.

Month-intervals chosen for the correlative tests between rainfall and tree growth were:

November-May	May-July
January-May	May-August
January-August	April
March-April	May
March-June	June
March-July	July
May-June	August

Rainfall data were then subjected to the treatment here outlined:

1. Addition of monthly rainfall totals in order to obtain the rainfall of the intervals listed above. These sums gave raw data in inches.

2. The raw data of each interval in inches were changed into percentages of its own mean in order to establish an identity of units and an identity of base line between rainfall and tree growth.

3. The raw percentages were smoothed by the formula

$$\frac{a+2b+c}{4}.$$

4. The raw percentages for the stations Chacon, Black Lake, Las Vegas, and Taos Canyon were merged into a group record for the intervals January-August and March-July. These stations were chosen because their interval averages were nearly the same.

Method of correlation.—Because the purpose of the study was the correlation of rainfall variation with growth variations and because the basic data constitute a continuous time series, the trend method[7] of correlation has been used. This method, in the coefficient *t*, gives a measure of parallel variation combined with amount of that variation. If *t* equals 1.00, the trends in both sets of data, tree growth and rainfall, are wholly parallel or in the same direction; if *t* equals −1.00, the trends are wholly opposite. Tests were constantly made to detect the undue influence of one or two entries should such be present. The ratios of opposite to parallel trends are included in the tables with the trend coefficients. With the trend method of correlation, secular trends or long-period fluctuations did not have to be eliminated. These are ignored for the present especially because the history of the stand and the histories of the individual trees are unknown except as revealed on the wood itself.

The quality of the correlations between tree growth and rainfall on identical years was tested by application of a one-year lag and by reversal of data. In all cases, the correlations dropped to a value of no significance.

Although the purpose of the work was the comparison of year-to-year variations, correlations involving smoothed data (second intermediate) were nevertheless carried through the main part of the calculations. The majority of the coefficients did not increase significantly over those using raw data; in fact, many decreased.

The initial questions, then, to be answered by use of the trend method, were: If rainfall increases or decreases, does tree growth, as shown by such simply obtained samples as increment cores, increase or decrease in like direction? To which rainfall interval does the tree growth correspond? As the work progressed new problems came to light and soon carried the study far beyond the original objectives.

STUDY OF THE GROWTH LAYERS

Cross-dating.—This process consists of establishing the identity in time of growth layers on different sequences by matching narrow growth layers, in particular, from one specimen to another. Judgment as to narrowness depends upon visual comparison with immediately adjacent growth layers and should not be confused with or substituted for mathematical expressions. Obviously, cross-dating can possess various degrees of excellence. What constitutes reliable cross-dating is a moot point and may, perhaps, be largely dependent

[7] A rapid method of correlation for continuous time series. Amer. Journ. Sci., vol. 240, pp. 437-442, 1942.

upon the individual investigator. Here, it is important to know if cross-dating is a prerequisite to the merging of sequences for correlation purposes.

Figure 2 shows the so-called skeleton plots for HPC 1 to 9 and a master plot made by a synthesis of the nine. The heights of the inked lines bear an inverse ratio to the widths of the growth layers on the wood as judged by the eye. No actual measurements enter the skeleton plots. In order to judge the quality of the relationships, the above figure should be compared with figure 3, which shows excellent cross-dating from a forest-border area. The conclusion is obvious: cross-dating as exhibited by the Holman Pass specimens is of remarkably poor quality. One is tempted to say it does not exist at all, for, if the dates were entirely unknown and within a range of several centuries, one would have difficulty in convincing others that the sequences match growth layer for growth layer as they stand. In the present case the validity of the cross-dating, or the only assurance that the growth layers grew on the dates assigned to them on the skeleton plots, rests on two circumstances: (1) the narrowness of the growth layers designated 1880 and 1893 and (2) the probability that the soil moisture in the zone where the trees grew was sufficiently adequate to prevent a temporary halt in growth during any one growing season.

A detailed comparison of the growth layers on all specimens for each date in succession (fig. 2) brings out a lack of correspondence that appears to emphasize a certain degree of individuality in the site factors at each tree.

An analysis of figure 2 was made, and the results were arranged in table 1. The record covers 116 years. Out of this length of record only two cases exist, the growth layers designated 1880 and 1893, wherein the growth layers are notably narrow on the eight specimens bearing them. Two cases, 1836 and 1934, could perhaps be classed with the previous two because the one growth layer that does not conform on each exists on a so-called uniform sequence, one on HPC 7 and the other on HPC 6. Entries in table 1 wherein no narrow growth layer exists on any one of the specimens number 55 cases. With the number of specimens in the count disregarded, there are 22 cases where one growth layer is atypical, 23 cases where two growth layers are atypical, 12 where three are atypical, and 2 where four are atypical. For more than half the years the sequences are from 11 to 50 percent out of agreement with one another.

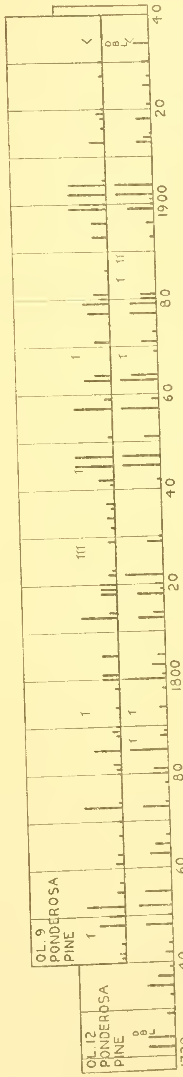

FIG. 3.—Matched skeleton plots showing excellent cross-dating. These represent trees that grew at the forest border in northern Arizona. They should be compared with the poor cross-dating shown on figure 2.

TABLE 1.—*Incidence of growth-layer type*

Analysis of figure 2

Year	Narrow	Av.	Thick	Dbl.	Year	Narrow	Av.	Thick	Dbl.	Year	Narrow	Av.	Thick	Dbl.
1831....	0	4			1871....	4	3			1911....	0	8	1	
	0	4				0	7				0	8	1	
	0	4				4	3				2	5	2	
	0	4				0	7				0	7	2	
	0	4				1	7				0	9		
	3	1		1		0	8				0	8	1	
	2	2				0	8				4	5		
	0	5				0	7	1			3	6		
	0	5		1		0	8				0	9		
	0	5				8	0				1	7	1	1
1841....	0	5			1881....	1	7			1921....	0	8	1	
	1	4				2	6		1		7	2		1
	2	4				0	8		1		2	7		
	1	5				0	7	1			0	9		
	1	5				0	8				7	2		1
	1	5				1	7				0	9		
	1	5				0	8				2	7		1
	0	6		1		0	8				3	6		
	0	6				0	8		1		0	9		
	0	6				0	8				2	7		1
1851....	4	2			1891....	1	7			1931....	1	8		
	2	4				0	8				0	9		
	3	3		1		8	0		1		2	7		
	1	5				0	8				8	1		
	1	5				0	8				0	9		
	0	6				5	3		3		5	4		
	1	6				2	7				1	8		
	0	7				0	7	2			1	8		
	3	4				7	2		1		2	7		1
	2	5				6	3				2	7		
1861....	5	2			1901....	0	8	1		1941....	0	7	2	1
	1	6				3	5	1	3		0	9		
	2	5				0	8	1			3	6		
	1	6				7	2				0	9		
	1	6				2	6	1			2	7		
	0	7		1		0	8	1			6	2	1	
	0	7				0	7	2						
	0	7		1		1	8							
	0	7				0	9							
	3	4				3	6							

NOTES:

1836—an average growth layer on HPC 7, a uniform sequence.
1934—an average growth layer on HPC 6, a uniform sequence.

Correlation.—Because of the poor quality of the cross-dating and because of the desire to compare the sequences each with the other based upon precise measurements, the sequences were subjected to statistical correlation. Table 2 gives the trend coefficients and the ratios of opposed to parallel trends for certain trees and certain groups. The bases of selection are evident from the captions in the table.

A comparison of the averages for uniform and variable sequences shows that the uniform have a considerably higher trend coefficient, whereas the variable have a very slightly lower trend ratio. If anything, the uniform have a slight advantage.

TABLE 2.—*Holman Pass collection*

Trend coefficients and ratios of opposed trends

	1850 to 1897		1898 to 1941	
Uniform sequences				
4 vs. 6			0.82	(0.36)
4 vs. 7			0.83	(0.41)
6 vs. 7	0.66	(0.38)	0.57	(0.36)
4 vs. 8			0.88	(0.27)
Variable sequences				
1 vs. 5	0.36	(0.53)	0.73	(0.20)
1 vs. 9	0.32	(0.42)	0.81	(0.23)
5 vs. 9	0.26	(0.42)	0.71	(0.25)
Intergroup				
4 vs. 5	0.90	(0.32)	0.88	(0.20)
4 vs. 9	0.72	(0.36)	0.87	(0.23)
5 vs. 9	0.52	(0.49)	0.76	(0.27)
10 vs. 11	0.94	(0.21)	0.97	(0.14)

	1850 to 1897		1898 to 1941	
Trees east of Pass				
1 vs. 2	0.62	(0.40)	0.90	(0.23)
1 vs. 3	0.86	(0.34)	0.94	(0.20)
1 vs. 4			0.79	(0.32)
2 vs. 3	0.85	(0.30)	0.97	(0.11)
2 vs. 4			0.83	(0.23)
3 vs. 4			0.96	(0.25)
Trees on Pass				
5 vs. 6	0.79	(0.34)	0.91	(0.20)
Trees west of Pass				
7 vs. 8			0.87	(0.23)
7 vs. 9	0.72	(0.40)	0.63	(0.30)
8 vs. 9			0.70	(0.30)

Intragroup comparisons east of the Pass, on the Pass, and west of the Pass indicate on the whole that correlations are distinctly higher between trees within their own groups than between trees in different groups. If the groups are averaged, this higher correlation is shown even more clearly. Hence, trees grouped together appear to correlate more closely than those rather widely separated.

The matter of distance merits further attention. If the trend ratios of the trees in table 2 are arranged in order of distance within the group, table 3 results. Among the species, PP means ponderosa pine, FP foxtail pine, WF white fir, and DF Douglas fir. The interval of years in either case ends on 1941. Table 3 is divided into three groups: the first comprising trees east of the Pass, the second on the Pass, and the third west of the Pass.

In general, agreement declines with increasing distance, a distance measured in feet. Site factors at the surface appear to the eye to be nearly identical among the trees of any one group, but apparently the factors do change within short distances in spite of appearances. Proximity outweighs difference of species as well as presence or absence of variability. Factors present at the immediate location of the individual tree, or what may be called microsite factors, appear

Table 3.—*Holman Pass collection*

Ratios of opposed trends

Distance apart	Trees	Species	1898-1941	Total sequence
150 feet	2 vs. 3	PP vs. FP		
	1 vs. 3	PP vs. FP	0.18	0.24
	2 vs. 4	PP vs. WF		
300	1 vs. 2	PP vs. PP	0.24	0.29
	3 vs. 4	FP vs. WF		
450	1 vs. 4	PP vs. WF	0.32	0.34
60 (ca.)	5 vs. 6	DF vs. FP	0.20	0.27
50	7 vs. 8	PP vs. PP	0.23	
230	7 vs. 9	PP vs. PP	0.30	
	8 vs. 9	PP vs. PP		

to exert a strong measure of control on tree growth. That trees separated by a distance of a mile or more do show a parallel agreement of variation in a majority of years indicates the influence of a gross factor uniformly variable within limits over the area. However, when it is remembered that the trend between two growth layers on one tree compared with the trend between two growth layers of the same date on another tree, no matter how remote, can vary only in two directions, parallel or opposite, some allowance must be made for accidental similarities. The same principle, of course, holds true where visual comparisons are made in so-called cross-dating because in the consideration of two growth layers of same date in different trees one growth layer can only be thinner than, thicker than, or of the same thickness as, the other growth layer.

Correlations between groups (table 2) east of Pass, on Pass, and west of Pass are only fair. They show a mixed influence of site and distance. Groups 4 and 5 are relatively close together but have dissimilar sites—they have the highest correlation; groups 4 and 9 are far apart but have somewhat similar sites—they have correlation of intermediate value; and groups 5 and 9 are far apart and have very dissimilar sites—they have the lowest correlation.

Table 2 suggests something much more surprising than the dominant influence of local site factors. The correlation among different trees and among different groups as shown not only by the trend coefficients but also by the trend ratios are distinctly less for the period 1850-1897 than for the period 1898-1941. In fact, a few of the trends, and trend ratios, are of such poor quality as to indicate little relationship. Growth factors from 1850-1897 apparently must have had a localized variability which to a certain extent became less localized after 1897.

For further comparisons among the trees the trends were plotted for each tree against every other tree for the total years of record. A comparison of ponderosa pine with other ponderosa pines, of ponderosa with other species, and of other species among themselves shows that species has no bearing upon the trend agreements. A comparison of sequence types, such as variable with variable, variable with uniform, and the like, shows that the type of sequence being correlated is not an important factor. In general terms, however, the closer two trees are together the greater the number of parallel trends. During the period of 44 years from 1898 to 1941, where all nine trees are in the record, there are 15 years with parallel trends. Agreements are concentrated in the 10-year period, 1920-1929, which has 6 parallel trends. Back of 1898, the period of 48 years adds only 9 parallel trends to the 15 of the later period in spite of the fact that the record of the earlier period contains from one to three fewer trees. The striking lack of agreement prior to 1898 appears to fit in with the lack of correlation mentioned in the paragraph above. Again it seems that the microsite factors may have contrasted more acutely from tree to tree or that an over-all factor exerting a general influence on tree growth may have been more areally variable than later.

Growth-layer characteristics.—Table 4 shows the average of year-to-year variations of growth-layer thicknesses on single tree sequences and on three groups. These figures are the measured equivalents of the visual values embodied in the terms variable, fairly variable, and uniform. In the main, the numerical results militate against judgment by eye. Tree HPC 5, for instance, was judged variable and HPC 6 uniform; yet both have nearly the same average variation. However, greater consistency is shown by groupings: for the period, 1898-1941, the average of the variable sequences is 0.36, of the fairly variable 0.32, and of the uniform 0.28.

Table 4 emphasizes the importance of location, not species, as the apparent determinant of average variation. For instance, trees HPC 3 and 6 are both foxtail pines and yet have variations of 0.37 and 0.24, respectively (0.43 and 0.21 for 1898-1941), the higher value existing in the drier location. It is true that the ponderosa pines have higher variations in general than the other species but HPC 3, a foxtail pine, grew between HPC 1 and 2 and has even a slightly higher average variation.

TABLE 4.—*Holman Pass collection*

Average year-to-year variation

		—— to 1897	1898 to 1941	Entire
HPC 1........	1850–	0.22	0.40	0.30
2........	1850–	0.35	0.41	0.38
3........	1850–	0.31	0.43	0.37
4........	1880–	0.36	0.28	0.30
5........	1850–	0.29	0.19	0.25
6........	1850–	0.27	0.21	0.24
7........	1850–	0.18	0.35	0.26
9........	1857–	0.40	0.39	0.40

	1850 to 1897	1898 to 1941
G 10........	0.26	0.40
11........	0.38	0.27
7........	0.21	0.27

All trees from the wetter locations (group 11) had higher average variations for the period 1850-1897 than they did for the period 1898-1941. In contrast, the trees in the drier locations (group 10) had lower average variations in the earlier period.

Tables 5 and 6 giving average growth-layer thicknesses and average departures were prepared even though definitive results were not expected because secular trend and long-period fluctuations had not been eliminated. In table 5, group 10 shows an increase and group 11 a decrease of average growth-layer thicknesses from the period 1850-

1897 to that of 1898-1941. The individual trees of group 10 are not consistent among themselves in that HPC 1 and 3 increase decidedly, HPC 2 increases very slightly, and HPC 7 decreases. All trees in group 11 are consistent except for HPC 6 which decreases very slightly. Thus, four trees decrease, two remain practically unchanged, and two increase their average thicknesses for the period 1897-1941 contrasted with that of 1850-1897. Group 7 reflects these influences.

TABLE 5—*Holman Pass collection*

Average growth-layer thicknesses

		——— to 1897	1898 to 1941		1850 to 1897	1898 to 1941
HPC 1........	1850–	1.28	1.82	G 10........	1.53	1.70
2........	1850–	1.87	1.88	11........	2.26	1.96
3........	1850–	1.01	1.23	7........	1.90	1.83
4........	1880–	3.50	2.95			
5........	1850–	1.18	0.79			
6........	1850–	1.52	1.51			
7........	1850–	1.96	1.86			
9........	1861–	2.85	2.61			

TABLE 6.—*Holman Pass collection*

Average departures

		——— to 1897	1898 to 1941		1850 to 1897	1898 to 1941
HPC 1........	1850–	0.31	0.36	G 10........	0.32	0.36
2........	1850–	0.32	0.27	11........	0.34	0.30
3........	1850–	0.45	0.42	7........	0.18	0.20
4........	1880–	0.37	0.36			
5........	1850–	0.39	0.34			
6........	1850–	0.27	0.21			
7........	1850–	0.19	0.38			
9........	1861–	0.31	0.28			

In Table 6, group 10 shows an increase and group 11 a decrease of average departures from the period 1850-1897 to that of 1898-1941. All trees of group 11 are consistent among themselves in the decrease from the earlier to the later period. This is not true for the trees of group 10. Two of them, HPC 2 and 3, actually showed a decrease of average departures and thus conformed with the wet-site trees of group 11. In other words, trees HPC 1 and 7 do not conform with the remaining six trees, yet their influence is sufficiently great to determine the relative values as shown for groups 7 and 10 in table 6.

The data in table 7 were calculated in an attempt to obtain a measure of excess variation over normal. From the earliest to the latest periods shown, HPC 1, 2, 3, and 4 show a rise and decline; HPC 5, 6, and 9 show a general decline; and HPC 7 shows a general rise of values. Six of the trees, but not including HPC 1, have lower values for 1910-1941 than for 1850-1897. As in the case of average departures, it is HPC 1 and 7 which do not conform. In spite of their influence, group 7 shows a slight but progressive decline from the earliest to the latest period. If HPC 1 and 7 are eliminated from group 7, giving group 7 (restricted), the decline becomes more decided.

Table 7.—*Holman Pass collection*

Average departure from mean variation

	1850-1897	1898-1941	1910-1941
HPC 1	0.17	0.28	0.24
2	0.21	0.24	0.20
3	0.25	0.26	0.23
4	0.23	0.24	0.21
5	0.20	0.13	0.11
6	0.19	0.16	0.15
7	0.15	0.23	0.24
9	0.28	0.25	0.20
G 10	0.132	0.148	0.136
11	0.204	0.118	0.110
7	0.110	0.105	0.094
7 (restricted)	0.130	0.105	0.092

Table 8 brings together a short summary of characteristics on the wood in order to emphasize the differences between the two periods 1850-1897 and 1898-1941. Although the differences between groups 10 and 11 appear striking, they actually are due to the influence of two out of eight trees. Elimination of those two trees from group 7 brings it into harmony with group 11. There remain, then, the fundamental differences between the periods 1850-1897 and 1898-1941. Do they reflect a change in amount of rainfall with its attendant changes in rainfall characteristics, or a change in the rainfall interval important to tree growth, or both, or some other change? In a previous paragraph a striking dearth of trend agreements among the trees was pointed out for 1850-1897 in contrast with succeeding years. A reexamination of the data shows that the dearth does not apply quite so drastically to the trees from the wetter locations. This matter of trend agreement appears to be another facet of the general problem brought out by the changes of characteristics on the wood through the years from 1850 to 1941.

TABLE 8.—*Holman Pass collection*

Characteristics	1850-1897	1898-1941
Average variation		
G 10	0.26	0.40
11	0.38	0.27
7	0.21	0.27
Average thickness		
G 10	1.53	1.70
11	2.26	1.96
7	1.90	1.83
Average departure		
G 10	0.32	0.36
11	0.34	0.30
7	0.18	0.20
Average departure from mean variation		
G 10	0.132	0.148
11	0.204	0.118
7	0.110	0.105

STUDY OF RAINFALL CHARACTERISTICS

Two tasks were set out for consideration in connection with the rainfall data: (1) to determine the interrelationships among the stations of usable records in the vicinity of Holman Pass and (2) to determine the characteristics of those records. As to the first task, it is necessary to know the extent of the differences between two adjacent stations in order to appreciate and allow for the possible differences between the trees and the station nearest to them. As to the second task, it is desired to learn whether or not the rainfall shows any differences between the two periods 1850-1897 and 1898-1941, and, if it does, to compare the differences with those obtained from a study of growth-layer sequences.

Interstation correlations.—Table 9 shows the trend coefficients and ratios of opposed trends between Chacon, the nearest station to Holman Pass, and six other stations for eight selected time intervals. These intervals were chosen on the basis of their possible influence on tree growth. On the whole, the correlations show a remarkable consistency. Those comparisons which do not include part or all of the summer rainfall are commonly higher than those which do. Furthermore, the longer the interval under comparison is, the poorer the correlation in general. Black Lake, the nearest to Chacon in distance as well as elevation, does not have the best correlation with Chacon. Las Vegas has the greatest similarity, a station farther away, 2,100 feet lower, and out beyond the foot of the main range of mountains. Santa Fe rainfall correlates with that of Chacon to a degree equal to the correlation between Black Lake and Chacon. Even Albuquerque is little less in degree of similarity. The best correlations are for the March-April intervals with Black Lake and Albuquerque which show ratios of opposite trends with respect to Chacon of 0.12 and 0.09.

It is scarcely necessary here to do more than refer briefly to the many observations of differences in rainfall at gauges spaced rather closely together. For instance, Stout[8] records a study of July 1948 rainfall on a plot centering at El Paso, Ill. Two stations, 10 miles apart, had 10.44 and 5.93 inches of rainfall. Two other stations, 3 miles apart, showed a difference of 77 percent. Localization of single storms is on occasion even more pronounced. On June 30, 1947, near Lubbock, Tex., 4 to 5 inches of rain fell in a belt about 2 miles wide, whereas none fell 2 miles to the west and 0.26 inches 8 miles to the east. Of course, this may be unusual, but at least it is more or less typical of extreme forest-border conditions.

Furthermore, it must be remembered in comparing tree growth with the rainfall of a station that, as pointed out by Landsberg,[9] a rain gauge samples but does not measure rainfall and therefore "the areal significance of precipitation amounts caught at a station is very restricted. . . ." These characteristics of rainfall must be duly weighed when the growth of selected trees is compared with the record of a station some miles distant. The trees may respond to the rainfall they themselves receive but differ somewhat from that received by the weather station.

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[8] Weatherwise, vol. 1, pp. 112-113, 1948.

[9] Landsberg, H., Critique of certain climatological procedures, Bull. Amer. Meteor. Soc., vol. 28, pp. 187-191, 1947.

TABLE 9.—*Correlation between Chacon rainfall and that of other stations*

Trend coefficients and ratios of opposed trends

1909-1941

	Mar.-July	Jan.-Aug.	Mar.-June	May-Aug.	May-June	Jan.-May	Nov.-May	Mar.-Apr.	Av.
Black Lake	0.61	0.93	0.93	0.93	0.92	0.88	0.92	0.99	0.89
	(0.41)	(0.22)	(0.28)	(0.28)	(0.16)	(0.19)	(0.19)	(0.12)	(0.23)
Taos	0.86	0.78	0.89	0.87	0.85	0.80	0.86	0.90	0.85
	(0.16)	(0.22)	(0.22)	(0.22)	(0.19)	(0.31)	(0.23)	(0.25)	(0.22)
Taos Canyon	0.92	0.86	0.95	0.86	0.92	0.91	0.94	0.97	0.92
	(0.22)	(0.28)	(0.22)	(0.37)	(0.16)	(0.19)	(0.19)	(0.16)	(0.22)
Las Vegas	0.95	0.91	0.97	0.91	0.87	0.95	0.93	0.97	0.93
	(0.25)	(0.12)	(0.22)	(0.28)	(0.19)	(0.16)	(0.13)	(0.16)	(0.19)
Santa Fe	0.91	0.72	0.98	0.86	0.95	0.86	0.88	0.90	0.88
	(0.25)	(0.31)	(0.12)	(0.34)	(0.12)	(0.22)	(0.23)	(0.22)	(0.22)
Albuquerque	0.89	0.86	0.94	0.66	0.92	0.86	0.78	0.98	0.86
	(0.25)	(0.31)	(0.22)	(0.41)	(0.25)	(0.16)	(0.26)	(0.09)	(0.25)
Average	0.86	0.84	0.94	0.85	0.90	0.88	0.88	0.95	
	(0.26)	(0.24)	(0.21)	(0.32)	(0.18)	(0.19)	(0.19)	(0.16)	

From the qualitative standpoint, the trend ratios of table 9 give a rather clear indication of the amount of agreement to be expected between tree growth and rainfall where the two are as far apart as any two of the rainfall stations. Quantitatively, trend coefficients yield values to be expected in the same fashion. If variations in tree growth mirror variations in rainfall to a high degree then the cor-

TABLE 10.—*Correlation between rainfall intervals at Chacon*

Trend coefficients and ratios of opposed trends
1909-1941

Nov.-May vs. Jan.-Aug.	0.78	(0.26)	Jan.-May vs. Mar.-Apr.	0.92	(0.22)
Nov.-May vs. Jan.-May	0.99	(0.06)	Jan.-May vs. Mar.-June	0.84	(0.22)
Nov.-May vs. Mar.-June	0.82	(0.29)	Jan.-May vs. May-Aug.	0.14	(0.47)
Jan.-Aug. vs. Jan.-May	0.73	(0.28)	Jan.-May vs. May-June	0.18	(0.44)
Nov.-May vs. Mar.-July	0.77	(0.23)	Mar.-July vs. Mar.-Apr.	0.67	(0.31)
Nov.-May vs. May-Aug.	0.21	(0.48)	Mar.-July vs. Mar.-June	0.98	(0.12)
Nov.-May vs. May-June	0.17	(0.45)	Mar.-July vs. May-Aug.	0.85	(0.34)
Nov.-May vs. Mar.-Apr.	0.90	(0.23)	Mar.-July vs. May-June	0.81	(0.22)
Jan.-Aug. vs. Mar.-June	0.87	(0.25)	May-Aug. vs. May-June	0.94	(0.25)
Jan.-May vs. Mar.-July	0.72	(0.22)	May-Aug. vs. Mar.-Apr.	—0.33	(0.66)
Jan.-Aug. vs. Mar.-July	0.97	(0.22)	May-Aug. vs. Mar.-June	0.66	(0.44)
Jan.-Aug. vs. May-Aug.	0.92	(0.25)	May-June vs. Mar.-Apr.	—0.02	(0.47)
Jan.-Aug. vs. May-June	0.69	(0.22)	May-June vs. Mar.-June	0.87	(0.25)
Jan.-Aug. vs. Mar.-Apr.	0.56	(0.38)	Mar.-Apr. vs. Mar.-June	0.90	(0.25)

relation between Holman Pass trees and Chacon rainfall should closely approach or possibly equal the average values set out in table 9. Should this prove to be true, the conclusion is no doubt justified that trees growing in a zone well above critical moisture conditions rather faithfully record rainfall variations at the site from year to year, barring the impact of an "accidental" factor in concentrated form in any one year.

Table 10 sets forth correlations between various month-intervals in

Chacon rainfall. Good correlations in general result under three circumstances: In the lack of summer rainfall in the intervals compared, in the proportion of overlap between the two intervals, and in the length of the intervals. For instance, November-May versus January-May has a trend coefficient of 0.99 and a trend ratio of 0.06 whereas, contrariwise, May-August versus March-April has values of −0.33 and 0.66. The table as a whole shows great variation and indicates the necessity of comparing tree growth with different rainfall intervals. It goes farther than this. If tree growth is found to correlate with one particular month-interval, then a great quantity of xylem (as a thick growth layer) formed during a certain season suggests copious rainfall for that month-interval; it does not necessarily suggest that the entire year is a wet one.

Rainfall characteristics.—For a study of the influence of a single factor, such as rainfall, on tree growth it is necessary to have long records at the immediate site of the trees. Short records taken a matter of several miles distant can be highly indicative but not necessarily conclusive. In the present case the record at Chacon, 7 miles away, begins with 1909. Therefore, the longer records of Santa Fe and Albuquerque were used, in spite of greater distances, in order to determine possible differences in rainfall characteristics between the periods 1850-1897 and 1898-1941.

Table 11, in the first place, gives the March-July and January-August rainfall for 1909-1941 at the several stations. As will be shown later, the rainfall of March-July is a significant factor in tree growth. In the second place, table 11 gives the rainfall of Santa Fe and Albuquerque for the periods 1850-1897 and 1898-1941 set out for various month-intervals. Two points must be considered. First, there is the striking fact that the average rainfall of March-July for both Santa Fe and Albuquerque was less during the period 1850-1897 than during that of 1898-1941. The same is true for the average rainfall of Albuquerque for January-August. Second, there is the fact that the average rainfall of January-August at Santa Fe was greater during 1850-1897 than for the following 44 years. The reason for this inconsistency with the intervals mentioned in the first point above was suspected as soon as it was determined that the average rainfall of January-May, in contrast to the rainfall of January-August, was less during the earlier period, 1850-1897. Therefore, the average rainfall was computed for March-April, May-June, April, May, June, July, August, and September. Only July and August showed greater average rainfall for 1850-1897 than for 1898-1941. It was obvious at once that the greater rainfall of August aided by that of July caused the greater average rainfall of January-August during 1850-1897 at Santa Fe. In September, as a matter of interest, the averages swing back so that the figures are 1.58 inches for 1850-1897 and 1.66 inches

TABLE 11.—*Average rainfall (inches)*

	March-July 1909-1941	January-August 1909-1941
Chacon	10.34	15.80
Black Lake	8.42	12.66
Taos	5.96	8.83
Taos Canyon	9.64	14.68
Las Vegas	9.33	13.66
Santa Fe	6.88	10.14
Albuquerque	4.24	6.28

	Santa Fe		Albuquerque	
	1850-1897	1898-1941	1850-1897	1898-1941
March-July	6.34	6.74	3.16	3.97
January-August	10.60	10.11	5.60	5.92
January-May	3.94	4.82	1.75	2.50
March-April	1.54	1.92	0.58	1.07
May-June	2.14	2.61	1.26	1.43
April	0.71	1.08	0.29	0.67
May	0.99	1.19	0.36	0.73
June	1.15	1.18	0.79	0.69
July	2.66	2.21	1.37	1.47
August	2.89	1.90	1.59	1.26
September	1.58	1.66	0.90	0.98

Albuquerque, 1850-1897, 27 years of record only.

for 1898-1941. This situation no doubt should be given emphasis: the average rainfall for the interval March-June began to increase somewhere near 1898 whereas that for the interval July-August decreased. Calculation shows that the average for March-June began to increase slowly just before the turn of the century and that the increase accelerated after 1909. The simultaneous increase and decrease of two sequential month-intervals is a point of importance in relation to the period of greatest tree growth within the season.

Table 12 gives the average year-to-year variation of rainfall arranged in two parts, the first of which sets out the variations of March-July and January-August rainfall for the period 1909-1941 at the several stations. In view of the differences in elevation, the average variation of the rainfall is of the same order of magnitude

TABLE 12.—*Rainfall*

Average year-to-year variation

	March-July 1909-1941	January-August 1909-1941
Chacon	0.36	0.26
Black Lake	0.38	0.29
Taos	0.36	0.25
Taos Canyon	0.28	0.22
Las Vegas	0.41	0.34
Santa Fe	0.35	0.27
Albuquerque	0.63	0.45

	Santa Fe		Albuquerque	
	1850-1897	1898-1941	1850-1897	1898-1941
March-July	0.42	0.33	0.79	0.60
January-August	0.39	0.27	0.63	0.44

TABLE 13.—*Rainfall*

Average departures

	March-July 1909-1941	January-August 1909-1941
Chacon	0.22	0.17
Black Lake	0.25	0.19
Taos	0.27	0.20
Taos Canyon	0.20	0.17
Las Vegas	0.30	0.26
Santa Fe	0.24	0.20
Albuquerque	0.43	0.31

	Santa Fe		Albuquerque	
	1850-1897	1898-1941	1850-1897	1898-1941
March-July	0.33	0.22	0.58	0.40
January-August	0.30	0.19	0.45	0.30

as that of the Holman Pass trees. The second part of the table shows the average variation of 1850-1897 to be greater than that of 1898-1941, which is no doubt to be expected because of the lower average rainfall of the earlier period. Even the interval January-August at Santa Fe has the same decrease in the later period.

Table 13 gives average rainfall departures. In the first portion of the table the departures for the rainfall of March-July and January-

August during the period 1909-1941 are given for the several stations. These average departures are noticeably less than the comparable values for the growth layers of the Holman Pass collection. In the second portion of the table the average departures of the period 1850-1897 are distinctly higher than those of the period 1898-1941. The contrast between the two periods stands thus: a lower average

TABLE 14.—*Holman Pass tree growth and Santa Fe rainfall—characteristics*

	1850-1897	1898-1941
Average magnitude		
Rainfall (inches)	6.34	6.74
Growth layers (mm.)		
G 10	1.53	1.70
11	2.26	1.96
7 (restricted)	1.99	1.83
Average variation		
Rainfall	0.42	0.33
Growth layers		
G 10	0.26	0.40
11	0.38	0.27
7 (restricted)	0.33	0.32
Average departure		
Rainfall	0.33	0.22
Growth layers		
G 10	0.32	0.36
11	0.34	0.30
7 (restricted)	0.35	0.31
Average departure from mean variation		
Rainfall	0.25	0.22
Growth layers		
G 10	0.132	0.148
11	0.204	0.118
7 (restricted)	0.130	0.105

rainfall during the earlier period is accompanied by a higher average variation and by a higher average departure. On the whole, such characteristics are to be expected.[10]

There remains, then, a comparison between the characteristics of the growth layers and those of rainfall for which the records of Santa Fe are used because of their length and continuity. Table 14 makes

[10] Mixer, C. A., The rainfall year, Bull. Amer. Meteor. Soc., vol. 15, pp. 22-23, 1934; Williamson and Clark, Variability of annual rainfall in India, Geogr. Rev., vol. 21, pp. 675-676, 1931.

these comparisons using March-July rainfall. An increase in average rainfall (as between 1850-1897 and 1898-1941) is accompanied by an increase of average growth-layer thickness on dry sites (group 10) and by a decrease on wet sites (group 11); an increase in rainfall giving a decrease in its average variation is accompanied by an increase of average variation among growth layers from dry sites and by a decrease among growth layers from wet sites; an increase in rainfall giving a decrease in its average departure is accompanied by an increase of average departure among growth layers from dry sites and by a decrease among growth layers from wet sites; and an increase in rainfall giving a decrease in its average departure from mean variation is accompanied by an increase of average departure from mean variation among growth layers from dry sites and by a decrease among growth layers from wet sites.

In other words, changes of average variation, average departure, and average departure from mean variation among growth layers from wet sites follow the changes of the same features in the rainfall whereas the growth layers from dry sites react in the opposite direction. The case is reversed as regards changes in growth-layer thicknesses: the growth layers from the dry sites follow the changes in average rainfall amounts. However, as discussed under the study of growth layers, two trees, HPC 1 and 7 of group 10, determine the characteristics of the group. Their elimination from the complete record leaves a homogeneous group consisting of the other two trees of group 10 and all trees of group 11 (HPC 8 is not included because its sequence is too short). This group of six trees, group 7 (restricted), is conformable within itself, and the changes in its characteristics from 1850-1897 to 1898-1941 agree with those of Santa Fe rainfall.

Nevertheless, there remains the problem of why the average variation of the dry-site trees increased with a decrease of average variations in rainfall during 1898-1941. Calculation of the average variation of rainfall for different months and month-intervals shows that only April and May increased their average variations during the period 1898-1941. It might be, therefore, that the dry-site trees were more influenced by April-May, or spring, rainfall than the wet-site trees were. Or the problem may concern limiting factors and optimum or near optimum soil-moisture conditions in that the wet-site trees grew under conditions where the trees responded directly and consistently to changes in rainfall.

It is clear that the relations of tree growth to rainfall are highly complex not by themselves alone but also by the interplay of the entire range of growth factors, a circumstance emphasized by plant physiologists and ecologists.[11] The problem calls for much more work—it is far from finished. The observational method of field selection and laboratory analysis remains secondary to direct experiment on growing trees under controlled conditions.

In any event, the present work comparing tree growth and rainfall characteristics strongly suggests that trees selected from certain sites and from the proper rainfall or soil-moisture zone can be sensitive indicators of rainfall changes through the use of average variation, average departure, and average departure from mean variation.

CORRELATION OF TREE GROWTH AND RAINFALL

Range of tests.—Fairly extensive correlations were made between tree growth and Chacon and Santa Fe rainfall both for groups and for individual trees. The trend method was applied in its complete form until it was determined that variations of 1 or 2 years did not unduly distort the results. In addition to the more extensive correlations, selected tests were made between tree growth and the records of other rainfall stations.

Tree growth (groups) and Chacon rainfall.—Groups 1 to 9 were correlated with Chacon rainfall for the month-intervals shown in table 15. However, the table includes only those groups which were most significant.

The table shows that correlations with March-July and January-August rainfall are the highest, and of these two intervals March-July is the more important. July rainfall is necessarily included as is indicated by the lower correlations of March-June. Of the 5 months, March-July, the rainfall of May-June is more important to tree growth than that of March-April and the rainfall of April is of less importance than that of May, June, or July. Apparently tree growth, as represented by the trees selected, responds directly to the rain which falls during and the several weeks immediately preceding the actual growing season.

The most striking fact obvious at first sight is the correlation between group 7 (all trees) and March-July rainfall, the trend coefficient being 0.965 and the ratio of opposed trends 0.12. A trend ratio of 0.12 means that the trend of rainfall was opposite to the trend

[11] Bot. Rev., vol. 7, pp. 651-655, 1941.

of tree growth for 4 years out of 32 of variation. Of these opposite trends that for 1910 contains 84 percent of the numerical disagreement and, if 1910 be eliminated, the trend coefficient rises to 0.994. A comparison of the rainfall among all seven stations with the tree growth of group 7 for the 4 years of opposite trend, 1910, 1912, 1913,

TABLE 15.—*Correlation of tree groups and Chacon rainfall*

Trend coefficients and ratios of opposed trends
1909-1941

	G 4	G 5	G 7	G 9	G 10	G 11
Mar.-July	0.93	0.82	0.965	0.88	0.96	0.92
	(0.22)	(0.31)	(0.12)	(0.19)	(0.16)	(0.22)
Jan.-Aug.	0.92	0.73	0.95	0.88	0.94	0.91
	(0.16)	(0.31)	(0.19)	(0.25)	(0.22)	(0.28)
Mar.-June	0.85	0.82	0.89	0.77		
	(0.28)	(0.28)	(0.16)	(0.28)		
May-Aug.	0.80	0.68	0.80	0.66		
	(0.25)	(0.37)	(0.28)	(0.28)		
May-June	0.73	0.70	0.72	0.49		
	(0.31)	(0.34)	(0.28)	(0.34)		
Jan.-May	0.72	0.32	0.70	0.62		
	(0.25)	(0.44)	(0.28)	(0.41)		
Nov.-May	0.71	0.26	0.68	0.59		
	(0.23)	(0.42)	(0.26)	(0.39)		
Mar.-Apr.	0.50	0.44	0.55	0.52		
	(0.41)	(0.44)	(0.37)	(0.50)		
May-July	0.84	0.71	0.85	0.71		
	(0.22)	(0.31)	(0.19)	(0.25)		
April	0.04	0.20	0.09	0.14		
	(0.47)	(0.47)	(0.56)	(0.56)		
May	0.75	0.34	0.64	0.27		
	(0.25)	(0.44)	(0.34)	(0.41)		
June	0.42	0.79	0.59	0.54		
	(0.47)	(0.25)	(0.37)	(0.44)		
July	0.62	0.48	0.66	0.63		
	(0.41)	(0.50)	(0.37)	(0.37)		
August	0.39	0.33	0.35	0.27		
	(0.37)	(0.44)	(0.41)	(0.41)		

and 1931, shows that from one to three stations disagree with the remainder in each case. The 5 years of greatest parallel variation in the complete record have only one station disagreeing with the remainder for 1 year. Where the parallel variations are of small amount the different rainfall stations are much at variance with each other for all years. Therefore, it is possible to speculate that the rainfall at the site of the trees actually agreed with tree growth; however, the data at Chacon are the closest legitimate record and must be retained as they stand.

The quality of the correlation between tree growth and March-July rainfall at Chacon for the 33-year interval (table 15) is all that can be ecologically expected considering the distance between Holman Pass and Chacon, and considering the quality of the correlations between the rainfall of two stations approximately as far apart as Holman Pass and Chacon. This suggests that the trees as a group follow with a high degree of accuracy the fluctuations of rainfall at the immediate site.

In general, group 7 shows slightly higher correlations than the others and group 5 slightly less; otherwise there is little choice among them. Group 4, the closest to Chacon, has a very slight advantage over group 9, and both have higher correlations than group 5, which is ecologically less similar to the other two than they are between themselves. In the case of groups 10 and 11, the former (from the drier sites) has a slightly higher correlation than the latter although not sufficiently so to justify any conclusions. Group 7, containing all trees, possesses slightly better correlation than group 7 (restricted), the values for March-July being 0.95 and (0.28) and for January-August 0.94 and (0.19).

Figure 4 shows Chacon rainfall for March-July compared with tree growth of the several pertinent groups.

The charted correlations of group 7 with Chacon rainfall in figure 6 indicate in general that the absence of summer rainfall and the presence of winter rainfall militate against high agreement. It is neither spring rainfall alone nor spring combined with winter rainfall which gives highest correlations but spring added to early and midsummer rainfall.

Tree growth (individual trees) and Chacon rainfall.—Individual trees were correlated with the two rainfall intervals of March-July and January-August (table 16). The results are to be expected, no doubt, in view of the former group correlations. In general, the trees agree a little better with March-July than with January-August rainfall. Tree HPC 3, a foxtail pine, has the highest correlation and HPC 9, a ponderosa pine, has the lowest. However, HPC 5, a Douglas fir, runs a close second to HPC 9. As a matter of fact, tree HPC 3, which stands between HPC 1 and 2, could be used as a fair substitute for group 7. Ponderosa pines have no advantage over the other species. On the whole, the trees east of the Pass correlate better than those on the Pass and these latter slightly better than those

TABLE 16.—*Correlation of Holman Pass trees and Chacon rainfall*
Trend coefficients and ratios of opposed trends
1909-1941

	March-July	January-August
HPC 1	0.92	0.90
	(0.25)	(0.31)
2	0.89	0.90
	(0.25)	(0.25)
3	0.92	0.92
	(0.19)	(0.12)
4	0.89	0.83
	(0.25)	(0.25)
5	0.81	0.68
	(0.34)	(0.41)
6	0.78	0.77
	(0.31)	(0.31)
7	0.90	0.87
	(0.22)	(0.34)
8	0.88	0.90
	(0.22)	(0.22)
9	0.51	0.62
	(0.28)	(0.34)

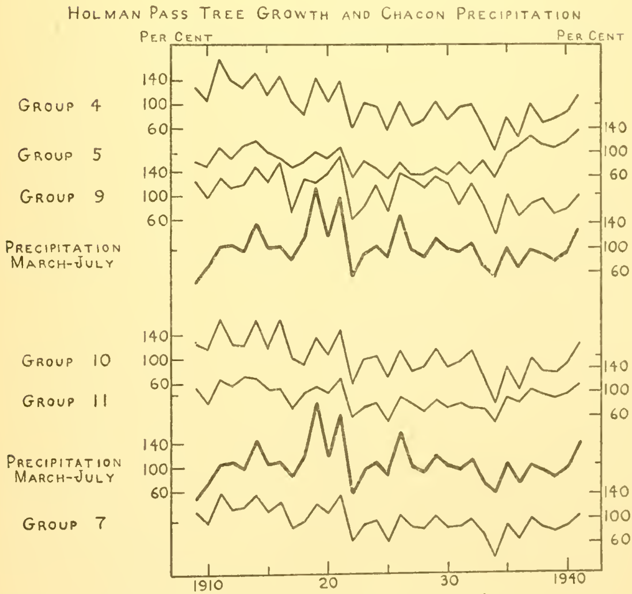

FIG. 4.—Graphs of tree growth and rainfall 7 miles distant, in raw percentages. Group 4, east of Pass; group 5, on Pass; group 9, west of Pass; group 10, normal or dry-site trees; group 11, wet-site trees; and group 7, all trees.

west of the Pass although there are individual exceptions. The most striking contrast appears between the trees from the drier sites, group 10, and those from the wetter, group 11.

In summary, it is rather clearly evident, first, that a group is superior to single trees for a record of rainfall variations and, second, that the variations shown among the trees in table 16, especially in the ratios of opposed trends, emphasize the influence of what has previously been referred to as microsite factors. A union of several tree records apparently generalizes the record of response to rainfall. When consideration is given the facts that the trees do differ from each other by an amount to be expected over a short term, in view of the variations among different rainfall records themselves; that the trees are several miles from Chacon; that rainfall is but one growth factor in a complex; and that rainfall itself is rather remote from its incorporation into the hydrostatic system of the plant, the correlations not only between rainfall and tree groups but also between rainfall and individual trees are surprisingly high for the period 1909-1941.

Tree growth (groups) and the rainfall of other stations.—Certain groups were correlated with the rainfall of the stations at Black Lake, Taos Canyon, Taos, and Albuquerque. The results for four of the groups are shown in table 17. Before continuing it should be mentioned that these particular correlations were not included to demonstrate that tree growth can be compared to distant rainfall with significant results or to indicate favor for such correlations. They are shown rather because they appear to indicate that detailed influence of specific rainfall subsides with distance and only general variations common to the region remain. With ratios of opposed trends ranging from 0.22 to 0.50, tree growth in one locality gives a poor picture of rainfall variations at a distance.

On the one hand, correlations with March-July rainfall, the best in the case of Chacon, are mixed and poor; it is difficult to read any significance into them. On the other hand, correlations with the more general interval of January-August rainfall are higher and more consistent and emphasize the regional regime. Even so, the number of instances in which the trees respond in a direction opposite to the rainfall trends militates against the use of tree growth, as exemplified by the Holman Pass collection, for an accurate gauge of regional rainfall variations from season to season. This is not to say that smoothing would not bring out general trends if the influence of other

TABLE 17.—*Correlation of tree groups and rainfall*

Trend coefficients and ratios of opposed trends
1909-1941

	G 4		G 5		G 9		G 7	
	Mar.-July	Jan.-Aug.	Mar.-July	Jan.-Aug.	Mar.-July	Jan.-Aug.	Mar.-July	Jan.-Aug.
Black Lake	0.32	0.78	0.36	0.75	0.33	0.80	0.37	0.86
	(0.41)	(0.31)	(0.44)	(0.34)	(0.50)	(0.28)	(0.44)	(0.22)
Taos Canyon	0.79	0.79	0.79	0.71	0.75	0.89	0.84	0.89
	(0.37)	(0.28)	(0.31)	(0.38)	(0.41)	(0.28)	(0.34)	(0.22)
Taos	0.74	0.65	0.62	0.66	0.66	0.80	0.79	0.80
	(0.25)	(0.31)	(0.34)	(0.34)	(0.28)	(0.28)	(0.22)	(0.28)
Albuquerque	0.77	0.86	0.79	0.81	0.61	0.77	0.81	0.88
	(0.28)	(0.28)	(0.28)	(0.41)	(0.37)	(0.37)	(0.31)	(0.31)

factors were eliminated and if the trees were properly selected from the region and from the proper zone.

Further to test the general relationships, the March-July and January-August rainfall of Chacon, Las Vegas, Taos Canyon, and Black Lake were combined for the period 1909-1941 and correlated with group 7. The results follow.

	Raw percentages	Smoothed percentages
March-July	0.95	0.96
	(0.19)	(0.22)
January-August	0.96	0.86
	(0.16)	(0.31)

Although these values are high no advantage results from the use of the combined rainfall. The raw percentage values for group 7 (restricted) correlated with combined rainfall of March-July are 0.955 and (0.22), and of January-August rainfall 0.955 and (0.12).

An analysis of table 17 shows, further, that altitude in general has some effect: the correlations are slightly higher for group 9, which is closer to the average elevation of the rainfall stations.

TABLE 18.—*Correlation of tree groups and Las Vegas rainfall*

Trend coefficients and ratios of opposed trends

	March-July		January-August	
	1893-1941	1910-1941	1893-1941	1910-1941
G 4	0.78	0.93	0.73	0.89
	(0.33)	(0.28)	(0.20)	(0.16)
5	0.73	0.81	0.66	0.73
	(0.31)	(0.27)	(0.22)	(0.22)
9	0.59	0.64	0.63	0.63
	(0.47)	(0.44)	(0.39)	(0.37)
7	0.79	0.91	0.73	0.86
	(0.35)	(0.31)	(0.27)	(0.25)

Trees HPC 3, 5, 7, and 9 were correlated with the stations listed in table 17. The results are similar to those for the groups in the table except for somewhat lower values.

Tree growth and Las Vegas rainfall.—With the exception of Santa Fe, Las Vegas has the longest rainfall record of any station in the general area but it is some 37 miles distant from Holman Pass and 3,000 feet lower. Table 18 gives the trend coefficients and the ratios of opposed trends between tree growth and Las Vegas rainfall for the intervals and years noted. On the whole, the correlations with March-July rainfall slightly exceed those with January-August. They decrease in quality with distance; that is, correlations of group 4 (east of Pass) are highest and those of group 9 (west of Pass) are lowest.

The most striking feature of the table is the decided increase in correlation of the period 1910-1941 over the period 1893-1941. During the later period (1910-1941) the trees follow more closely the variations in rainfall as recorded at Las Vegas.

Tree growth and Santa Fe rainfall.—Although Santa Fe is distant some 40 miles from Holman Pass it is worth while, because of the length of record, to compare Santa Fe rainfall with tree growth in order to determine if the quality of correlation varied throughout the length of that record. Nine tree groups were correlated with all rainfall intervals for the periods 1850-1897 and 1898-1941 separately.

Data most pertinent to the study appear in table 19, which gives the trend coefficients and ratios of opposed trends for the periods mentioned above. The remainder of the data, not shown, simply corroborate what the table itself shows. On the whole, tree growth correlates considerably better with March-July than with January-August rainfall. Here, however, in contrast with Chacon rainfall, groups 4, 5, and 7 agree somewhat better with March-June rainfall.

General correlations are fair; they possess little value except to show a regional tendency toward similarity during a portion of the years. This appears in table 20 where trend coefficients for the period of 1850-1941 vary from 0.52 to 0.67 and the ratios of opposed trends from 0.24 to 0.37. The values for group 7 are 0.65 for the trend coefficient and 0.35 for the ratio of opposed trends. Thus, a case of 35 opposite trends against 65 parallel gives neither high nor dependable correlation. Surprisingly, the trees from the wetter sites, group 11, compare most favorably with Santa Fe rainfall for the period 1850-1941. In view of the quality of correlation between Holman Pass tree growth and Chacon rainfall on the one hand and between Chacon and Santa Fe rainfall on the other, the correlation between tree growth and Santa Fe rainfall possesses values consistent with the relative distances.

Figure 5 shows Santa Fe rainfall for March-July compared with tree growth of the several pertinent groups. Figure 6 shows the correlations in charted form. For the period 1898-1941 the trend of the graph resembles that for the Chacon correlations. It contrasts notably with the graph for the period 1850-1897, where the emphasis seems to be on spring rainfall.

TABLE 19.—*Correlation of tree groups and Santa Fe rainfall*

Trend coefficients and ratios of opposed trends

	G 4		G 5		G 9		G 7	
	1850-97	1898-1941	1850-97	1898-1941	1850-97	1898-1941	1850-97	1898-1941
Mar.-July	0.51	0.67	0.36	0.83	0.44	0.70	0.51	0.77
	(0.47)	(0.27)	(0.40)	(0.20)	(0.40)	(0.32)	(0.43)	(0.27)
Jan.-Aug.	0.24	0.70	0.01	0.77	0.05	0.76	0.12	0.86
	(0.47)	(0.34)	(0.49)	(0.25)	(0.49)	(0.30)	(0.51)	(0.25)
Mar.-June	0.61	0.67	0.53	0.79	0.45	0.62	0.64	0.73
	(0.40)	(0.27)	(0.30)	(0.23)	(0.42)	(0.32)	(0.32)	(0.27)
May-Aug.	0.09	0.72	0.10	0.67	0.00	0.64	0.04	0.79
	(0.60)	(0.32)	(0.49)	(0.23)	(0.51)	(0.32)	(0.55)	(0.23)
May-June	0.38	0.68	0.47	0.70	0.16	0.59	0.40	0.72
	(0.45)	(0.39)	(0.34)	(0.30)	(0.40)	(0.39)	(0.36)	(0.34)
Jan.-May	0.51	0.61	0.21	0.72	0.18	0.58	0.35	0.62
	(0.40)	(0.18)	(0.38)	(0.20)	(0.47)	(0.27)	(0.43)	(0.23)
Nov.-May	0.36	0.68	0.04	0.73	0.12	0.60	0.17	0.69
	(0.27)	(0.16)	(0.37)	(0.23)	(0.39)	(0.34)	(0.39)	(0.25)
Mar.-Apr.	0.52	0.32	0.30	0.44	0.63	0.34	0.61	0.34
	(0.36)	(0.39)	(0.34)	(0.41)	(0.45)	(0.48)	(0.32)	(0.50)

The most important, perhaps, and certainly the most startling information yielded by tables 19 and 20 is the great increase in the quality of correlation from the period 1850-1897 to the period 1898-1941. Table 20 shows this in abbreviated form for March-July rainfall, which appears to have most influence on tree growth. In addition, table 20 includes the period 1910-1941. It is to be noted that correlation is higher for 1910-1941 than for 1898-1941; in other words, there is a general increase in correlation toward recent years. Of all the groups, numbers 5 and 11, containing trees from the wetter sites, show not only the greatest increases but also the highest correlations for the periods 1898-1941 and 1910-1941. And of these two groups, number 5, composed of trees on the Pass, exceeds even group 11. Group 10, in contrast, containing trees from the drier sites, and group 4 exhibit the least increases. Table 11, giving the March-July rainfall of Santa Fe for the periods 1850-1897, 1898-1941, and 1910-1941, shows the rainfall to have been 6.34, 6.74, and 6.88 inches, respectively, for those periods. Furthermore, the low incidence of parallel trends, growth layer to growth layer, among the trees prior to 1897 as compared with the years following 1897 (as noted above under study of growth layers), and the lower correlations between trees and groups (table 2), suggest emphatically that the above phenomena are closely related.

TABLE 20.—*Correlation of tree groups and Santa Fe rainfall*

Trend coefficients and ratios of opposed trends
March-July rainfall

	1850-1897	1898-1941	1910-1941	1850-1941
G 4	0.51	0.67	0.77	0.61
	(0.47)	(0.27)	(0.22)	(0.37)
5	0.36	0.83	0.87	0.52
	(0.40)	(0.20)	(0.16)	(0.31)
9	0.44	0.70	0.71	0.58
	(0.40)	(0.32)	(0.25)	(0.36)
7	0.51	0.77	0.85	0.65
	(0.43)	(0.27)	(0.22)	(0.35)
10	0.51	0.69	0.76	0.62
	(0.43)	(0.25)	(0.19)	(0.34)
11	0.42	0.81	0.90	0.67
	(0.38)	(0.30)	(0.22)	(0.24)
7 (restricted)	0.46	0.82	0.89	0.63
	(0.45)	(0.27)	(0.22)	(0.36)

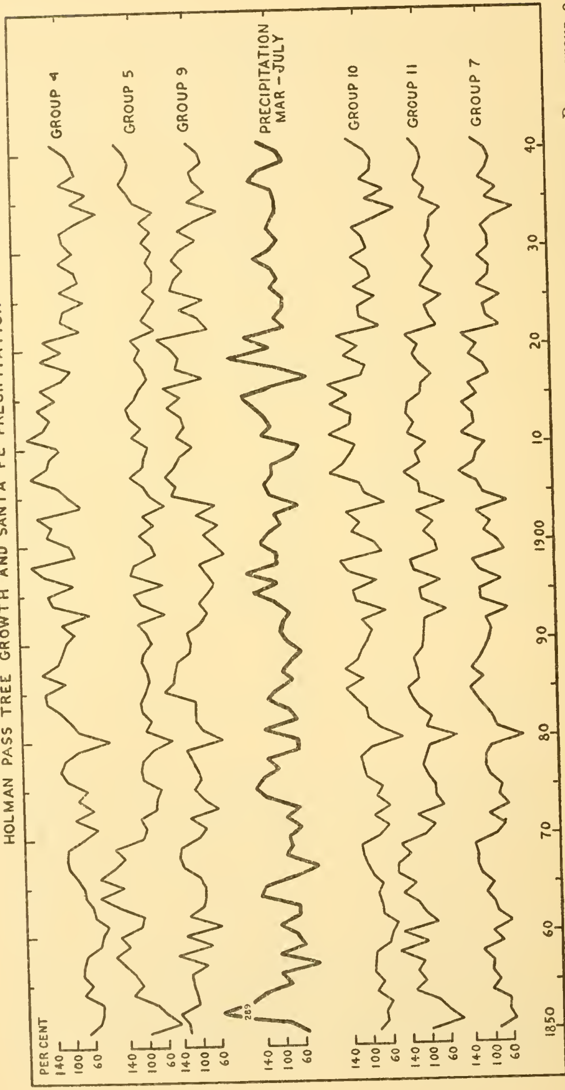

FIG. 5.—Graphs of tree growth and rainfall 40 miles distant, in raw percentages. Group 4, east of Pass; group 5, on Pass; group 9, west of Pass; group 10, normal or dry-site trees; group 11, wet-site trees; and group 7, all trees.

Table 19, as stated heretofore, shows a higher correlation for 1898-1941 than for 1850-1897. This is true for all month-intervals except for March-April which has lower correlations in groups 4, 7, and 9 for 1898-1941. Apparently March-April rainfall had greater influence on tree growth during the earlier period than during the later. Group 5 did not conform except in the ratio of opposed trends. An examination of the temperature records readily available gives table 21.

Obviously, a thermochemical or thermophysiological approach to temperature problems via direct experimental evidence in conjunction

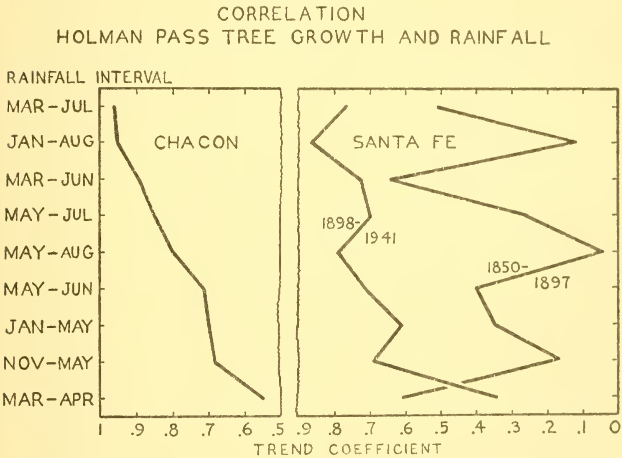

Fig. 6.—Charted correlations between tree growth of group 7 and rainfall of various month intervals.

with exact knowledge of growth initiation would give a much better idea of relationships among temperature, soil moisture, and growth. However, table 21 shows that for March, April, and May the average temperatures and the average maxima were somewhat higher for the period 1874-1897 and progressively lower thereafter except in the case of May when they were slightly higher again during 1910-1930. June follows the same pattern but in a less decided fashion. It is perhaps not illogical to speculate that with higher temperatures during 1874-1897 growth began earlier in the spring and was therefore influenced by March-April rainfall to a greater extent than after 1897. This may be linked up with the discussion, under the preceding section, of the parallel increase of average variation in dry-site trees and

April-May rainfall for the period 1898-1941 over that of 1850-1897. Again, figure 6, showing the charted correlations of group 7 with Santa Fe rainfall for 1850-1897, shows the emphasis to be on spring rainfall. These relationships emphasize the multiple nature of growth factors and the complexity of the problems involved.

Before the contrasts between the periods 1850-1897 and 1898-1941 are summarized, mention should be made of two points, one having to do with the incidence of opposed trends and the other with cumulative variations. First, the incidence of opposed trends was calculated for each 10-year interval for several of the groups against the various rainfall intervals. In the case of groups 7, 10, and 11 compared with March-July rainfall the incidence of opposed trends shows a general decline from early to recent years. The same is

TABLE 21.—*Santa Fe temperatures*

	1874-1897	1898-1930	1910-1930
March			
Average	39.9	39.4	39.0
Maximum	51.4	50.5	50.1
Minimum	28.0	28.4	27.9
April			
Average	47.4	46.75	46.5
Maximum	60.0	58.45	58.2
Minimum	34.76	35.1	34.8
May			
Average	56.5	55.1	55.5
Maximum	69.4	67.2	67.7
Minimum	43.5	43.0	43.3

true, in fact, for all rainfall intervals except that for March-April in which the incidence increases from 1850 to 1941, thus agreeing with the decrease of tree growth-rainfall correlation. Second, figure 7 gives the plotted cumulative variations of Santa Fe March-July rainfall and certain tree groups. Groups 5 and 11 and groups 4 and 10 were each combined into one graph because the separate graphs very nearly coincided. If groups 4 and 5 had been omitted there would have been no change. The graphs illustrate the close correspondence between the variations of Santa Fe rainfall and the variations of tree growth as represented by group 11 which contains the trees from the wetter sites.

The various tables have brought out the contrasts between the periods 1850-1897 and 1898-1941. These may now be summarized in respect to March-July rainfall at Santa Fe. In so far as data are available, the rainfall records of Albuquerque and Las Vegas corroborate the results obtained by the use of Santa Fe rainfall.

For the rainfall of the period 1898-1941, against the period 1850-1897: amount of rainfall increased; and average variation, average departure, and average departure from mean variation decreased.

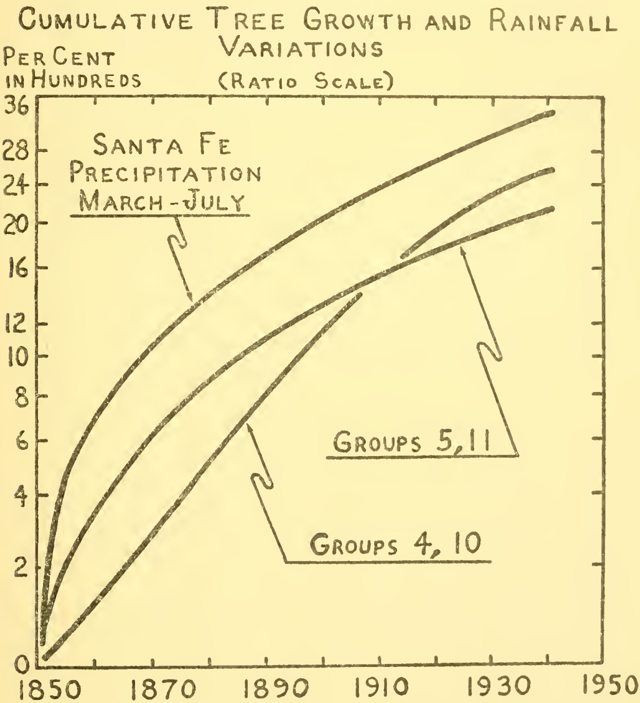

FIG. 7.—Cumulative variations of tree growth and rainfall. Trees in groups 5 and 11 were from wet sites and those in groups 4 and 10 chiefly from dry sites.

For group 11 contrasted in the same manner: average variation, average departure, and average departure from mean variation decreased; and correlation with rainfall increased to an extent comparable to that with Chacon rainfall considering the much greater distance.

For group 10 contrasted in the same manner: average variation, average departure, average departure from mean variation, and correlation with rainfall increased.

For group 7 contrasted in the same manner: average variation and average departure increased; average departure from mean variation decreased very slightly; correlation with rainfall increased; and internal agreement of the trends among the several trees increased.

For group 7 (restricted) contrasted in the same manner: average variation, average departure, and average departure from mean variation decreased.

The substance of the above summary is that the characteristics of group 11, made up of wet-site trees, and group 7 (restricted) agree with those of rainfall whereas most of the characteristics of group 10 and group 7 disagree except for correlation with rainfall. Also, *intra-correlation on the wood rises in quality with greater rainfall.*

Obviously, these findings must be translated into a method whereby study of the wood alone can be made to reveal changes in rainfall. Two of the trees from the drier sites (in group 10) for some reason reacted oppositely in comparison with the remainder of the collection and when combined into group 7 (all trees) overbalanced the influence of the remainder save for the one characteristic, average departure from mean variation. It is clear in respect to the Holman Pass trees that agreement of variation among the trees rises with increased rainfall. Such increase in rainfall would be expected to lessen the variation of rainfall within short distances on the ground as it affects growth and thus permit greater agreement among the trees. This is well shown by table 2 especially among groups. Reasoning from a knowledge of rainfall characteristics one can expect average variation to decrease with increase of rainfall.

Therefore, in regard to a study of the wood alone for evidence of rainfall changes, the Holman Pass collection suggests the use of the following methods: (1) the amount of agreement in directional variation, including correlation and trend parallelism, among the trees themselves; (2) the change in average variation, average departure, and average departure from mean variation among growth layers of trees grown under conditions, or in a zone, at least as moist as those for group 11 or for group 7 (restricted).

RÉSUMÉ

In bringing together a résumé of results it is well to recall the several aspects of the study: The site chosen extended from well within the Transition Zone up into the Canadian; the number of trees sampled was limited to nine; the collection contained trees of four different species and comprised three groups geographically and hypsometrically; the trees, in the field, divided themselves ecologically into two groups, the one (group 10) representing normal water relationships without excess drainage to or from the trees, and the other (group 11) representing slightly above-normal water relationships for the general locality; the samples consisted of increment cores —essentially one radius to represent the entire volume growth of a tree; site factors were judged solely by inspection on the spot; the terrain was mountainous; the nearest rainfall station, Chacon, was 7 miles distant at an elevation intermediate between the highest and lowest trees; and analyses were based on raw (i.e., unsmoothed) data.

The present study brings out many points in summary which are distinctly secondary to the main objectives. In the present stage of investigations of this type, all points, secondary as well as primary, are highly suggestive only. It remains to be determined if the principles and methods here used in the field and in the laboratory are of more general application. Only then can growth-layer sequences be interpreted in the absence of nearby rainfall stations. Obviously, we must know how trees reveal their ecologic information before we can determine what they tell.

Study of growth layers.—1. Cross-dating of high quality is not a necessary prerequisite to the correlation of growth-layer thicknesses and rainfall, and its nearly total absence does not indicate a lack of significant response on the part of the trees to rainfall variations.

2. The presence or absence of high-quality cross-dating does not necessarily constitute the criterion whereby a tree record is included in a group average or excluded from it. Some other criterion should be applied for the elimination of certain growth-layer sequences after the collection is brought to the laboratory, if such elimination is attempted with justification.

3. Partial disagreement among the various trees, growth layer to growth layer, emphasizes a definite localization of site factors to each tree.

4. Disagreement among the trees increased with increasing distance, distance measured in yards rather than in miles.

5. Intergroup correlations (of groups 4, 5, and 9) were merely fair, not at all striking. They show a dual influence of site and distance.

6. In so far as the collection from Holman Pass is concerned, the nature of the species is clearly subordinate to the influence of site.

7. Correlations among different trees and among different groups were distinctly lower for the period 1850-1897 than for the period 1898-1941.

8. A simultaneous comparison of trend among all trees yielded 9 complete agreements among the trees during the 48 years of the period 1850-1897 and 15 during the 44 years of the period 1898-1941.

9. For group 10 (dry sites) average year-to-year variation, average departure, and average departure from mean variation increased whereas for group 11 (wet sites) they decreased for the period 1898-1941 in contrast with the period 1850-1897. However, the average departure of two of the trees in group 10 actually agreed with group 11.

10. The average departure from mean variation of group 7 (restricted) and group 7 itself decreased for the period 1898-1941 in contrast with the period 1850-1897.

11. A study and comparison of the growth-layer sequences emphasize the role of site factors local to each tree and the striking contrast of characteristics between the two periods, 1850-1897 and 1898-1941.

Study of rainfall characteristics.—1. Chacon rainfall was correlated with that of the other six stations for eight different month-intervals. Trend coefficients ranged from 0.61 to 0.99 and ratios of opposed trends from 0.41 to 0.09.

2. No clear-cut pattern emerged from this correlation between Chacon and the other stations. However, the values declined with the presence of summer rainfall and with an increase in the number of months in the month-intervals. Within the area from which rainfall stations were drawn, distance from Chacon made little difference in the variations among the several stations.

3. The average trend coefficient between Chacon and the other stations was approximately 0.89 and the ratio of opposed trends 0.23. If the trees were responding directly to the rain falling at the immediate site, they may be expected to correlate with Chacon rainfall to a degree equaling or slightly exceeding (because of the distance involved) the average of the correlations between Chacon and the other rainfall stations.

4. Correlations among the eight different month-intervals at Chacon ranged from −0.33 to 0.99 for the trend coefficients and from 0.66 to 0.06 for the ratio of opposed trends. Such divergences demanded that tree growth be tested against the full series of month-intervals.

5. If tree growth shows high correlation with a certain rainfall interval, as March-July, and if that interval has high correlation with a second one, as January-August, then tree growth may be expected to show high correlation with the second interval even though part of the rainfall of the longer interval may not influence growth.

6. Within limits, maximum correlation combined with minimum-length month-intervals should be the focus of critical information on the response of trees to rainfall.

7. The average March-July rainfall at Santa Fe was higher during the period 1898-1941 than during the period 1850-1897 and higher during the period 1909-1941 than during the period 1898-1941.

8. Average year-to-year variation, average departure, and average departure from mean variation of March-July rainfall at Santa Fe was less during the period 1898-1941 than during the period 1850-1897.

9. For the contrasted periods 1850-1897 and 1898-1941, the characteristics of the dry-site trees ran counter to those of rainfall whereas those of the wet-site trees ran parallel.

10. When a criterion of conformity, based on average departure, was applied and the two trees not conforming were eliminated, the characteristics of the resultant group 7 (restricted) followed those of rainfall.

Correlation between tree growth and rainfall.—1. Correlations between tree growth and rainfall of Chacon, the nearest station, were highest for the rainfall of the March-July interval of the same year. This is consistent with the principle of maximum correlation with minimum-length month-interval. The next best correlation, with January-August, was also high, but the reason was held to be the rather high correlation between that interval and March-July.

2. The growth of the trees composing the Holman Pass collection correlated directly with the precipitation which fell immediately before and during the season of greatest growth.

3. Correlation between the Holman Pass trees and Chacon March-July rainfall, based on raw (unsmoothed) data, attained the following remarkably high values: a trend coefficient of 0.965 and a ratio of opposed trends of 0.12.

4. The accumulated evidence points rather clearly to the conclusion that the trees respond very nearly 100 percent to fluctuations of rainfall at the immediate site.

5. Correlations between individual trees and Chacon rainfall were lower than those for groups. A few were surprisingly high.

6. The nature of the species appeared to make little difference in the quality of correlations.

7. The variations among the trend coefficients and ratios of opposed trends of individual trees emphasized again the localized influence of site factors on the single tree, the so-called microsite factors.

8. Correlations between tree growth and rainfall of stations other than Chacon gave mixed and rather poor results. Certain regional tendencies remained, but they are of little or no value.

9. Correlations between tree growth and Las Vegas rainfall were higher for the period 1910-1941 than for that of 1893-1941.

10. General correlations between tree growth and Santa Fe rainfall were fair to poor and have little value as regards season-to-season fluctuations. Such results were to be expected in view of the distances involved and the areal differences in rainfall as measured from station to station.

11. The higher the correlations were among the trees themselves, the higher their correlation with rainfall. An increase in amount of rainfall was accompanied by greater agreement among the trees.

12. The most important information brought out by the correlation of tree growth and Santa Fe March-July rainfall for the periods 1850-1897, 1898-1941, and 1910-1941 was this: The quality of the correlations was lowest for the first period and highest for the last. All tree groupings conformed. The amounts of March-July rainfall at Santa Fe showed a similar increase for the three periods.

13. In the above correlations, the trees from the wetter sites showed not only the highest correlations but also the greatest increases.

14. A change in temperature that affected the time of growth initiation in the spring probably shifted the month-interval of rainfall to which the trees responded.

15. Trees from drier sites, as a group, were poor recorders of changes in rainfall characteristics; individually, two out of the four conformed in part to the wet-site group.

16. A summary of changes from the period 1850-1897 to the period 1898-1941 follows:

In March-July rainfall:

- Average variation, average departure, and average departure from mean variation decreased with an increase in average rainfall.

In tree growth:

- Among all trees, internal agreement increased.
- For dry-site trees, group 10, average variation, average departure, and average departure from mean variation increased.
- For all trees, group 7, average variation and average departure increased whereas average departure from mean variation decreased.
- For wet-site trees and group 7 (restricted), average variation, average departure, and average departure from mean variation decreased, thus agreeing with changes in March-July rainfall.

CONCLUSIONS

A study of the Holman Pass collection, which came partly from the Transition and partly from the Canadian Life Zones, permits two general conclusions.

First, the evidence indicates rather clearly that variations in tree growth follow variations of March-July rainfall from year to year very nearly 100 percent at the immediate site of the trees.

Second, the evidence strongly suggests that changes of internal agreement among the trees and changes of average variation, average departure, and average departure from mean variation can be used as a method to reveal changes in rainfall through the years where amount of rainfall, and hence derived soil moisture, approximately equals that present at the location of the dominant members of the Holman Pass collection.