TREE-RING BULLETIN

VOL. 25 DECEMBER 1962 NOS. 1-2

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PUBLISHED BY THE TREE-RING SOCIETY
with the cooperation of
THE LABORATORY OF TREE-RING RESEARCH
UNIVERSITY OF ARIZONA

Subscription $2.00 per Volume

Manuscripts and inquiries should be directed to the Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona.

THE RELATION OF GROWTH RING WIDTHS IN AMERICAN BEECH AND WHITE OAK TO VARIATIONS IN CLIMATE*

HAROLD C. FRITTS

ABSTRACT

An analysis is made of beech from Ohio and white oak from Illinois using a stepwise multiple regression technique to evaluate ring growth and climatic relationships. Ring widths for beech are directly related to the moisture supply during August and to temperatures for May-July of the preceding year. They are equally related to moisture during June-August of the current year and somewhat dependent upon the precipitation of the previous winter. The earlywood width of white oak is directly related to available moisture during the preceding September and to moisture during the current June, and inversely related in slight degree to the temperature of April. Latewood width of oak is primarily dependent upon the availability of moisture during the current June and July but is somewhat related to the moisture during May of the previous year. Serial correlation is prominent from growth layer to growth layer in both species. The physiological relationships which may produce these results are discussed. Some relationships involving considerable lag in the growth response are possible controls of bud formation and food accumulation, while others involving more immediate response are primarily the effect of moisture stress within the tree.

The relation of tree-rings to climate has received considerable attention during the past 75 years (Glock 1955; Schulman 1956). Simple correlation techniques have frequently been used but with limited success, since such techniques presuppose that a single factor is the only major control of growth. More often the interaction of environmental factors (Billings 1952) complicates growth relationships making it difficult to analyze tree-ring width in terms of a single climatic variable. In studying tree growth some workers have successfully used more advanced mathematical techniques such as analysis of variance and covariance, orthogonal polynomials, and multiple regression which may take into account the complexity of the environment (Larson 1957; Davis and Sampson 1936; Schumacher and Day 1939).

Diller (1935) studied annual rings of beech in northern Indiana and reported that ring width was directly correlated with June precipitation (r. as high as 0.69) and in some cases there was a one-year lag for the effect of low June precipitation on growth. The average temperature in June was found to be inversely related to growth and more highly correlated than precipitation (r. as high as –0.80). However, Fritts (1956, 1960) reported

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*This study was supported in part by the American Philosophical Society, Johnson Fund. Extensive computing time and assistance was provided by the I. B. M. Corporation, Argonne National Laboratory, and the University of Arizona Numerical Analysis Laboratory.

that daily growth of beech in central Ohio was directly related to temperature when the effects of atmospheric humidity and soil moisture were taken into account, and that growth was greatly reduced when humidity and soil moisture were low. He suggested that such dry periods were frequently accompanied by high temperatures, and, thus, a negative correlation between ring width and temperature would be the result.

Schumacher and Day (1939) studied the relationship of white oak growth and precipitation in the southeastern United States. They found that variation in ring width was related in part to average monthly precipitation over a 15-month period, and in part to its distribution during that period. The rainfall of June of the previous year and November-July rainfall of the current year were directly related to growth, while August-October rainfall of the previous year and August rainfall of the current year were inversely related. They found that only 9 to 12 percent of the variation in width of the annual ring could be ascribed to fluctuation in meteorological factors.

Studies by Friesner and Friesner (1941) and Miller (1950) on white oak in Indiana showed that the highest growth-rainfall coefficients were with precipitation during June-August, May-August, or June. Kleine, Potzger, and Friesner (1936) reported that in addition to direct correlation of growth in white oak with precipitation of June-August, there was an inverse relation of growth with average temperature of June-August. They also stated that little correlation existed with spring temperature, only slight correlation with precipitation in April and May, and little correlation with droughts of the previous year.

Some studies have dealt with differences in width of earlywood and latewood. Lodewick (1930) found that precipitation from mid-June to mid-October had the greatest effect on the production of latewood in long-leaf pine in western Florida, while earlywood formation was almost constant irrespective of rainfall. No effect of temperature was noted. Larson (1957) reported that the percentage of latewood in slash pine increased with increasing June-July precipitation and decreased with increasing January-February precipitation. Fifty percent of the variance was accounted for by using percent of summer precipitation as an independent variable.

Smith and Wilsie (1961) found an inverse relationship between June-October soil water deficits and the width of latewood in 17-year-old loblolly pine from Arkansas. During a year of low water deficit there was a low percentage of latewood at the apex of the tree and a high percentage of latewood at the base, whereas, in years with greater water deficits the trend was less pronounced or even reversed. The width of the latewood zone and radial count of the tracheids in the latewood were similarly related to soil water deficits.

Fritts (1956, 1958) reports that radial growth of beech in central Ohio starts in late April or early May, continues rapidly during May and June, and declines during the month of July. He (Fritts 1958, 1960, 1961) analyzed daily radial growth of both Ohio beech and Illinois white oak by applying multiple regression techniques. It is the purpose of this study to apply similar techniques to annual ring width of the same species in the same areas for the purpose of evaluating the factors operating from year to year.

METHODS

The study areas were Blacklick Woods, a relatively undisturbed beech-maple and swamp-forest tract 10 miles SSE. of Columbus, Ohio, and an oak-hickory ravine forest 2 miles south of Charleston, Illinois. In the Ohio study, increment cores were taken from nine mature American beech *(Fagus grandifolio* Ehrh.) trees located on moderately well drained sites and five mature beech trees which were adjacent to a poorly drained depression. The soil characteristics in these sites were described by Fritts and Holowaychuk (1959). In Illinois, cores were taken from five mature white oak (*Quercus alba* L.) trees on a south-facing slope and from five trees on a north-facing slope of a small ravine. Three radii were sampled from each tree. The cores were mounted on grooved boards, prepared by sanding or planing, crossdated, and the ring widths measured to 0.001 inch under a dissecting microscope equipped with a mechanical stage and dial micrometer. The thickness of porous earlywood and the denser latewood was measured for the white oaks. The measurements for the several trees on each site were averaged so that yearly values were obtained in beech for 1900-1951 and in white oak for 1901-1958.

Monthly weather data for the above periods were obtained from the U. S. Weather Bureau records for the Columbus airport and for the city of Charleston. Estimates of monthly soil moisture storage and monthly evapotranspiration deficits were calculated according to Thornthwaite and Mather (1957).

Stepwise multiple regression routines (Fritts 1962b) were employed to ascertain the "best fitting" equation for predicting ring width as a function of the most effective "independent" variables. Ring measurements for each site were analyzed three times using three different measures of the moisture variable: (1) monthly precipitation, (2) monthly soil moisture storage, and (3) monthly evapotranspiration deficit. The analysis of white oak was further subdivided in order to evaluate the width of the earlywood and latewood as well as total ring width.

Ten independent variables were included in each analysis to represent moisture conditions for May-September of the season preceding the formation of the growth ring and April-August for the season of ring formation. Average monthly temperatures for the same months were used as 10 additional variables. Each analysis had additional variables as follows: total soil moisture surplus of the winter and spring preceding growth, the number of the year (01-51 or 02-58), year number squared, year number cubed, and year number to the fourth power. In the analysis of beech data the width of the previous year's ring was included as an independent variable so that serial correlation in the data could be taken into account (Quenouille 1952). In the analyses of white oak data the earlywood and latewood of the previous season were used for the same purpose and in the analysis of latewood, the earlywood of the current year was included.

In addition to sampling tree-rings, dendrographic studies (Fritts and Fritts 1955) were carried on in Illinois as a means of estimating when the earlywood and latewood increments were laid down. The ring widths and the annual growth measured by dendrographs were first shown to have a one to one relationship and to be highly correlated (Fritts 1962a). Then the daily growth record during the growing season was compared to the percent earlywood in two white oaks during four consecutive years and estimates were made of the relative time periods during which each tissue was produced.

RESULTS

The results of the analyses are presented in Table 1 and Figures 1-6. It is apparent from Table 1 that the multiple correlations are high in these analyses, accounting for 60 to 84 percent of the variance. In the beech study, the use of monthly evapotranspiration deficits provided the highest multiple correlations while calculated soil moisture storage gave the lowest. For white oak, monthly precipitation provided the highest correlations for analysis of earlywood while the use of evapotranspiration deficits gave higher correlations for latewood. In the analysis of total ring width, there were no significant differences between the multiple correlations.

TABLE 1. Statistical Parameters Obtained in the Regression Analyses of Tree-Ring Widths Using Different Moisture Variables.

	Average Monthly Precipitation		*Calculated Monthly Soil Moisture Storage*		*Calculated Monthly Evapotranspiration Deficits*		*Standard Deviation of Y*
	Multiple Correlation R	*Standard Error of Estimate*	*Multiple Correlation R*	*Standard Error of Estimate*	*Multiple Correlation R*	*Standard Error of Estimate*	
Beech on well drained sites	.800	11.9	.788	12.2	.830	11.1	19.9
Beech on poorly drained sites	.804	12.2	.778	12.9	.850	10.8	20.5
White Oak on south-facing slope:							
Earlywood	.893	06.5	.888	06.6	.871	07.1	14.4
Latewood	.835	34.2	.812	36.3	.884	29.1	62.1
Total ring	.830	38.8	.764	44.9	.842	37.6	69.5
White Oak on north-facing slope:							
Earlywood	.914	05.1	.875	06.1	.857	06.4	12.5
Latewood	.894	23.7	.894	24.2	.903	23.2	54.0
Total ring	.892	28.3	.884	29.3	.880	29.7	62.6

The figures provide a basis for determining which variables made the greatest contribution to ring width variation. Each bar represents the relative size and sign of the standardized partial regression coefficient while the dots indicate their significance. Figures 1 and 2 represent two analyses of beech; one of trees growing on well drained sites and the other of trees growing on poorly drained sites. The figures differ in that monthly precipitation was used as the moisture variable in Figure 1 while monthly evapotranspiration deficit was the moisture variable in Figure 2. Figures 3-6 each represent three analyses of white oak rings: the first of variation in earlywood widths, the second of variation in latewood widths, and the third of variation in total ring widths. Figures 3 and 4 represent analyses of the trees growing on the south-facing slope, while Figures 5 and 6 represent analyses of trees growing on the north-facing slope. The environmental variables are comparable to those in Figures 1 and 2. The standardization of the regression coefficients for Figures 3-6 differs from the usual calculation in that the unstandardized coefficient was multiplied by the standard deviation of the independent variable divided by the standard deviation of the total ring width. Thus the bars in the figures represent the proportional contribution of each variable to total ring width.

The results of the analyses employing soil moisture storage are not illustrated because of their lower correlation and larger standard errors which make interpretation more difficult. These results did not differ markedly from the other analyses.

DISCUSSION

American Beech. It is apparent from Figures 1 and 2 that ring width variation in beech is dependent upon: (1) ring width of the previous year, (2) climate of the previous growing season, and (3) climate of the current year. The standardized coefficients for growth as a function of the previous ring width are larger for the trees on well drained sites, while the coefficients for many of the environmental variables are larger for the trees on poorly drained sites. This suggests that a carry-over effect (serial correlation) is less prominent for trees on the poorly drained sites and that ring widths vary more with changes in the climate. This is in agreement with previous findings based on daily growth and soil analyses in the same study area (Fritts 1956; Fritts and Holowaychuk 1959). Beech trees on the poorly drained sites were shown to be shallow-rooted and readily affected by a rapid decline in soil moisture supply and, consequently, their radial growth was severely restricted by mid-summer droughts. Since the relief in this

Graphs of Standardized Regression Coefficients for Final Regression of Ring Width and Environmental Relationships

Fig. 1. Beech with monthly precipitation as the moisture variable.
Fig. 2. Beech with monthly evapotranspiration deficit as the moisture variable.
Fig. 3. White oak on a south-facing slope with monthly precipitation as the moisture variable.
Fig. 4. White oak on a south-facing slope with monthly evapotranspiration deficit as the monthly variable.
Fig. 5. White oak on a north-facing slope with monthly precipitation as the moisture variable.
Fig. 6. White oak on a north-facing slope with monthly evapotranspiration deficit as the moisture variable.

Symbols

CEW—earlywood width of current season
PEW—earlywood width of previous year
PLW—latewood width of previous year
PR —previous spring
SMS —soil moisture surplus during previous winter

Single letters—months
Significance levels
· = .950
: = .990
⋮ = .999

FIG. 1

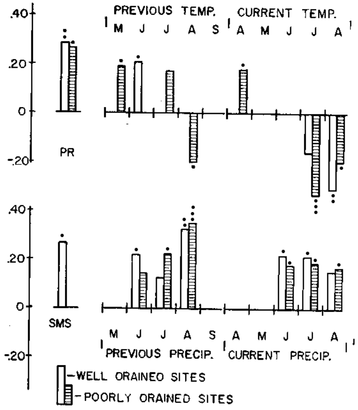


FIG. 2

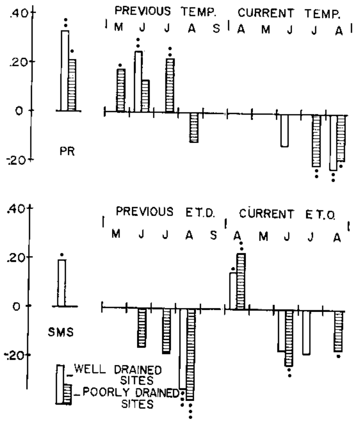


FIG. 3

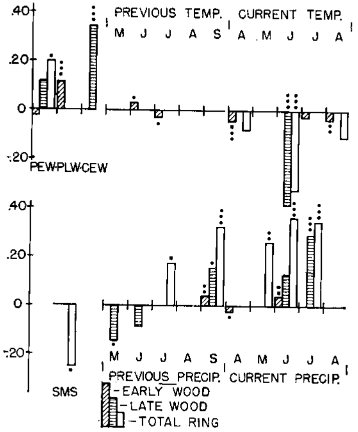


FIG. 4

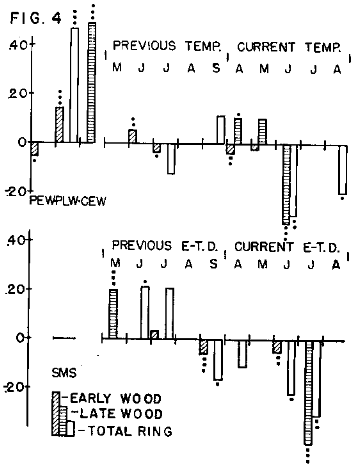


FIG. 5

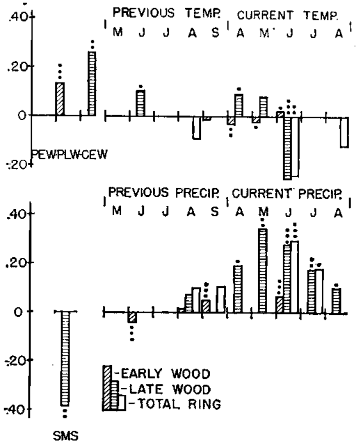
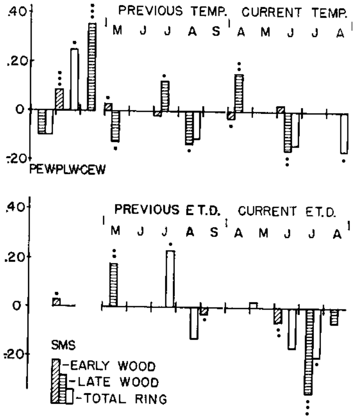


FIG. 6



particular study area was no greater than 10 feet, the well drained sites represent optimum rather than extreme conditions for growth of beech (Fritts and Holowaychuk 1959). The extremely well drained soil type is not present in the area. Thus, the poorly drained sites are actually the extreme and most limiting environments and the variation in tree-ring widths exhibits the greatest "sensitivity" to environmental variables.

It appears from Figures 1 and 2 that the environmental conditions of the previous season are equally or even more effective on ring width variation than the conditions current to the formation of the ring. The regression coefficients for growth as a function of drought of August of the previous year (represented by high temperatures or high evapotranspiration deficits) are the largest and most significant coefficients obtained in the analyses. Monthly temperatures during May through July of the previous year appear somewhat directly related to growth. These relationships probably are a result of the food supply available for xylem production the following year. A warm early season would favor leaf growth as well as bud initiation for the following year's leaves, while a drought in August, when the current radial growth is essentially complete (Fritts 1958), would be considerably limiting to photosynthesis and the accumulation of the following year's food reserves.

An abnormally dry or warm April appears to favor larger rings, especially for trees on the poorly drained sites, while a high soil moisture surplus during the previous winter is directly related to ring width only for trees on well drained sites. Consideration of the microenvironmental relationships provides a possible explanation for these results. The poorly drained soils usually are saturated, with poor aeration and low soil temperatures prevailing well into June (Fritts and Holowaychuk 1959). As a result, initiation of radial growth may be delayed or the growth rate reduced during an average or wet spring. However, a dry, warm April or a winter of little excess moisture will result in better aeration and higher soil temperatures, allowing for more early season growth (Fritts 1956, 1960). On the better drained sites, excess winter precipitation might conceivably be favorable to ring growth. In these sites tree roots are deeper, soil permeability is higher, and drainage is better (Fritts and Holowaychuk 1959). Excess winter precipitation would result in deeper moisture penetration but not reduce aeration. The trees would thus have a greater moisture supply during the following growing season and hence a larger ring.

Droughts during June-August of the current year, especially if accompanied by high temperatures, may limit the current year's ring production. The results indicate that high July temperatures are more limiting to tree-ring growth in poorly drained sites, while high August temperatures are more limiting to ring growth in the better drained sites. This is also in agreement with earlier findings that daily radial growth of trees on poorly drained sites is frequently limited by high temperatures in July (Fritts 1956). While such conditions cause abrupt cessation of growth in these trees, the trees on the better drained sites may continue growing well into August.

The results of this study indicate that relationships between ring growth and the environment in central Ohio are somewhat different than those reported by Diller for northern Indiana (Diller 1935). The effect of precipitation during the previous August on variation in ring width appears to be equal to, if not more important than, the current precipitation. The simple correlation for this relationship is as high as –0.45. Precipitation during July rather than June of the current year gives the higher simple correlation (r. = 0.34). The two studies agree in that the simple correlation between June temperature and growth is the highest obtained (r. = 0.57

in Ohio). Unfortunately, this relationship may be only an apparent one, for in the stepwise multiple regression routine, June temperature enters early in the analysis with a significant F ratio, but as new variables are entered in the equation, the intercorrelations are such that this variable becomes of low significance and is even dropped from three of the four analyses (F. < 1.0) represented in Figures 1 and 2.

White Oak. The average date for initiation of growth in two white oaks, as measured by dendrographs for four years, was April 7 with a maximum range of ± 8 days. The calculated average date for transition from earlywood to latewood, estimated from a comparison of growth records and relative ring widths, was May 24 with a maximum range of ± 8 days. The average date for growth cessation was August 22 with a maximum range of ± 19 days. Since the dendrograph measurement of growth includes both cell division and cell enlargement, it is quite likely that cambial initiation of the first formed latewood cells started before the calculated May date while expansion of some earlywood cells may have occurred as late as June. Thus, it appears that April-June represents the approximate period of earlywood growth and May-August the period of latewood growth.

Analyses of the white oak data indicate that total ring width is not as highly related to growth of the previous season as it was in beech. In every case, earlywood width is highly related to latewood of the previous year, and latewood is highly related to the amount of earlywood of the same year. Serial correlation is very high and is exhibited mainly between adjacent growth layers which make up the ring.

The analyses of total ring width exhibit the combined effect of the environment on earlywood and latewood, although the variability of latewood is larger (Table 1) and is the major contributor to total ring width.

A wide earlywood layer appears to be consistently related to abundant moisture during September of the previous season, and to low temperatures in April and abundant moisture in June of the current growing season. The relationship of earlywood width and available moisture in September of the previous year undoubtedly involves photosynthesis and accumulation of food reserves utilized in growth since a large portion of the early season growth occurs before the leaves are sufficiently expanded to carry on maximum photosynthesis (Fritts 1960). The inverse relationship with temperatures in April may possibly be due to a greater efficiency in assimilation and conversion of food materials to cell parts when temperatures are low. The direct relationship with moisture in June suggests that cell enlargement of the earlywood may occur as late as June if the season is abnormally wet.

The latewood portion of the ring appears highly dependent upon the width of the earlywood. It also appears to be significantly related to dry conditions during May of the previous year. It is possible that this condition during the previous year favors initiation of the leaf primordia and a larger leaf area the following year and, therefore, produces a greater available food supply for latewood growth.

Latewood width, however, is more markedly influenced by the climate of the current season wherein average June temperature and July evapotranspiration deficit constitute the major factors. When precipitation amounts for April-August are used as variables, the results appear to be equivalent to, and the inverse of, the results when using evapotranspiration deficits—at least for the trees on the north-facing slope. These relationships illustrate the importance of an adequate water balance during the time of latewood growth, which was shown by means of dendrograph studies to largely occur during the months of May, June, and July. The direct relationship, which is apparent with temperature in April, may be associated with the inverse relationship that was present between temperature and width of earlywood, or perhaps the temperature during this period influences the rate of the transition from production of earlywood to latewood cells. The physiological basis for such a mechanism, if it exists, is not presently apparent.

CONCLUSIONS AND SUMMARY

Tree-ring and environmental relationships are evidently complex but appear to yield to multiple regression analysis. The relatively high multiple correlations attest to the success of this technique.

Tree-ring variation is highly related to width of the preceding ring as well as to variation in climate. Monthly precipitation and mean monthly temperature values were relatively satisfactory in analyzing the ring width and climatic relationships. However, the calculated monthly evapotranspiration deficits gave higher correlations in the analysis of beech and in the analysis of latewood in white oak.

The width of growth rings of beech is equally if not more highly related to environmental conditions of the previous season than to the current one. Ring width is inversely related to the severity of drought during August of the previous year but somewhat directly related to May-July temperature of the previous year. The conditions of the preceding winter and early spring may also be important since high moisture reduces growth on the poorly drained sites whereas it may favor growth on the well drained sites. The most limiting climatic conditions concurrent with the period of tree growth are droughts and high temperatures during June-August.

The trees on the poorly drained sites respond more readily to high July temperatures of the current year than do those on well drained sites. The season's growth appears less related to the growth increment of the previous season. Hence, the ring patterns for trees on these sites exhibit more variation and may be considered more "sensitive" to environmental differences from year to year than those from well drained sites.

White oak also exhibits serial correlation between adjacent growth layers. In addition, a large earlywood width is highly related to available moisture during the preceding September, and to low temperatures in April and abundant moisture in June of the current year. The variation in width of latewood is larger than the variation in width of earlywood. It is inversely related to the severity of drought represented by high temperatures in June and high evapotranspiration deficits in July. Latewood width also exhibits some direct correlation with evapotranspiration deficits during May of the previous year.

The relationships between ring width and the environment of the previous season may be due to: (1) early season conditions which affect bud initiation and thus influence the potential photosynthetic area which will be produced the following year, and (2) late season conditions which influence food accumulation and the total food reserves available for growth during the following year. The relationships of growth and environment of the current season are thought to be direct results of limiting factors occurring throughout the growing period. The periods of earlywood and latewood growth, as calculated from dendrograph measurements, indicate that the correlations have a reasonable cause and effect basis.

Growth rings of beech would be somewhat difficult to use in dendroclimatic evaluation, as the effects of the preceding season could not be isolated from those of the current one. However, the rings of white oak can be subdivided into earlywood and latewood, and since latewood width is highly variable and predominantly related to summer drought, rings from this species have definite dendroclimatic possibilities as estimators of the severity of summer drought.

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Laboratory of Tree-Ring Research
University of Arizona, Tucson

THE TREE-RING SOCIETY

MAY 1962 MEETINGS

Hosts for the twenty-seventh annual meeting of the Society for American Archaeology, May 3, 4, and 5, 1962, at the University of Arizona, Tucson, were the Arizona State Museum, the Department of Anthropology, and the Laboratory of Tree-Ring Research, with the collaboration of the Amerind Foundation and the Tree-Ring Society. As a part of these meetings on May fifth, there was a morning symposium on tree-ring dating, a luncheon meeting of the Tree-Ring Society, and, in the afternoon, an Open House at the Laboratory of Tree-Ring Research.

The symposium on tree-ring dating was led by a panel consisting of R. E. Bell, W. W. Caldwell, J. L. Giddings, E. W. Haury, W. G. McGinnies, J. C. Mc.Gregor, and B. Bannister, Chairman. A tribute to A. E. Douglass "HH-39: Recollections of a Dramatic Moment in Southwestern Archaeology" was first presented by E. W. Haury. The program following consisted of a survey of tree-ring dating throughout the world, new applications of tree-ring data, new techniques in the collection and analysis of tree-ring materials, and an open discussion of the future expansion of tree-ring activities.

Thirty-four Society members and interested individuals attended the Tree-Ring Society Luncheon. A short business meeting followed with President John C. Mc.Gregor presiding. In the afternoon, a gratifyingly large number of conference delegates visited the Laboratory of Tree-Ring Research during its Open House. Through the courtesy of W. G. McGinnies, Director of the Laboratory, copies of the Douglass memorial issue (Vol. 24, Nos. 3-4) were made available to all attending.

Minutes of the Tree-Ring Society meeting. The treasurer's report briefly stated that the disjunctive phasing of subscriptions and *Tree-Ring Bulletin* publications had delayed bookkeeping and billing. Recent sale of a few of the remaining full sets of the *Bulletin* and of large orders of the recently republished *Dating Archaeological Ruins by Tree-Rings* has put sufficient monies into the treasury to pay for the publication of Volume 25. No advance in subscription rate is anticipated in the next few years. A portion of the current mailings are being held up due to the need for evaluation of many accounts on an individual basis.

The editor of the *Tree-Ring Bulletin* reiterated his policy of accepting manuscripts dealing both with archaeological and with modern phases of tree-ring studies. Announcement was made that Volume 24, Numbers 3-4 was in print and that manuscripts were shortly expected for Volume 25.

In lieu of an election of officers, it was agreed that the present slate would continue in office.

The following resolution was submitted by J. L. Giddings and unanimously approved by those present:

> Resolved: That the Tree-Ring Society herewith expresses its sense of deep loss in the death of Dr. Andrew Ellicott Douglass who some 57 years ago initiated the study of dendrochronology and who throughout this period by his wisdom, energy, and dedication directed the development and destinies of this important branch of science, a study which gave unique meaning to archaeology and which has materially contributed to such diverse fields as astronomy, climatology, and ecology.

C. W. Ferguson
Secretary-Treasurer