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COMPUTER PROGRAMS FOR TREE-RING RESEARCH

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Abstract

Computer programs are described for: (1) the derivation of tree-ring indices and associated statistical parameters, (2) the dating of unknown tree-ring series against a longer master chronology using correlation techniques, (3) the calculation of cross-correlation to evaluate covariation among a large number of series, and (4) the estimation of variance components for sampled tree-ring series. General applications of these programs are illustrated by reference to an example of archaeological dating, a study of correlation among tree-ring series as a function of distance, and several ecological evaluations of tree-ring variability.

The more recent application of modern statistics to tree-ring problems and the consequent demand for greater replication and objectivity (Bryson and Dutton 1961; Matalas 1962; Fritts 1962a, 1962b) has required the development of new methods for rapid processing and computing of data from measured tree-ring series. During the last two years the author has been engaged in developing several computer programs to meet this growing need. These programs are now integrated into a unified package and are an integral part of the standard procedures used by the Laboratory of Tree-Ring Research. They are written in FORTRAN for use on an IBM 7072 computer, and are compatible with one another, so that the output of certain programs may be used directly as input for others.

Derivation of Tree-Ring Indices

Individual samples of ring series may differ markedly in the average ring width due to differences in growth potential for specific trees or sides of the tree. Ring widths also vary with distance from the central ring. In southwestern America, the datable species exhibit an abrupt rise in growth from the pith to a maximum which occurs about five to ten years from the center, after which the expected ring width diminishes approximating the exponential function $y = ae^{-bx}$, where y is the expected ring width and x is the number of years from the period of maximum growth (Matalas 1962).

However, the absolute variation in ring width also tends to decrease with distance from the center, so that tree-ring widths are a nonstationary time series. To facilitate statistical analyses, these nonstationary series must be transformed to stationary series by deriving indices which are the equivalent of the expected value for the exponential growth curve divided by the corresponding ring width measurement. The variance of this transformed series was shown to be essentially independent of time (Matalas 1962).

The program developed for deriving indices converts ring widths to natural logarithms and calculates by least squares techniques the linear regression coefficient (b, in the above equation) for logarithms of ring width as a function of time which is equal to, or less than, zero. The constant, a, in the above equation, is then calculated so that $\int_{x_{0.5}}^{x_{n+0.5}} ae^{-bx}dx$ equals the sum of the ring widths, thus forcing the average index for every series to approximate 1.00. The mean sensitivity, an additional parameter used in tree-ring evaluation, is calculated as the difference between two adjacent rings divided by their mean. The above data are printed for each ring and the indices are punched on a format of ten indices per card. The index values are also stored on magnetic tape for summarization after all ring series have been transformed. At the end of each series, several summary parameters are printed and punched. These are the first order serial correlation of the indices, their standard deviation, mean, and their sum and the sum of their squares; the mean ring width; the mean sensitivity for the series; and the a and b coefficients for the exponential growth function. The mean sensitivity for the entire series is calculated by squaring and adding the individual values, dividing by n-1, and extracting the square root.

Control cards are used to call back specific series of indices which are added to others to produce a new series representing mean yearly indices. The individual sums, sums of squares, N number, standard deviation, standard error and mean sensitivity are calculated for each year, as well as the above summary parameters for the mean indices. These new indices are also punched in the ten per card format, along with the N number represented by each mean index value. At the end of the program, after all compilations are made, the sums and the sum of the squares for all series are punched on cards, and these are used as input for the analysis of variance program. The index determination program can handle approximately 10,000 ring width values per hour.

Correlation Programs

Two correlation routines are written to process the output from the index program: one measures the cross-correlation at all possible matches between two series of indices, and the other calculates all possible correlations between a group of matched series.

The first correlation routine can be used to date series which cannot be conclusively dated by skeleton plot techniques (McGinnies 1963). For example, archaeological tree-ring samples collected at the Casas Grandes site (Scott 1963) were used to derive a 486-year floating (undated) chronology in northwestern Chihuahua, Mexico. Visual comparisons between this series and the long chronologies from the Rio Grande and Flagstaff areas, which were 400 miles distant, failed to yield conclusive matches. The tree-ring data were converted to indices, and the output representing the chronology for the mean of the Casas Grandes series was correlated with the Flagstaff and Rio Grande master chronologies by means of this program for end dates ranging from 1060 to 1644. In both comparisons, the match at 1336 provided the only significant correlation coefficient (0.001 level) which had a probability markedly less than .0001 of arising by chance alone ($t = 4.44$, $df = \infty$). A plot of these correlations with the Flagstaff series for only the fourteenth century is presented in Figure 1. The program prints the mean of the indices, standard deviation, covariance, correlation coefficient, 0.999 confidence interval, and the null "t" at each match.

The second correlation routine can be used to compare and contrast

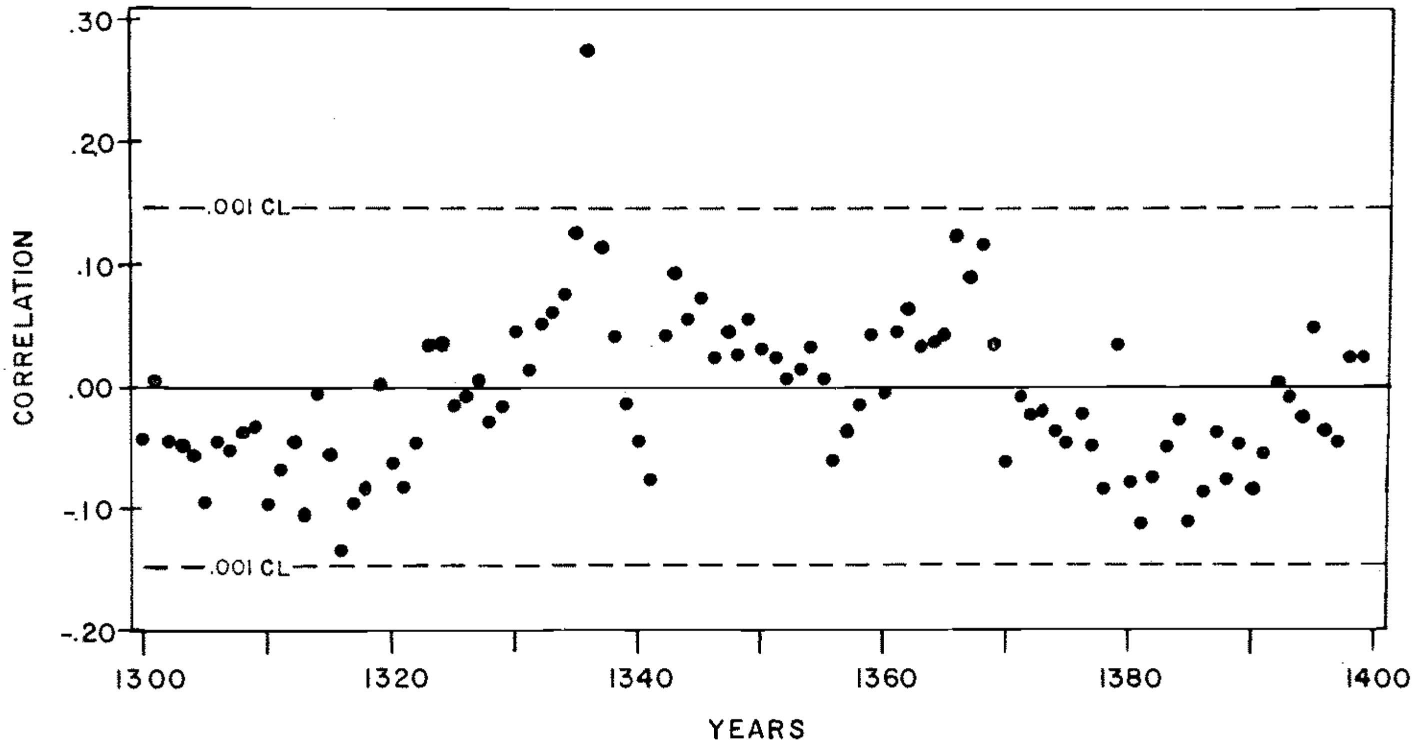

FIG. 1. Correlations of the Casas Grandes indices with the Flagstaff master chronology at every match for end dates during the fourteenth century. The marked high correlation is for 1336.

correlations between series of the same length. The program is written to compute all possible cross-correlations, the group means, standard deviations, and first order serial correlations. It has been employed to evaluate correlations among replicate samples within the same tree, among trees within the same group, and among groups for different sites or species.

Figure 2 is a further example of the use of the second correlation routine. Twenty-one stations in western America were selected where tree-ring indices had been determined (Schulman 1956). The stations ranged from Durango, Mexico, north to the Frazer River Valley of Canada, and from near Susanville, California, east to the Big Bend area of Texas. Tree-ring indices from 1650 through 1920 were used to obtain all possible cross-correlations between pairs of the 21 stations and the correlations were then plotted as a function of the distance between the pairs. These data show that there is highly significant correlation for series less than 300 miles distant, that on the average tree-ring series exhibit significant correlation with distances up to 700 miles, and that some series may exhibit significant correlations where distances are as great as 1100 miles. The superimposed curve in Figure 2 represents an idealized relationship of the correlations of monthly precipitation for December, January, and February at Dodge City, Kansas, with other North American stations plotted as a function of distance (Mitchell 1962). The similarity between the correlation of tree-ring data and the correlation of winter precipitation data with distance is marked.

Both correlation programs read from the output of the index program without format change or card sorting, and as an added feature, both calculate the linear correlations for tree-ring indices then convert them to natural logarithms and repeat the same operations. Minor alterations in the program will allow for any standard transformation.

ANALYSIS OF VARIANCE

An analysis of variance program was written to handle a balanced sample of indices for any length but requiring more than one core per tree

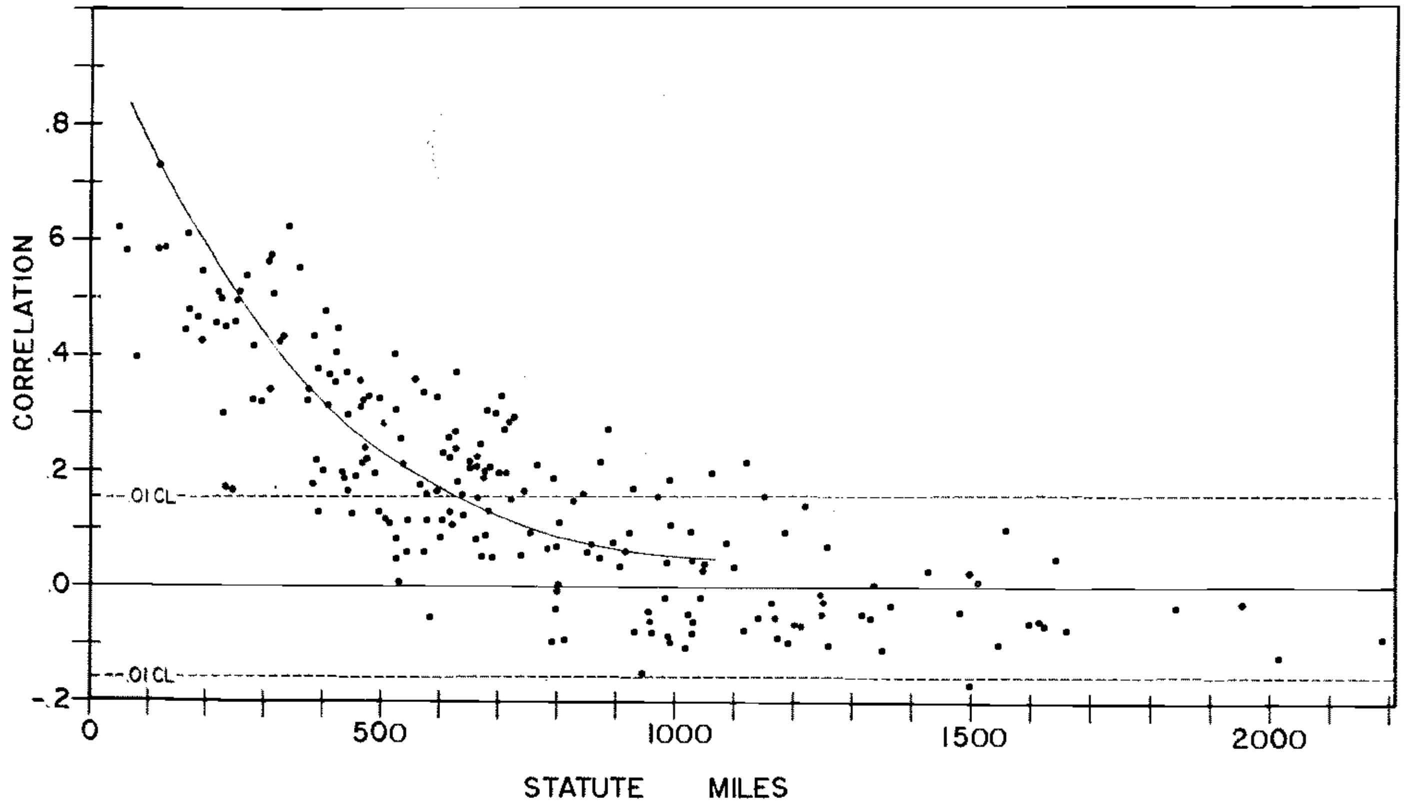

FIG. 2. The correlation between tree-ring series as a function of distance for 21 stations in western North America. The superimposed curve is an idealized relationship for correlation of winter precipitation as a function of distance (Mitchell 1962).

and more than one tree per group. This program uses the last output cards from the index routine as input, and calculates the mean squares and the variance component for the chronology of the total sample, the individual groups, individual trees, individual radii sampled per tree, as well as interactions of the above classifications (Snedecor 1956). This provides an estimate of the sampled variability so that by structuring a sample along environmental, edaphic, or biotic gradients, one can evaluate the relative similarities and differences in the tree-growth response. In addition, such information is of value in estimating the reliability of sampling procedures in tree-ring work.

The program has been used for analyzing a wide variety of samples from five different species in southwestern United States. The highest variance retained in the group chronology is generally found where trees are near their lower forest border, while the highest percent variance attributed to chronology differences among radii and among trees occurs in the forest interior or upper forest border. The species, Douglas-fir, exhibits the greatest similarity in variation among radii of the same tree and among trees of the same group and thus has the highest percent variance attributed to the group chonology, while ponderosa pine is intermediate and pinyon pine and bristlecone pine appear to exhibit the lowest percent variance due to the group chronology.

Table 1 includes four analyses used in an ecological study of three groups of ponderosa pine growing on the same site but distinguished by needle numbers per fasicle (Dodge 1963). The phenotype with three-needle fasicles ranged from the study site to higher elevations, and the five-needle phenotype generally extended to lower elevations. The group with fasicles varying in needle numbers exhibited a range intermediate to the above two classes. The variance sample includes 80-year chronologies from six trees per group and two cores per tree which had been processed by the computer routine for index derivation. The analysis of the total sample showed that differences in the year-to-year chronology of the three groups (Y x G, see Table 1) were small; but the analyses of individual needle classes indicate that the five-needle group, which was at its upper alti-

TABLE 1. Analyses of variance for three-needle, mixed-needle and five-needle ponderosa pine from the Santa Catalina Mountains, Arizona.

TOTAL ANALYSIS					ANALYSES OF INDIVIDUAL GROUPS		
Source of Variation	*Mean Square*	*df*	*Estimated Mean Square*	*Percent EMS*	*Percent EMS*		
					Group		
					Three-Needle	*Mixed Needle*	*Five-Needle*
Groups	.012	2	......				
Cores	.004	1	......				
Trees	.019	15	......				
C x G	.013	2	......				
C x T	.005	15	......				
Years	3.395	79	.092	55	65	64	41
Y x G	.170	158	.006	3	....	....	....
Y x T	.101	1185	.032	19	14	17	30
Y x C	.029	79	.000	0	1	1	0
Y x C x G	.042	158	.001	1	....	....	....
Y x C x T	.036	1185	.036	22	20	19	29

tudinal limits, had only 41 percent of the total variance retained in the group chronology (Years, see Table 1), while the three-needle group, which was growing near its limits, retained 65 percent of the total variance in the group chronology.

Since high variance for the group chronology is associated with trees near their lower forest border while proportionally lower variance for the group chronology is associated with trees in the forest interior or upper forest border, these results are thought to indicate different growth potentials for the two extreme phenotypes. Thus in the sampled site the three-needle trees are nearer their lower altitudinal limits than the five-needle trees, yearly climatic variation is more frequently limiting to their growth, and the year-to-year ring patterns among the radii and among trees of the group are more similar. These two needle classes appear to be hybridizing and producing the mixed-needle class (Dodge 1963), and the analysis of variance indicates that the ring patterns for this class are more similar to the three-needle parent.

SIGNIFICANCE

Once tree-ring samples are crossdated, measured, and ring widths punched on cards, one can make a number of analyses on any series with a minimum of card handling and computer time. For example, a recent sample of eighty 100-year long cores from twenty trees was completely analyzed, including correlation and variance analysis of a variety of groups and subgroups with five trees per group and four cores per tree, and the computer time used was less than two hours. An even more significant feature is that once specimens are dated and measured, the treatment is objective, making results completely reproducible. In addition to the rapid and objective derivation of indices, estimates are automatically provided on a variety of other statistical parameters.

Although there are still cases where traditional methods of eye-fitted curves and manual derivation of indices may be more economical, in cases where large numbers of data are to be handled, and where there is interest in statistical measures on the parameters of tree-ring variation, a computer package of this nature is a major necessity.

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