A Statistical Study of Dendroclimatic Relationships in South Central Wisconsin

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ABSTRACT

Stepwise multiple regression analysis applied to annual radial growth increments of mid-latitude hardwood samples indicates that satisfactorily high levels of reduction of the growth variance can be achieved only by utilizing a number of climatic and temporal parameters, both simple and compound. A large part of the variance, as might be expected, is associated with the secular trend of the growth rate. Of the climatic parameters, July precipitation and July evaporative stress were found to be most significant. In particular, since these parameters occurred in the combination precipitation minus evaporative stress, a strong dependence of growth rate on water availability was found.

1. Introduction

The growth of trees is affected to a great extent by the environmental conditions under which they live. The most variable part of a tree's physical environment consists of the various climatic parameters, and these same variables influence the amount and rate of growth of individual specimens in which genetic and other edaphic factors are nearly constant. If the exact relationships between growth and the climate can be ascertained, it is theoretically possible to establish the magnitude of such climatic variables by studying the past growth record of trees. The purpose of this paper is to examine the statistical relationships between climate and the annual radial growth variance, or year to year variation in growth of early, late, and total wood from trees obtained from a mid-latitude hardwood stand. This will be investigated by means of stepwise multiple regression techniques as applied to species mean growth values.

Before proceeding with this study a brief review of the results reported in the literature is in order. Most dendroclimatological studies hold that, in general, only two climatic variables, temperature and precipitation, are important in influencing and limiting tree growth. Results of research performed in arid regions of the southwestern United States have stressed the importance of precipitation as a limiting factor to tree growth (Schulman, 1956; Douglass, 1928; etc.). Holmesgaard (Eklund, 1956) feels that temperature in winter and early spring are of great importance to the growth increment of Alder, Scotch pine, and Douglas fir. Hare (1950) similarly holds the view that northern forests are governed in their growth by temperature, and that precipitation is everywhere adequate to supply the needs of growth under such cool conditions. Miller (1950) states that the Arctic timberline can easily be shown to have nothing to do with precipitation except where muskeg and anaerobic conditions deter growth. Siren (1961) again indicates that the mean temperature of the period June through August is the most significant climatic determinant of tree growth.

While it may be true that temperature and precipitation are of singular importance to tree growth under the rigorous conditions of the desert or the Arctic, growth-climate relations become considerably more complex as one leaves such regions. Giddings (1943) showed some insight into the complexity of the problem by stating that, irrespective of species, the ring record loses its pure temperature significance as one retreats from the timberline and becomes a mixed record of temperature, growing season, and unknown factors.

With few exceptions little research has been carried out in the field of mid-latitude hardwood dendroclimatology. One exception is that of Fritts (1962), working in the Charleston, Illinois, area. Fritts utilized stepwise multiple regression techniques in relating annual radial tree growth of ten mature white oaks to several statistically selected climatic factors. His study indicates that, considering only climatic variables, a significant portion of the growth variance of late wood may be explained by mean June temperature, and the product of July evapotranspiration deficit and June temperature.

As has been inferred, tree growth in mid-latitudes is a complex function of several interacting environmental factors. Acknowledging the general complexity of the problem we proceed with the present analysis.

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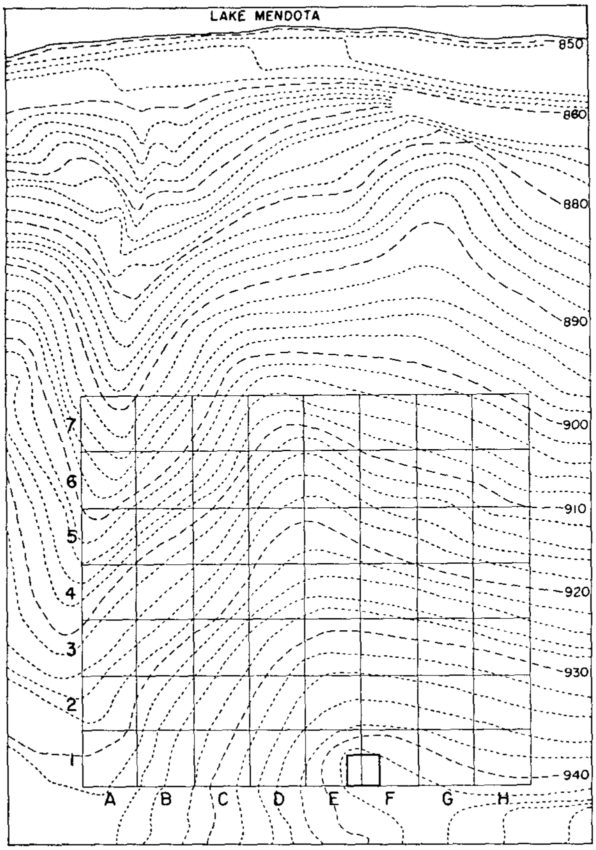

FIG. 1. Stand subdivided into 40 foot squares, with contour lines in feet. Heavy outline in section 1E/1F indicates a local landmark.

2. The materials for present study

A. Biotic. When a portion of Bascom Woods, on the University of Wisconsin campus (lat 43°08′ N Long., 89°20′ W), was cut in March of 1961, it was possible to secure a cross section of each tree felled. The stand site consisted of a fairly uniform slope to the north-northwest of approximately 18 per cent, ranging in altitude from 942 down to 890 ft above sea level. The lowest part of the stand was approximately 40 ft above nearby Lake Mendota (Fig. 1). The site was well drained and possessed a Gray-Brown Podzolic soil association, the dominant type of which is Dodge silt loam, glacial outwash substratum phase (F. D. Hole, personal communication).

Eighty-two samples were obtained in all and included: Burr, Red, White and Black Oak, Elm, Ash, Larch, Locust, and Hackberry (Table 1).

The size of the annual growth rings is very dependent upon the age of the tree. In general a sapling will put on much larger annual rings than an older tree, regardless of climatic conditions. This is probably due to the fact that as a young tree matures, the ability to carry out photosynthesis, as determined by leaf surface, and the carbohydrate production decrease in proportion to the total mass of the tree (Kramer, 1960). Furthermore, in a stand of relatively uniform age, as was the Bascom Woods stand, the saplings are relatively free of competition, allowing for rapid growth. As maturation takes place, increased competition reinforces the physiological trend toward slower growth rates.

The ring thicknesses were measured on a Gaertner specially adapted 1949 model traversing microscope with a 8× Wetzler ocular and a 16 mm Zeiss objective commensurable to the nearest ten thousandth of an inch. Both early wood and late wood growth were measured, differentiating on the basis of relative cell wall thickness and summed to give an annual or total wood value. Two radii (of one diameter) were measured in this manner and averaged to give a more representative composite value. The data were then punched on IBM cards.

B. Climatic. In selecting the climatic variables used in this study, an attempt was made to include as many as could possibly be significantly related to the variance of the growth time series. Monthly values of the "standard" variables, mean temperature and total precipitation, were chosen. Their importance to radial growth has been adequately suggested elsewhere (Kramer, 1960; Schulman, 1956; Hustich, 1949; etc.). Winter averages of these variables were also used because they expressed the integrated effect of the individual parameters during the non-growing season, a period in which monthly values would have little meaning. It was hoped that these variables might indicate whether winter moisture storage or severity as reflected by means of temperatures during the dormant season, could be related to the annual growth variance.

The other two variables used were monthly values of total hours of bright sunshine and mean values of evaporative stress (which will be defined below). Sunshine, while not necessarily limiting, is important in its microclimatic thermal and evaporative effects. Evaporative stress is a complex variable which considers the combined effects of temperature, humidity, and wind speed. It expresses the conditions for physiological drought through the process of desiccation.

TABLE 1. Number of samples and range of tree ages, according to species.

Species	Number of samples	Age range
Burr Oak	5	78–139
Red Oak	25	75–109
White Oak	13	71–107
Black Oak	7	80–108
Elm	13	48–70
Ash	13	10–56
Larch	1	76
Locust	3	14–33
Hackberry	1	55

Winter mean values of sunshine and evaporative stress were not included since there was no reason to believe that such variables could explain any part of the annual radial growth variance.

The meteorological variables used in this study (Table 2) were measured at the U. S. Department of Commerce Weather Bureau office at Madison,[2] located less than a tenth of a mile from the stand site. Thus the often faced problem of using inadequate data, or data requiring major adjustments for location was not present.

Winter mean values for temperature and precipitation were obtained by averaging the monthly mean values from October through March of the prior and current year. That is, the average of six mean monthly values preceding the April value for the year in question. All the climatic variables used in the present study were directly measured except the monthly mean values of evaporative stress, which were calculated using the formula $E_v = e_d \times w$ where e_d is the monthly mean vapor pressure deficit and w the monthly mean wind speed. Values of e_d were determined from the expression

$$e_d = (100 - RH)e_s$$

where RH is the relative humidity and e_s the saturation vapor pressure at the monthly mean temperature. Since the units of e_d are inches of mercury and those of w, MPH, mean evaporative stress was determined in units of miles per hour × inches of Hg.

3. Statistical techniques: Stepwise multiple regression—and application

Let us now consider which of the many climatic parameters are most significantly related to the year to year variance of the tree growth series. If the climatic variables considered were completely independent of each other, the simplest way to obtain our results would be by means of a straightforward correlation matrix. Such a technique would yield the simple product moment correlations between each variable and every other one without regard to their possible interdependence. A slightly more sophisticated analysis, the simple multiple regression, would compute the partial correlations between the independent variables and the dependent one, but would still only partially take into account the interaction between the independent variables.

These interactions are considerable. For instance consider evaporative stress and temperature. Evaporative stress is computed from relative humidity and saturation vapor pressure, both highly related to temperature. Similarly, total hours of bright sunshine are related, in varying amounts, to precipitation, evaporative stress, and temperature.

Thus a statistical technique is required that, in determining the tree growth variance explained by the climatic variables, considers the important interactions between the independent variables themselves. For this purpose it was decided to use a stepwise multiple regression technique.[3] With such a technique one tests the significance of the relationship between the individual independent variables (climatic factors) and the dependent variable (early, late, and total wood growth), without neglecting the varying interdependence among climatic variables. The following is a basic description of the stepwise multiple regression process.

The simple regression equation may be expressed as $Y = A + A_1X_1 + A_2X_2 + \cdots + A_nX_n$ where the dependent variable is Y, $A \cdots A_n$ are the coefficients, and $X_1 \cdots X_n$ are preselected independent variables. In the stepwise multiple regression analysis the "stepping" process considers the amount of variance contributed by the independent variables and eliminates those which are not significant according to predetermined criteria. These criteria will be described below. This is done by calculating the standard errors of each coefficient as well as the residual errors. The number of equations possible with n total independent variables and r independent variables appearing in the final equation is given by the binomial $\left(\frac{n}{r}\right)$ or $\frac{n!}{r!(n-r)!}$. Of these equations the one selected according to our statistical specifications will give the greatest reduction in variance.

The procedure for deleting and selecting variables in the stepwise regression equations is given elsewhere (Fritts, 1962). In the analysis of variance performed in the development of the final equations, F tests are applied after each variable is added to determine the reduction in variance by the addition of the particular variable. This is required because the importance of a variable may be altered after it is placed in the regression equation due to its interaction with the other variables. Similarly within the regression analysis, Student's t tests were applied and only those variables with regression coefficients determined significant to the 0.99 level were selected.

Table 3 presents the final regression equations, as determined by the above analysis of the total wood growth of the various species. The terms on the right side of the equations consist of the regression coefficients times the subscripted independent variable (see Table 2). These and other variables were initially selected as significant by the program according to the above mentioned criteria. As a final step all variables found to explain less than 5 per cent of the variance of the independent variable were deleted, resulting in the equations presented in Table 3. The independent

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[2] The only exception being sunshine which was recorded at the city office until 1 January 1947, after which it was obtained at the airport office, located $5\frac{1}{2}$ miles to the northeast.

[3] Malone, T. F., 1958: Studies in statistical weather prediction. *Final Report* AF19(604)-1590, Travelers Weather Research Center, Hartford, Conn.

TABLE 2. Identifier numbers* of independent variables**.

Description of element	Prior year						Winter	Current year					
	Apr.	May	Jun.	Jul.	Aug.	Sep.		Apr.	May	Jun.	Jul.	Aug.	Sep.
Mean temperature (°F)	—	11	12	13	14	15	10	4	5	6	7	8	9
Evaporative stress (MPH × inches of Hg)	22	23	24	25	26	27	—	16	17	18	19	20	21
Total hours bright sunshine (hours)	—	33	34	35	36	37	—	—	28	29	30	31	32
Total precipitation (inches)	45	46	47	48	49	50	44	38	39	40	41	42	43

* Number 1 is year number; number 2 is year number squared; number 3 is year number cubed.

** Standard U. S. Weather Bureau instruments used in obtaining the data included the mercury thermometer, wet and dry bulb thermometers, Marvin sunshine recorder, eight inch rain gage, Epply pyrheliometer, 4 cup anemometer to the mid 1930's, and a 3 cup anemometer from the mid 1930's to the present.

TABLE 3. Regression equations with mean total wood growth as the dependent variable and climatic and temporal factors as independent variables. The equations are truncated so as to include only those independent variables which reduce at least 5% of the dependent variance. Asterisks refer to prior year variables.

Red Oak	$Y = -0.01967278x_{18} + 0.00315112x_{41} + 0.00260555x_{39} - 0.00110200x_{11}^* + 0.01199449x_{22}^*$
Black Oak	$Y = -0.00008561x_1 + 0.00000138x_2 - 0.01119473x_{17}$
Hackberry	$Y = -0.04240462x_{22}^* + 0.00485715x_{10} - 0.00312798x_4$
Burr Oak	$Y = 0.00151306x_{41} - 0.00902201x_{19} + 0.00879209x_{22}^* - 0.00091872x_{13}^* + 0.00123843x_{49}^*$
White Oak	$Y = -0.00012157x_1 + 0.00000434x_2 - 0.00000004x_3 + 0.00163831x_{41}$
Elm	$Y = -0.01937974x_{19} - 0.00127702x_{12}^* + 0.01938341x_{16} - 0.00000732x_1 + 0.01756032x_{22}^*$
Larch	$Y = -0.00010106x_1 + 0.00000168x_2 + 0.00025981x_{37}^* - 0.00225099x_{12}^*$
Ash	$Y = 0.00315403x_{41} + 0.00527618x_{38} + 0.00292561x_{39} + 0.00252929x_{49}^*$

variables in these equations are presented in the order of selection which corresponded to the amount of variance reduced.

Examination of these equations makes it apparent that the temporal variables, year number and year number squared in particular, are important. Indeed the greatest reduction in variance can be shown to be due to variables X_1 and X_2. This is a result of natural physiological trend evident in tree growth. The most significant climatic variables in terms of reduction of total radial growth variance were July precipitation and July evaporative stress. The fact that the regression coefficients for these two variables are of opposite signs, as would be expected, positive for July precipitation and negative for July evaporative stress, indicates a strong dependence of the radial growth rate on water availability. This is of particular interest in that Madison is located in a vegetational transition or tension zone between the prairie, to the south and west, and the forest, to the north and east. If one were to place the isoline indicating equal annual precipitation and potential evapotranspiration on a map of the north central states, this line would coincide fairly well with the prairie-forest border (Lindsay, 1953), which is not far from Madison. The importance of the relationship of evaporation or evaporative stress and precipitation to tree growth in this transitional zone is indicated by the present results.

Other climatic variables appearing in the equations and given in order of the amount of growth variance they reduce include the following: Evaporative stress of April for the prior year, May precipitation, April precipitation. June evaporative stress, temperature of June for the prior year, and precipitation of August for the prior year. The surprising importance of several "prior year" climatic variables may indicate a dependence of annual radial tree growth on favorable growth conditions the year before.

4. Conclusion

Most prior dendroclimatic studies have considered the relationship between a single climatic variable and tree growth. The choice of the climatic factor used was dependent on the geographic area studied. It has been shown here, by means of stepwise multiple regression techniques, that the growth variance of mid-latitude hardwood samples can be satisfactorily explained only by numerous factors, climatic as well as temporal (Table 3). The greatest part of the cumulative growth variance was explained by the time terms, indicating the importance of long-term trends in the growth series. Considering only the climatic factors, the two explaining the largest growth variance were July precipitation and July evaporative stress. In particular, since these parameters occurred in the combination precipitation minus evaporative stress, a strong dependence of growth rate on water availability was found.

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