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wide geographic distribution of member nations. It derives its authority from an International Council, consisting of the chairmen of member nation delegations. Business is conducted on the basis of one vote per member nation. Resolutions of the Council are submitted for approval to the General Assembly of a Congress.

The business agenda of the IX Congress will be announced at least three months in advance of the Congress and all matters for consideration on the agenda must reach the Secretary–Treasurer of INQUA at least six months in advance, that is, by June 1, 1973. To be most effective such matters should be submitted through your National INQUA Committee. Each member country is entitled and urged to submit the name of one nominee for membership in the Executive Committee, without regard to position, no later than the first day of the Congress. Names received are paired on ballots for particular positions by a Nominating Committee for vote by the International Council. You have the right to suggest a nominee to your National INQUA Committee.

The sixteen Commissions of INQUA, some of which include several subcommissions, cover a wide range of Quaternary problems. They have been authorized somewhat haphazardly since 1953. Some are active, others less so. A committee has been appointed to make recommendations for their restructure and the procedures for their establishment.

The IX Congress in New Zealand will be the first held in the southern hemisphere. It will provide an unusual opportunity to study similarities and contrasts with environment in the northern hemisphere, as well as to learn something of the unique ecological conditions in New Zealand. Field study excursions are designed to demonstrate the local environmental conditions and their history during the Quaternary, including the effects of man-induced and climate-induced environmental change. Topics for Congress sessions and symposia have been chosen to bring together worldwide data and viewpoints on problems of current interdisciplinary interest. A first circular has been issued and a more definitive second one will be mailed shortly. It can be obtained upon request to the Secretary-General of the Congress.

A United States delegation to the Congress will be selected by the U. S. National Committee for INQUA, N.A.S.–N.R.C. It will represent as many INQUA disciplines as possible. Your nominations of well-qualified individuals is sought, and should be sent to the Chairman of the Committee. Partial travel grants will be available both to the official delegation and to some additional participants from the United States. Application forms may be obtained from the Chairman of the Committee, which will meet to consider them early in 1973.

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Dendroclimatology and Dendroecology

HAROLD C. FRITTS[1]

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Dendrochronology is the science of dating annual growth layers (rings) in woody plants. Two related subdisciplines are dendroclimatology and dendroecology. The former uses the information in dated rings to study problems of present and past climates, while the latter deals with changes in the local environment rather than regional climate.

Successful applications of dendroclimatology and dendroecology depend upon careful stratification. Ring-width samples are selected from trees on limiting sites, where widths of growth layers vary greatly from one year to the next (sensitivity) and autocorrelation of the widths is not high. Rings also must be cross-dated and sufficiently replicated to provide precise dating. This selection and dating assures that the climatic information common to all trees, which is analogous to the "signal," is large and properly placed in time. The random error or nonclimatic variations in growth, among trees, is analogous to "noise" and is reduced when ring-width indices are averaged for many trees.

Some basic facts about the growth are presented along with a discussion of important physiological processes operating throughout the roots, stems, and leaves. Certain gradients associated with tree height, cambial age, and physiological activity control the size of the growth layers as they vary throughout the tree. These biological gradients interact with environmental variables and complicate the task of modeling the relationships linking growth with environment.

Biological models are described for the relationships between variations in ring widths from conifers on arid sites, and variations in temperature and precpitation. These climatic factors may influence the tree at any time in the year. Conditions preceding the growing season sometimes have a greater influence on ring width than conditions during the growing season, and the relative effects of these factors on growth vary with latitude, altitude, and differences in factors of the site. The effects of some climatic factors on growth are negligible during certain times of the year, but important at other times. Climatic factors are sometimes directly related to growth and at other times are inversely related to growth. Statistical methods are described for ascertaining these differences in the climatic response of trees from different sites.

A practical example is given of a tree-ring study and the mechanics are described for stratification and selection of tree-ring materials, for laboratory preparation, for cross-dating, and for computer processing. Several methods for calibration of the ring-width data with climatic variation are described. The most recent is multivariate analysis, which allows simultaneous calibration of a variety of tree-ring data representing different sites with a number of variables of climate.

Several examples of applications of tree-ring analysis to problems of environment and climate are described. One is a specification from tree rings of anomalies in atmosphere circulation for a portion of the Northern Hemisphere since 1700 A.D. Another example treats and specifies past conditions in terms of conditional probabilities. Other methods of comparing present climate with past climate are described

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along with new developments in reconstructing past hydrologic conditions from tree rings.

Tree-ring studies will be applied in the future to problems of temperate and mesic environments, and to problems of physiological, genetic, and anatomical variations within and among trees. New developments in the use of X-ray techniques will facilitate the measurement and study of cell size and cell density. Tree rings are an important source of information on productivity and dry-matter accumulation at various sites. Some tree-ring studies will deal with environmental pollution. Statistical developments will improve estimation of certain past anomalies in weather factors and the reconstructtion of atmosphere circulation associated with climate variability and change. Such information should improve chances for measuring and assessing the possibility of inadvertent modification of climate by man.

INTRODUCTION

The widths of growth rings in woody plants can serve as natural records of climate when they vary as a function of some limiting climatic factor. In arid and semiarid regions, ring widths have been shown to vary directly with the intensity and duration of drought. In cold regions, the rings of trees may be narrow when the temperature of the growing season is low. Ring widths from trees in temperate regions often are not as closely correlated with single climatic conditions as those for trees from arid or cold regions, but on certain limiting sites ring widths have been shown to contain rather significant information on climate.

Features other than the width of the ring may indicate certain environmental events. Cells may be damaged and distorted by frost (Glerum and Farrar, 1966). Cell size, wall thickness, and the corresponding density of the woody tissue within the ring also may be affected by limiting climatic conditions at the time the cells are being formed (Zahner, 1968; Glerum, 1970; Parker and Henoch, 1971). The growth rate of trees may be altered or the growing tissue may be damaged by fire, avalanche, landslide, erosional events, changes in water table, lightning strike, ice damage, an approaching ice front of a glacier, or insect infestation. Distortions or changes in ring structure may be used to date these events which often result from significant environmental phenomena or changes.

The general term, *dendrochronology,* may be defined as the science of dating the annual growth layers in woody plants and the exploitation of information they contain on the environment. The term *dendroclimatology* is restricted to dendrochronological studies that use climatic information in dated growth layers to study variability in present and past climates, while *dendroecology* is a term used for those dendrochronological studies that specifically deal with problems of present and past local environments.

Not all woody plants produce ring-width sequences that are datable and usable for climatic inference. In some species the rings are not clearly defined and not easily recognized. Other species may form several growth layers per year. In still other species the ring widths are little affected by natural variations in the environment. Some of the genera that have been used for dendroclimatic interpretations are: *Araucaria, Artemesia, Fagus, Juniperus, Libocedrus, Abies, Picea, Pinus, Pseudotsuga, Quercus, Sequoia, Tsuga.*

Successful recovery of climatic or ecological information from annual growth layers usually involves more than a random sampling and counting of rings. A dendroclimatologist or ecologist who is selecting tree-ring materials in the field must utilize keen ecological insight and apply the dendrochronological principles of site selection, sensitivity, and cross-dating. He should understand what climatic information he is after and have some idea as to the various ways tree growth is influenced by the environment and how the trees translate climatic information into the features observable in the growth ring. For example, if a worker has sampled trees in which the growth layers have not been limited by the environmental factor that he wishes to study, no amount of subsequent statistical manipulation can extract the desired information from the rings. If a scientist ignores significant climatic factors that operate by preconditioning the plant while the growing tissues are dormant, he is likely to obtain an incomplete understanding of the environmental information contained in tree rings. If a worker samples trees limited by climate but does not cross-date the rings, his data may contain unrecognized missing sets, double rings, or simple counting errors, so that some of the growth layers are not assigned to the year when they were actually formed. As in other sciences, dendrochronology employs certain procedures which assure that results are verifiable.

This article summarizes some basic concepts and principles currently employed in dendroclimatology and dendroecology and attempts to illustrate how these concepts and principles are applied to the reconstruction of environmental variation that has occurred in the past.

SOME FACTS AND PRINCIPLES OF TREE GROWTH

Annual rings are growth layers formed within the xylem, the woody tissue, in stems and roots. Growth usually starts in conifers when the buds swell and open in the spring. The xylem cells are differentiated toward the inside of the cambium, the dividing layer of cells that lies just inside the bark. Phloem or food-conducting tissue is differentiated toward the outside of the cambium (Fig. 1). The first-formed xylem cells in conifers become large and thin-walled, forming the "earlywood" portion of the annual growth layer. As successive layers, or sheaths, of cells are differentiated throughout the growing season, physiological conditions within the tree gradually change, so that the resulting xylem cells are smaller and have thicker walls than those cells formed earlier in the season. In the outer portion of the xylem layer, the cells are small and the wood is dense enough to appear darker than the inner portion. The dense tissue, called "latewood," forms a distinct boundary adjacent to the lighter earlywood of the next-formed xylem layer. The details of wood structure vary among species, but the contrast in structure that occurs between the first-formed and last-formed cells of each season is often used to delineate the boundaries of the annual ring.

The transition in cell size from earlywood to latewood within any one annual growth layer is often gradual, but the number and structure of cells within this transition may vary from one year to the next, depending on environmental and physiological factors that have limited the rate of cell division, enlargement, and maturation (Zahner, 1968; Budelsky, 1969). Therefore, both the width of the layer in a radial direction and its appearance due to the cell structure can be functions of environmental factors that exist prior to and during the period of growth, as well as functions of the hereditary potential of the tree. Until recently, dendrochronological research has focused almost exclusively upon differences in width of the growth layers because the changes in cell structure are more difficult to measure with adequate replication than the width of the ring. In addition, physiological factors governing cell size and structural changes across the growth layer often appear exceptionally complex and difficult to interpret in terms of external environmental factors.

Each year's xylem layer forms a tissue that is continuous, or sometimes discontinuous, throughout the entire stem and root.

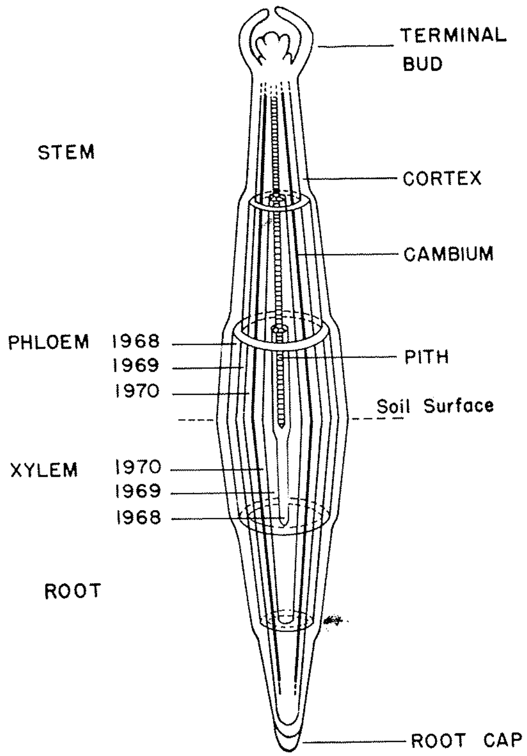


FIG. 1. A diagrammatic representation of the xylem and phloem layers in a 3-year-old tree. The xylem layers are differentiated from the inner surface of the cambium which extends from the terminal bud to the root cap. The boundary between adjacent xylem layers approximates a pair of conical surfaces with tips marking the positions of the terminal bud and root cap and the bases joined in the oldest portion of the stem at the soil surface. The phloem layers are differentiated from the outside surface of the cambium and are eventually crushed along with the cortex as new tissues are produced from the underlying cambium. Redrawn from Transeau, Sampson, and Tiffany (1953).

A three dimensional view of the main stem and root would show the boundaries of the xylem layers as a series of paired superimposed conical surfaces with bases of the pairs joined at the ground line and tips representing the positions of the terminal bud and root tip at the end of the year when each growth layer was formed (Fig. 1).

The dimensions and structure of these growth layers are a function of the tree's heredity and environment acting throughout the life history of the developing and aging individual (Kramer and Kozlowski, 1960; Fritts, 1966). The measurement of any one dimension, which is commonly the widths of the rings along a transverse section at the stem base, represents the product of a variety of gradients acting through time within the existing structure of the tree (Duff and Nolan, 1953; Smith and Wilsie, 1961; Fritts, Smith, Budelsky, and Cardis, 1965). For example, the foliage of the crown is the principal manufacturer of growth regulators and food, as well as the primary surface through which water transpires. As new layers of wood are added above and outside the existing layers, the tree crown is also growing and lower branches are dying. As the tree increases in height with increased age, the mean crown position gradually moves upwards along the main stem. Organic materials must travel a greater distance along the stem from the tree crown to reach a given cambial area near the stem base. The water supply to leaves must overcome increasing hydrostatic forces. Also, in a theoretical tree that exhibits a constant increment in volume growth, the most recently formed rings in the outer portions of the stem have a larger circumference and must be narrower than the inner rings, if a constant volume increment is maintained.

It has been shown (Fritts *et al.*, 1965) that these changes within the tree associated with age and stem height cause structural changes to occur from the innermost to outermost rings, especially those in the lower portions of the main stem. The first few rings that lie next to the pith (central tissue, Fig. 1) often are narrow, but the encircling rings near the stem center increase in width. Outside this zone of wide rings, the rings generally become narrower and are more likely to vary in width from year to year than those in the more youthful portions near the stem center.

On sites that are optimum for tree growth, rings are generally wider in the stem segments within the tree crown than at the stem base (Farrar, 1961). However, in mature trees on arid sites, a growth layer may have approximately the same average width throughout the main stem except in the uppermost, exposed portions of the tree where it is often narrower (Fritts *et al.*, 1965). Sometimes the ring widths vary throughout the stem as a result of changing climatic conditions (Smith and Wilsie, 1961). Generally, the year-to-year changes in ring widths at the stem base are greater and more closely associated with macroclimatic variation than the ring-width changes in the upper regions of the stem which are more influenced by the microenvironment of the individual branches.

Initiation of cambial growth in the stems of coniferous trees generally occurs first in the terminal branches and last in the base, while growth cessation may occur first at the base and last in the branches (Larson, 1962). Thus, the growing season may vary as much as several weeks for different parts of the tree. As a result of these differences, changes in climatic factors that influence the initiation and cessation of cambial activity may exert a different effect on rings near the stem base than on those near the stem tips. Since the cambium in the stem tip is more likely to be actively dividing at the beginning or end of the growing season, frosts are more likely to damage cells of the young tips than those at the stem base, so that frost rings are most apt to be found in young stems (LaMarche, 1970).

Similar physiological phenomena can explain the higher frequency of partial rings and the low frequency of intra-annual bands of latewood in the outer portions of the stem near the base but above the ground level of the tree bole. During a year that is unfavorable to growth, the cambial stimulus, originating at the stem tips, may never reach the stem base. The ring for that particular year will be formed only in the upper, more vigorously growing portions of the stem so that it is absent at the base. At the stem base, intra-annual bands of latewood, sometimes referred to as false rings, are more likely to occur in the centrally located rings that were nearest the stem tips. In the upper stem they may occur adjacent to large branches of the tree crown (Fritts *et al.*, 1965). The association of intra-annual bands of latewood with the proximity of the tree crown is attributed to concentrations of growth-controlling substances and to availability of water. These substances are more likely to vary in the tissues that are near the stem tips than in tissues that are far removed from the growing crown and near the roots.

Most dendroclimatological investigations are more fruitful if changes in ring structure and size associated with tree age are assessed and separated from changes associated with climatic variation. The changes in ring width associated with increasing tree age are estimated and removed from the ring-width series by a process called standardization. This is accomplished by using specific computer programs developed at the Laboratory of Tree-Ring Research (Fritts, 1963; Fritts, Mosimann, and Bottorff, 1969). A growth curve is fitted to the ring-width data and the value of the actual ring width for each year is divided by the calculated value of the growth curve for that year to obtain a standardized value or ring-width index (Fig. 2). It is sometimes desirable to avoid the young and fast-growing portion of trees and utilize only the oldest portions of stems where the ring widths change the least with tree age and have been most influenced by variations in climate.

BASIC PRINCIPLES

There are several important principles or concepts that underlie the appropriate use of ring widths to make inferences about past environment. A few of the basic principles are described in the following subsections.

Law of limiting factors. There is a well-known biological law that may be stated simply: A biological process, such as growth, cannot proceed faster than is allowed by the most limiting factor. If a factor changes so that it is no longer limiting, the rate of a process will increase until some other factor or factors become limiting. Thus, every process is always limited by some factor or set of factors that may arise from either external or internal conditions of the organism. Since the primary objective of dendroclimatology or dendroecology is to reconstruct the past environment from structural characteristics of the annual ring, it is important to use trees in which ring growth is more or less limited either directly or indirectly by some environmental factor.

For example, rate and duration of cell division and enlargement may be limited by water stress during the growing season (Zahner, 1968; Budelsky, 1969), by low temperatures (Hustich, 1948; Dahl and Mork, 1959; Siren, 1961), or by physiological conditions which were preconditioned by climate factors occurring before growth was initiated that particular year. More than one factor may sometimes be limiting and the environmental complex at different times within the year may influence growth in different ways.

Principle of site selection. This principle is an extension of the law of limiting factors. It emphasizes the necessity to utilize tree-ring information only from a highly stratified samples of trees wherein growth has been largely limited by the factor in question. Thus, in studies of drought, it is important to rely principally upon trees that are in the driest sites for each particular species. In studies of temperature, the best trees in polar regions are within 100 m of the upper climatic treeline because only near the treeline is temperature sufficiently limiting to growth to override other growth controlling factors.

Appropriate selection of trees from limiting sites maximizes ring-width variability (Fig. 3). It also maximizes the variation that is common among many trees, or the "signal" representing the climatic "input," but minimizes the ring-width variation arising from nonclimatic factors which could be referred to as "noise." Such "noise" is induced by differences within the site, by differences in the community status among trees, and by environmental differences in growth among various radii within trees. Thus, on sites where climatic factors are not especially limiting, the rings are wide—the variation in width does not correlate well among trees or even within trees. On sites where climatic factors are often highly limiting to growth, rings are narrow, but widths vary greatly from one year to the next. This variation in ring width correlates well with other radii throughout the stem among and

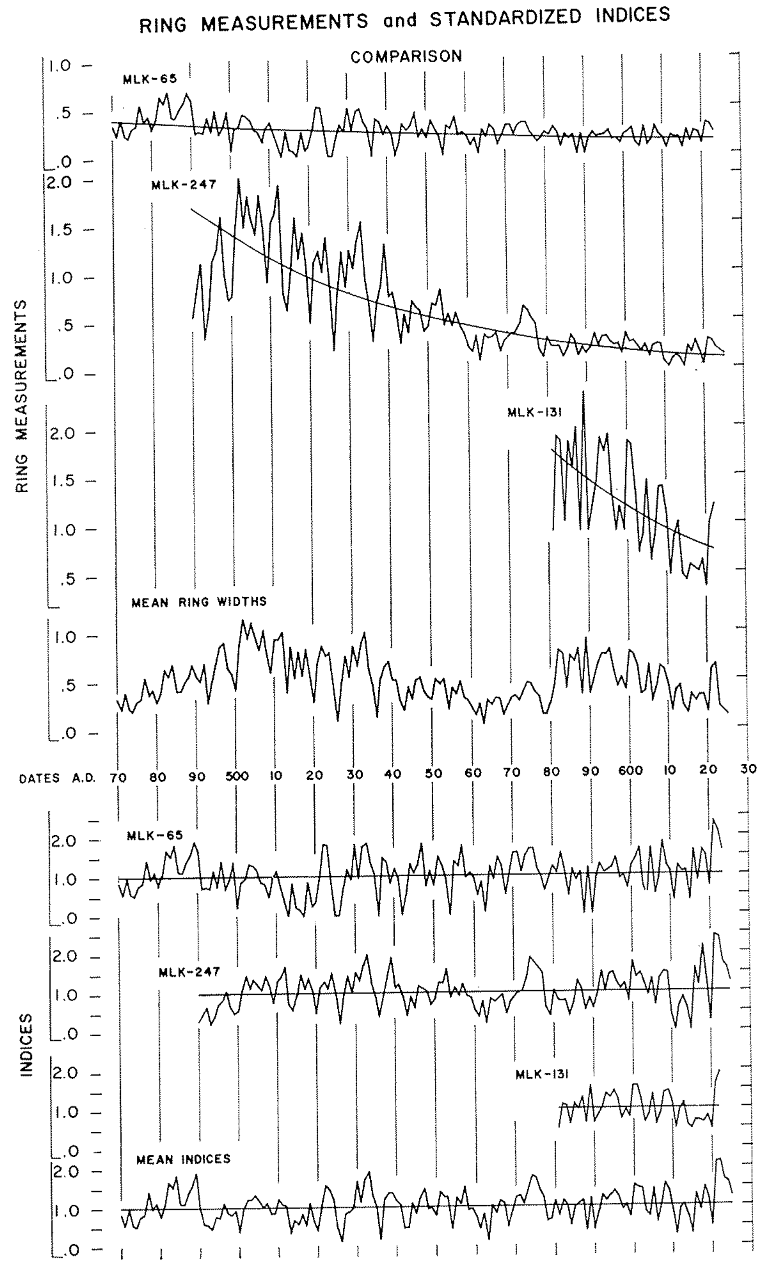


FIG. 2. Standardization is necessary because the first-formed rings are generally wider than those found in the older portions of stems and because some trees grow more rapidly than others. If ring-width measurements, plotted as a function of year of formation (upper plots) are averaged, the mean chronology will show long-term variations arising from differences in ring age and mean growth rate of different sampled specimens (fourth plot). When an exponential curve is fitted as shown in the upper plots and the value of this curve during each year is divided into the ring width for that year, new values are obtained which are referred to as indices (lower plots). These indices do not vary as a function of tree age and mean growth and have an expectation value of 1.0. Such indices may be safely averaged (lowest plot) to obtain a ring-width chronology that is likely to correspond to short-term fluctuations in climate that have limited the growth of the trees.

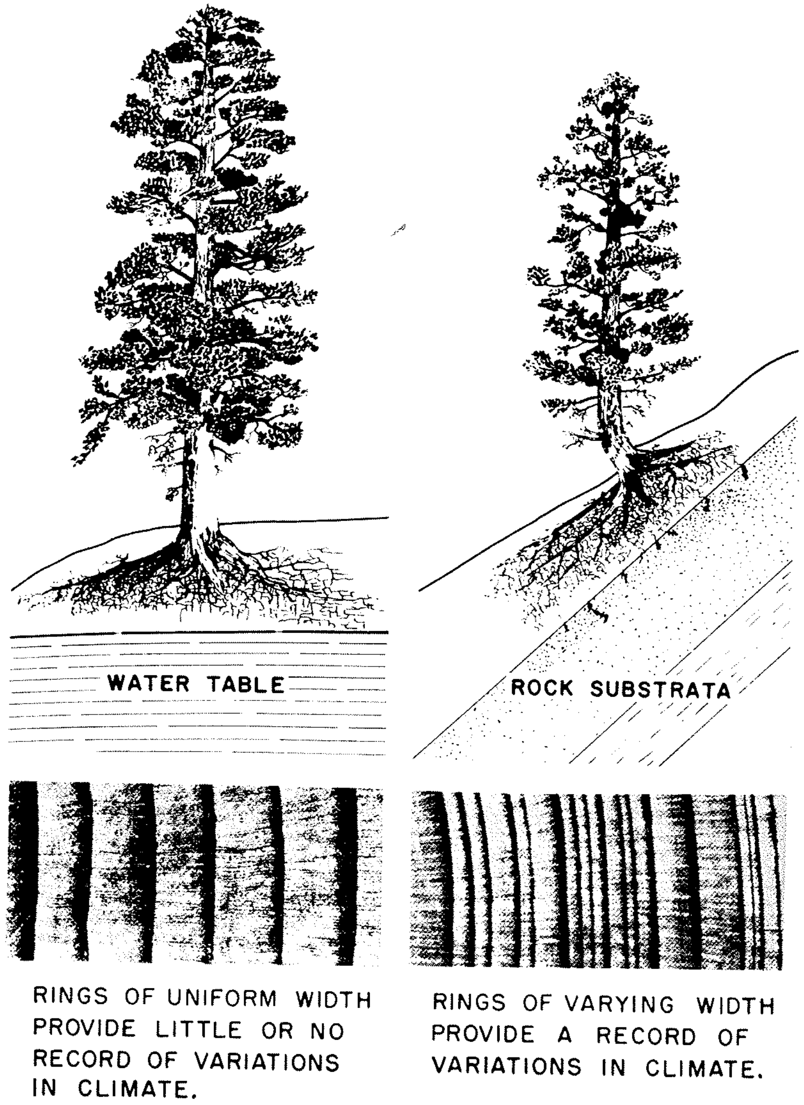


FIG. 3. Trees with ample moisture and favorable temperatures are not limited by climatic factors (left). Their rings are uniformly wide and there is little variation in thickness from one ring to the next. Trees on arid or extremely cold sites may often be limited by climatic factors (right). Their rings are narrow and there may be marked variation in ring thickness corresponding to variations in climatic factors which have limited growth.

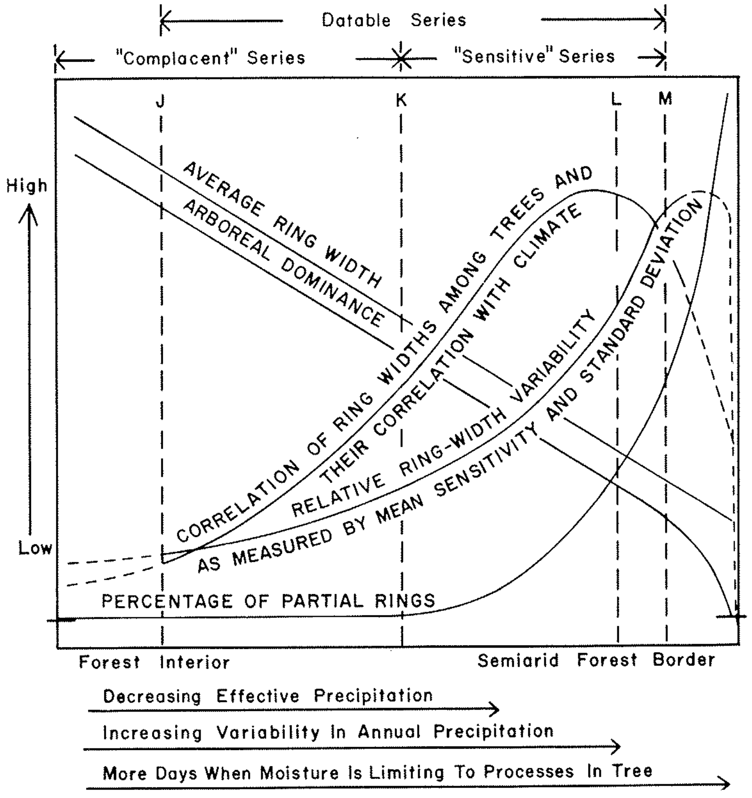


FIG. 4. Properties of ring-width series vary as a function of the environmental gradient from the mesic interior of a forest to the semiarid border of the forest. Changes in environmental factors are indicated below the graph and dendrochlonological categories are indicated above it. The average ring width decreases with increasing aridity. The correlation of ring widths among and within trees and their correlation with variations in climate increase to (L) and near the extreme forest border (M) these parameters begin to decrease. Relative ring-width variability also increases reaching its maximum near the forest border (M). Near the forest border the smaller rings may be partial so that they are absent along some radii within the stems and the percentage of rings that are partial within the stem increases exponentially from K to the arid limit of the forest. Some ring-width series are undatable because there is insufficient variation in width to see any correlation among trees (left of J) or because there are so many partial rings (right of M). In such cases, it is impossible to date and reconstruct the annual growth chronology with any degree of certainty.

within trees and is highly related to yearly variations in the macroclimate (Fig. 4). The amount of "signal" and "noise" in a given sample can be assessed by analyses of variance and other statistical techniques designed for tree-ring studies (Fritts, 1963). In newly sampled dendroclimatic regions, it is useful to obtain replicate samples of tree rings from two or more radii around the stem from various sites and species and utilize these specially designed statistical techniques to measure the effect of varying site and species on the amount of "signal" and "noise" that is found in the ring-width chronologies (Fritts, 1969a). Such analyses provide an objective means of evaluating the quality of the ring-width record and help in the search for better records and new situations where environmental information can be extracted from the rings of trees.

Principle of sensitivity and measurement of high- and low-frequency variability. The variability in width from one ring to the next provides one of the best indicators of climatic stress. As mentioned previously, this variability arises because, as stress increases from mesic to dry sites, climatic factors are more often limiting to growth, and rings will vary in width more from one year to the next in response to variations in climate. Such variations in ring width would not occur if climate did not vary markedly from year to year. Dendrochronologists refer to this variability in ring width as "sensitivity." The mean sensitivity for a series of ring widths is calculated as,

$$\frac{1}{n-1}\sum_{i=1}^{n-1}\left|\frac{2(x_{i+1}-x_i)}{x_{i+1}+x_i}\right| \qquad (1)$$

where x is either the ring width or the ring-width index for year i, and n is the total number of rings. Thus, mean sensitivity is a relative measure of first differences and emphasizes variation in narrow rings more than variation in wide rings. Since mean sensitivity measures the ring-width changes among adjacent rings, it is influenced largely by the short-term changes or high-frequency variations in climate.

Longer-term changes or low-frequency variations in the ring-width index can be measured by correlating indices with prior indices lagged one or more years. That is, one obtains the product moment correlations between x_i and x_{i-L}, where i varies from 1 to n representing the first to last year in a ring-width index series, and L is the number of years by which the series are lagged. When $L = 1$ the correlation is referred to as the first order autocorrelation; a lagging of $L = 2$ gives the second order autocorrelation; in general, when $L = n$, nth order autocorrelation coefficient is obtained. In contrast to mean sensitivity, autocorrelations provide measures of the long-term changes or low-frequency variation in growth. Different species and trees on different and contrasting sites may have varying autocorrelation structure in their ring-width series. Differences in autocorrelation structures may be attributed to differences in foliage growth and length of foliage retention by the trees (Eklund, 1956; Fritts, 1969a).

The normal statistic referred to as standard deviation, in contrast to mean sensitivity and the autocorrelations, measures variability in all frequency ranges. Standard deviation and mean sensitivity are not equivalent measures of variation because standard deviation is inflated more than mean sensitivity whenever long-term variations in growth occur. Dendrochronologists often prefer to use mean sensitivity rather than standard deviation because they are concerned mostly with the high-frequency variance that reflects short-term changes in climate. There is some evidence that the more gradual, long-term changes in climate are less commonly retained in the ring record of arid-site trees than in those from cold sites because the stand density, composition of the forest, and competition between trees on arid sites may change with the gradual changes in moisture available on a site. Thus, the width of rings from arid-site trees provides an excellent means of studying changes in climate with durations of less than a century, but they are less useful for assessing long-term climatic changes, which continue for more than a century. The ring records from trees at high latitudes or high altitudes appear to retain both high-frequency and low-frequency variations. Apparently the slowly changing features of the forest stand do not modify the microenvironment sufficiently to alter the growth response. V. C. LaMarche is attempting to identify what factors produce the low-frequency variations in ring widths from high altitude trees.

It is important that dendroclimatologists search for limiting sites. They often sample rings of trees and examine samples for sensitivity. Final selection for inclusion in a dendroclimatic chronology representing an arid site often is made on the basis of those tree rings that show the most high-frequency variation in width as measured by sensitivity and the least low-frequency change. It has been shown that those trees with rings exhibiting high-mean sensitivity indicating high ring-width variability also show a high ratio of "signal" to "noise" and are highly correlated with variations in climate (Fritts *et al.*, 1965) (Fig. 4). Since ring-width chronologies from arid-site trees contain less low-frequency information, marked, low-frequency changes in ring width not found in trees from neighboring regions are most likely to have originated from nonclimatic changes operating within the site. The dendroclimatologists would attempt to minimize such changes. On the other hand, anomalous low-frequency changes unique to certain trees or sites may be the information sought by the dendroecologist who is attempting to assess nonclimatic factors which are operating in a site.

Principle of cross-dating. The principle of cross-dating is the most unique and important principle for tree-ring analysis. It provides a type of "experimental" control on the placement in time of each growth layer, yet it is sometimes either neglected or not clearly understood. It requires that the variation in ring characteristics, especially ring width, be recognizable and synchronously matched among all samples from a given region, so that the year in which each ring was formed may be correctly ascertained. Cross-dating is possible because, during years of low growth, the same environmental conditions have limited the ring widths in large numbers of trees. Therefore, the year-to-year fluctuations in limiting environmental factors that are similar throughout a region produce synchronous variations in ring structure.

If a ring is partial so that it is absent on a portion of a stem, or if an intra-annual band of latewood is counted as an annual ring, the variation in ring widths in that portion of the stem will not coincide with the variation seen in other portions of the stem or in other specimens, in which the corresponding feature is clearly defined. The ring-width patterns will be out of phase by one year. Therefore, cross-dating includes matching of ring-width patterns among specimens, examing the synchrony, recognizing any lack of coincidence, inferring where rings may be absent or false, testing the inference against the ring structure in other specimens, and finally arriving at the regional chronology of wide and narrow rings based upon the collective sequences in all specimens from the region. If there is little sensitivity and low correlation of ring-width variation among trees, or if there are large numbers of partial or intra-annual bands, the final chronology may be uncertain and the sample must be considered undatable and unusable for dendroclimatic analysis (Fig. 4).

Even if partial rings or intra-annual bands are unlikely, as is often true for trees growing in temperate or cold regions, cross-dating should be employed to ensure that no mistake has been made in the recognition and counting of rings. Also, if cross-dating is not evident, it is unlikely that the environment has been sufficiently limiting to allow a meaningful analysis of climatic fluctuations from the width of rings. Stokes and Smiley (1968) and Ferguson (1970) provide excellent illustrations and further discussion of the cross-dating technique.

Principle of replication. Just as this principle is a necessary part of many statistical analyses, it is also a part of dendroclimatic research. Replication is implied in the cross-dating procedure. There must be sufficient replication to guarantee accurate dating. If few rings are absent and confusing intra-annual latewood bands are infrequent, accuracy in dating can be assured with a relatively small number of sampled trees. On the other hand, if climate has been less limiting than nonclimatic factors which vary from tree to tree, and the climatic "signal" in ring-width patterns is weak, it may be desirable to sample and analyze the average growth response of a large number of trees. By increasing the sample size, the nonclimatic "noise" is reduced in the averaging process, and the mean growth for each year approaches the climatic chronology for the site. On extremely limiting sites the expectation of locally absent rings may be high (Fig. 4), and a large sample may be required to assure accurate dating, although the climatic "signal" may not be significantly improved by increasing the sample size.

The dating and development of a specific chronolgoy is based first upon internal consistency in the patterns of wide and narrow rings within the selected sample of trees. Then the accuracy of this dating is verified by cross-checking the final chronology with nearby chronologies derived for independently dated trees. Literally hundreds of these independently dated tree-ring chronologies throughout western North America consistently show a synchrony with chronologies in an area within a 300-mile (480 km) radius and in some cases, at distances up to 1100 miles (1770 km) (Fritts, 1963). This repetition in nearby chronologies is the best evidence that cross-dating is real, that it can be used to precisely identify and reconstruct the annual growth chronology, and that the results are reasonable estimates of some component of regional climate.

Modeling the environmental relation. It is often convenient to construct, *a priori*, certain combinations of environmental variables which are expected to simulate the complex system that limits growth. For example, precipitation and temperature may be combined statistically to form a single parameter that represents the actual water budget which is presumably more closely related to water stress of the tree than are the individual meteorological factors (Zahner and Stage, 1966; Fritts, Smith, and Strokes, 1965; Julian and Fritts, 1968). Temperature may be summed in a fashion to simulate the potential energy available for respiration (Dahl and Mork, 1959). Such a transformation appears useful in cold regions where the course of cambial activity may follow a nonlinear function of temperature during the growing season. However, most transformations of this kind have not adequately simulated the factors limiting growth.

When the relationships between ring structure and climatic factors are not known precisely (as is the usual case), a flexible, rather than a rigid *a priori* model, using a number of climatic variables, is more useful. For example, Fritts, Smith, and Stokes (1965) and Fritts (1969a) utilized monthly precipitation, temperature, and evapotranspiration deficit, summed or averaged over a number of intervals corresponding to the different seasons. A series of multiple regression analyses were obtained which statistically predicted ring-width indices. Multiple regressions using each of the three types of measurements were applied in a stepwise fashion, and tests for significance were used at each step. The three types of climatic variables were combined and analyzed with growth, assuming additivity among the variables. Lastly, cross products between variables were included in the model to allow for interactions among variables. The gradual increase in complexity of the variables that were considered allowed assessment of the relative importance of each variable at each stage of complexity. The actual models were derived by selecting those that appear most reasonable physiologically, as well as those that provided the most significant regressions. Sometimes those regressions with cross products appeared most satisfactory because the cross products allowed for variable interaction. The predictions by the equations accounted for all but 9–13% of the unexplained variance in the ring-width chronology, i.e., total variance less the statistical error (Fritts, Smith, and Stokes, 1965).

The regression equations were solved by varying one climatic variable at a time. The amounts and changes in the calculated growth associated with specified changes in each climatic variable were used to estimate the relative importance of each climatic factor on growth.

Stepwise multiple regression has certain limitations. The technique was developed as a predictive tool and does not necessarily express the cause and effect relationships.

Variables entered in stepwise succession are not necessarily ordered in terms of their real importance but rather in terms of their apparent relationship as calculated from the correlation structure of the data. Stepwise regression adjusts at each step for intercorrelations with variables that are already entered into regression. High correlation with a variable already in the regression may prohibit an important variable from being included in regression until late in the stepwise sequence.

Many of these difficulties can be circumvented by transforming the environmental variables to a new set of orthogonal (uncorrelated) variables. Stepwise regression can then be applied effectively to these "new" variables because they are statistically independent, i.e., uncorrelated. Details on this newer approach are described in the section on "Tree-Ring Analysis in Practice."

A DENDROCLIMATIC MODEL FOR CONIFERS ON ARID SITES

Many studies of relationships between tree-ring width and climate have focused mainly on the limiting effects of the environment only during the period of growth and have failed to consider adequately the effect of climate during the so-called dormant period including the winter months. Climate was thought to be effective in arid sites insofar as it might directly limit water availability and influence either the length of the growing period or the production and enlargement of cells (Fig. 5).

However, Douglass (1914), Schulman (1956), and other workers in semiarid

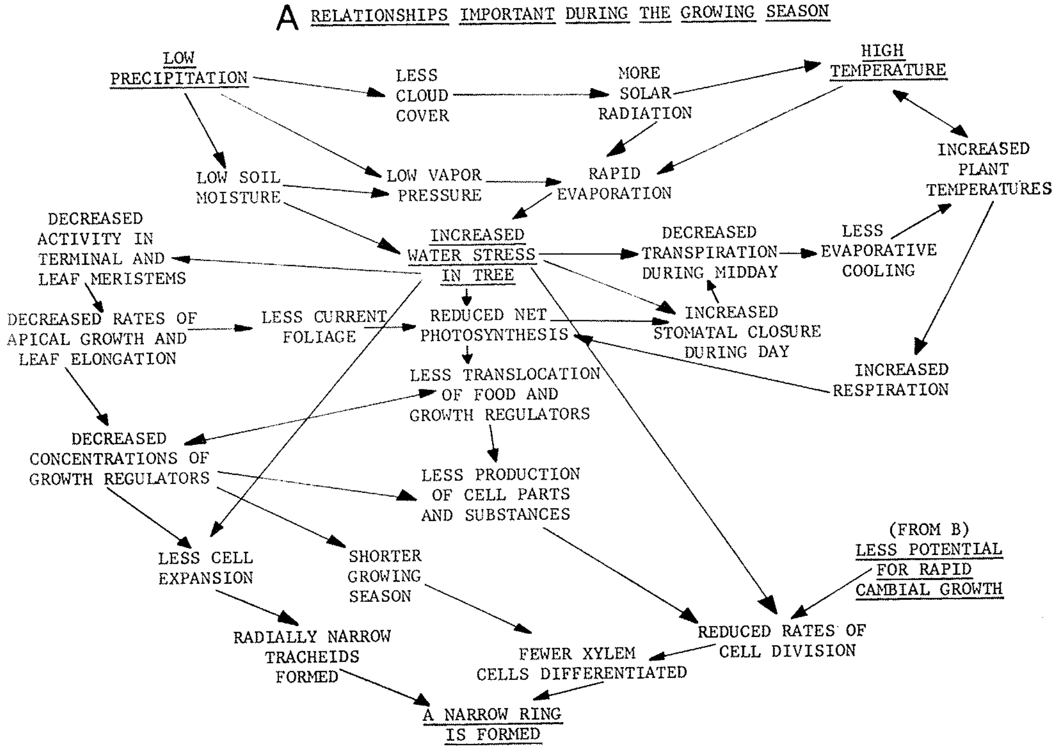


FIG. 5. Physiological Model A illustrating how low precipitation and high temperature during the growing season (season of cambial activity) may cause a ring to be narrow for conifers growing on semiarid and warm sites. The climatic conditions affect physiological processes which limit the rate of cell division, the amount of cell expansion, or the length of the growing season.

North America found that ring widths from arid-site conifers correlate best with the climate during the summer, autumn, winter, and spring that preceded the period of growth. Some workers suggested that such correlation could only be the result of water stored in the ground or by trees (Zahner, 1968). Intensive growth investigations on arid site trees at Mesa Verde, Colorado (Fritts, Smith, and Stokes, 1965; Fritts, 1965) as well as more recent studies (Fritts, 1969a) also indicate that climate during the growing season has less effect on ring width than the climate for an extended period preceding initiation of growth. The importance of prior climate was brought to the attention of the author when cambial growth during the 1962 season at Mesa Verde continued rather rapidly through June, July, and early August, a period of little precipitation and extended drought (Erdman, Douglas, and Marr, 1969). Cell division continued even though measurable shrinkage of stems occurred due to dehydration of the tree (Fritts, Smith, and Stokes, 1965). The unexpected continuation of growth during this dry season suggested that the previous summer, autumn, and winter, which had been moist, both preconditioned the trees and replenished soil moisture, so that an average-sized ring rather than a narrow ring was formed.

On the basis of these observations and the results from a variety of statistical analyses of tree-ring and climate relationships, it was hypothesized that the narrow rings of conifers on arid sites may be attributed largely to preconditioned internal factors such as limited reserves of food or growth substances as well as to depleted soil moisture (Fig. 6). Low reserves of food in arid-site conifers may result from reduced rates of net photosynthesis or high rates of respiration during dry periods of the previous summer, autumn, winter, and spring (Fig. 6) (Fritts, Smith, and Stokes, 1965). However, wide rings result if climatic conditions during the year prior to the beginning of growth have both favored high net photosynthesis and replenished soil moisture, and if there is an abundant supply of stored food and soil moisture throughout the growing season (Figs. 5 and 6) (Fritts, 1966).

What is the existing evidence that this model, which is diagrammed in Fig. 6, is possible? Krueger and Trappe (1967) measured food in Douglasfir seedlings and found an increase in sugars and total reserves of food during the winter period. More recently, Brown (1968) completed a study with this author on photosynthesis in southern Arizona Ponderosa pine (Fig. 7). He established that high rates of photosynthesis in an arid-site conifer occurred during the winter months when leaf temperatures during the day were well above freezing. But when soil moisture declined and air temperatures and solar radiation were relatively high, the daily net photosynthesis was reduced. These results confirm the possibility that a significant and important portion of the food available for growth in stem circumference may be made during the previous autumn, winter, and spring, and that dry and warm conditions during this period can reduce the accumulation of food. However, they do not demonstrate that food *per se* directly limits cambial activity. It is possible that some unrecognized process links variation in net photosynthesis with subsequent ring-width growth of arid-site conifers. However, the best inference at present is that food accumulated over the prior season by arid-site conifers can vary markedly from year to year and can limit the rate of cambial division and affect ring width.

There are other ways in which prior climatic conditions can affect the width of the rings in arid-site trees. Drought conditions of one year may limit the formation of new stems, buds, needles, and roots, and these structures may affect growth-controlling processes in following years (Fig. 6). In certain species and for certain sites, this effect is sufficiently important to produce persistence in ring width, shown by first order autocorrelations that frequently range from 0.3–0.5 (Eklund, 1956; Fritts 1965, 1966). In such cases, extremely wide rings are generally followed by wider-than-average rings, and narrow rings by narrower-than-average rings. Climatic conditions can also affect flower formation, fertilization, and fruit set. During years of heavy fruit production, the reserve food may be depleted and the growth of the annual ring may be reduced (Holmsgaard, 1962).

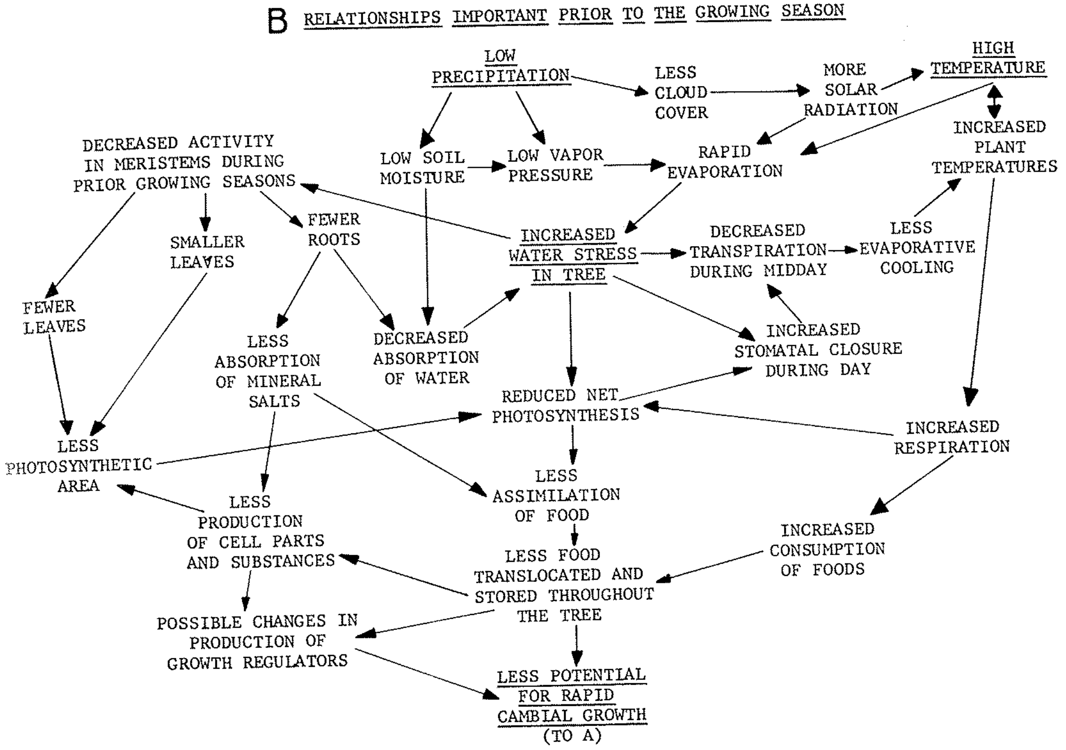


FIG. 6. Physiological Model B illustrating how low precipitation and high temperature prior to the growing season (season of cambial activity) may cause the ring to be narrow for conifers growing on semiarid and warm sites. The climatic conditions may affect physiological factors which precondition the plant, reduce the potential for rapid growth, and reduce the rate of cell division (shown in Model A) so that a narrow ring is formed.

Some lengthy, sensitive, and datable ring-width chronologies can be obtained from trees growing on sites where factors other than drought may sometimes limit growth. For example, at certain times in the year, high precipitation and low temperatures may actually produce conditions that ultimately limit subsequent cambial activity and ring growth. Some of the relationships that are likely to be involved are diagrammatically shown in Fig. 8. In general, as one progresses from arid to cool sites that occur at high latitudes or high altitudes, the conditions shown in Fig. 8 become more important for longer intervals of time throughout the year while those conditions shown in Figs. 5 and 6 become less important (Eklund, 1956; Hustich, 1948).

The relative width of a ring, W_i, may be

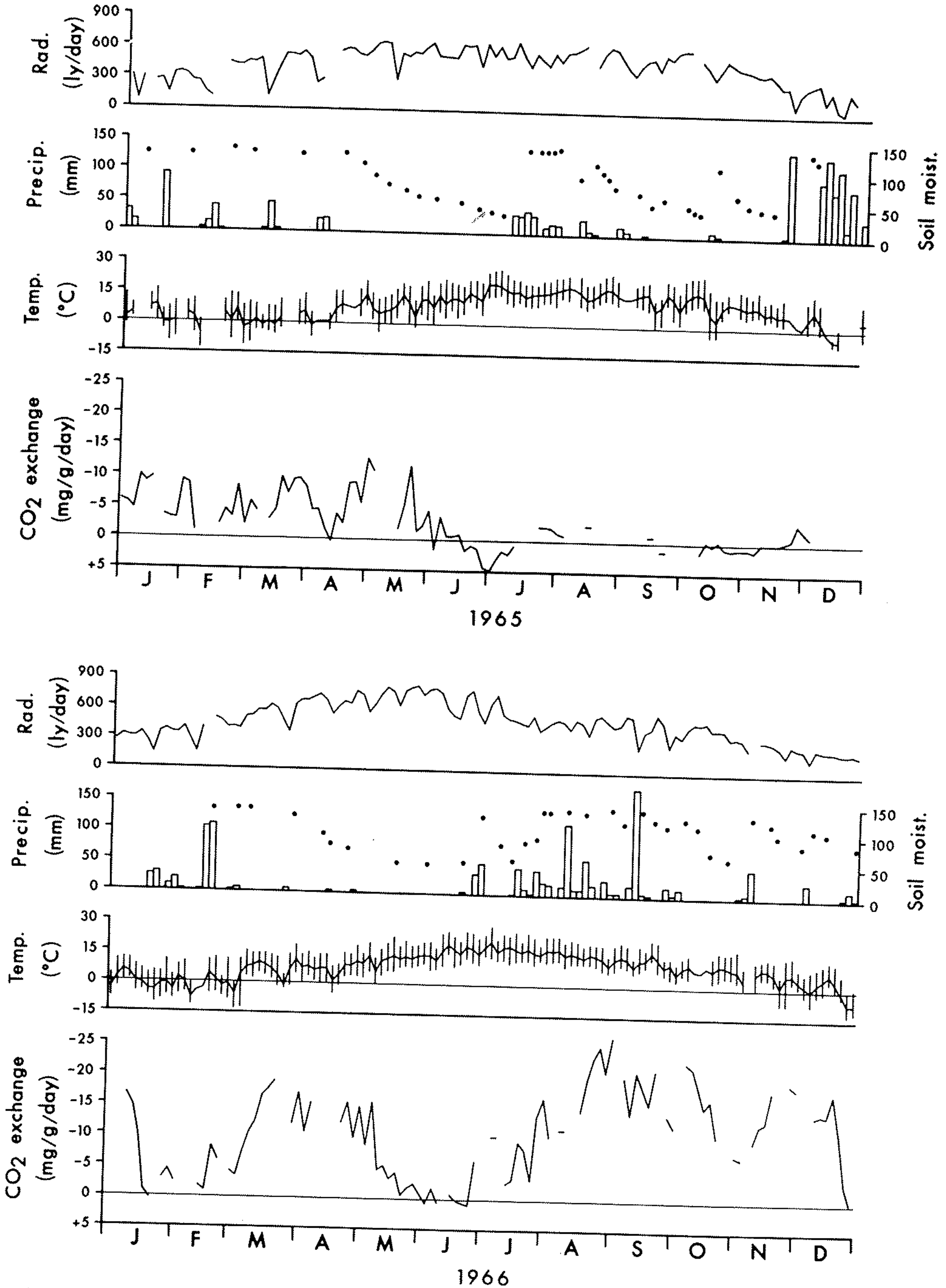


FIG. 7. The net exchange of carbon dioxide over a 24-hr period measured from a branch of a semiarid-site Ponderosa pine. A negative flux (about the zero line) indicates that photosynthesis exceeds respiration and a positive flux (below the zero line) indicates that respiration exceeds photosynthesis. Environmental factors shown are incident solar radiation, precipitation (vertical bars) and relative soil moisture (dots), mean air temperature, and the maximum and minimum air temperature (vertical lines). All values are plotted at 3-day intervals. The 2 years of data represent contrasting environmental regimes: the summer and autumn of 1965 were dryer than the summer and autumn of 1966. Photosynthesis, which consumes carbon dioxide, is reduced by dry and warm conditions while respiration, which releases carbon dioxide, increases. Photosynthesis is also limited by extremely low temperatures that may occur in midwinter. Since winter temperatures in the arid forest border sites are not extremely low, but spring, summer, and autumn temperatures are high and drought is frequent, the amount of wood produced is largely a function of the frequency and duration of moist and cool conditions throughout the year which have favored rapid photosynthesis and accumulation of food (from Brown, 1968).

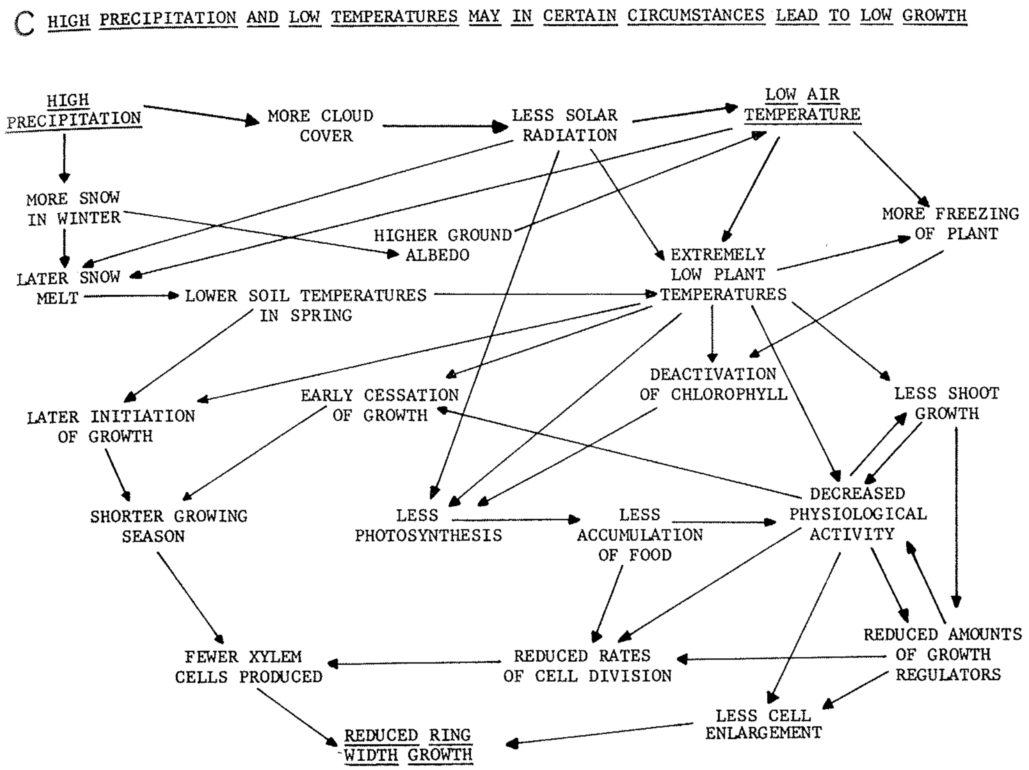


FIG. 8. Physiological Model C illustrating a variety of circumstances in which high precipitation and low temperatures may lead to reduced ring-width growth. Such climatic factors may become important on high-altitude or high-latitude sites, on north-facing exposures, or where pockets of cold air accumulate during the night.

expressed mathematically as a function of climate as shown in models A and B (Figs. 5 and 6) and model C (Fig. 8).

$$W_i = G_i(\alpha A + \beta B + \kappa C) \qquad (2)$$

where G_i is a growth function which varies inversely with tree age (i) and α, β, κ are weights representing the importance of each model diagram. For coniferous trees on semiarid and warm sites $\beta > \alpha > \kappa$. For deciduous trees on the same types of sites, or for trees in temperate regions $\alpha > \beta > \kappa$. In cold and moist habitats $\kappa > \alpha > \beta$.

THE CONCEPT OF THE CLIMATIC "WINDOW" AND RESPONSE FUNCTION

As indicated by the above discussion, the ring widths of different species, or for trees of one species in different sites, are not influenced by identical sets of environmental factors or by conditions prevailing during the same period of the year. Therefore, the tree may be thought of as a "window" or filter, which, by means of the physiological processes, passes and converts a certain climatic or environmental input into a certain ring-width output. One of the primary tasks in dendroclimatology is to identify the climatic "window" and response function for each species and to determine how they may vary from site to site.

In general, Douglas fir and Ponderosa pine from arid, forest-border sites in southwestern North America have similar climatic "windows," which allow a growth response to water stress occurring during any month of the year. Ring-width chronologies taken primarily from these two species have been used to analyze and map the fluctuations in moist and dry conditions throughout western North America for each decade since A.D. 1500 (Fritts, 1965). The rings from trees on less arid sites are more dependent upon the moisture falling during the growing season, and they are less related to climatic variability than the rings from trees on the arid sites (Fig. 9). Thus, trees on diverse sites may be limited by different sets of climatic factors and exhibit different climatic "windows."

Recent studies utilizing principal component analysis along with multiple regression have revealed not only differences in the climatic "windows" of the same species on contrasting sites and geographic locations, but, in some cases, the same environmental factor may influence different trees in different ways so that they exhibit different responses to the same environmental factors. If the climatic "windows" and response functions for two stands on contrasting sites or for different species on the same site can be adequately defined, and if the responses differ by only one factor, it may be possible to use the differences between the respective ring-width chronologies to estimate variations in the differing factor (Fritts, Blasing, Hayden, and Kutzbach, 1971).

TREE-RING ANALYSIS IN PRACTICE

Let us assume, for the purpose of illustration, that a climatologist is working in an area for which there exists only a 20 or 30-year climatic record and a hydrologist is working with an even shorter stream-flow record. Both scientists may be interested in the question as to whether the mean and the variance for the period of their short record are good estimates of the long-term mean and variance, i.e., whether they closely approximate the mean and variance for the period spanned by some longer record of climate, such as that obtained from the rings of 200–300-year old trees. They may wish to test whether it was either wetter of drier in the recent past, or may wish to study the time structure of their records in terms of recurrence of extremes such as prolonged droughts. How could they proceed in such an analysis using tree rings?

Collecting data is accomplished by selecting relatively undisturbed and open forests where the climatic factor of interest (in this case, drought) is most limiting to tree growth. The trees would consist of the "sensitive" type and would be located at the lower elevational or drier limits for each particular species. Within these restrictions of site, they could select groups of trees or individuals most representative of their study area or climatic region.

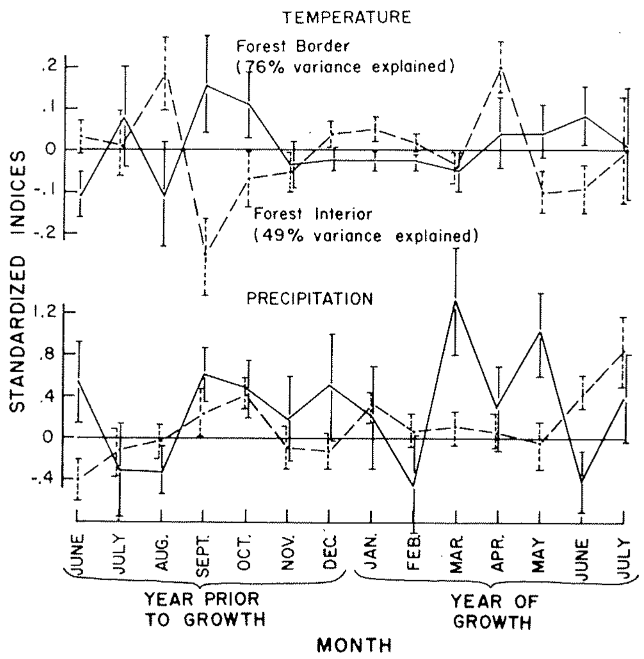


FIG. 9. The relative effect of a degree increase in monthly air temperatures and an inch increase in monthly precipitation on ring-width growth for two stands of Ponderosa pine, one growing near the forest border (solid line) and the other in the forest interior (dashed line) near Flagstaff, Arizona. The ring widths of forest border trees are affected primarily by the precipitation that falls in the period prior to the beginning of growth, while the ring width of forest interior trees is more affected by the precipitation falling during the growing season. The two stands show contrasting responses to temperature. Climate explains 76% of the ring-width variance for trees near the forest border and only 49% of the ring-width variance for trees in the forest interior. Relationships shown are a matrix representing the response function, ${}_1T_m$, scaled by dividing each element by the standard deviations of the climatic variables it represents (see equation 6). The ticks with vertical lines delinate the .95 confidence region for each element of the response function (Fritts *et al.*, 1971).

Actual field collections are then obtained, using a special tool called an increment corer. This tool extracts a cylinder of wood 4 mm in diameter from the stem. It is generally more expedient to locate the best sites by first coring a few trees and examining their rings to check the variability of width and the cross-dating. If the rings are generally wide with little variation from year to year, then the researchers would conclude that climatic factors have not been very limiting to tree-ring growth in the site. They should move to drier, more exposed or rockier sites. They need not be overly concerned about the precise location as trees may be sampled at distances of 32 km (20 or more miles) from a weather station without markedly reducing the correlation between ring width and climate at the recording station (Julian and Fritts, 1968). If the second choice of sites is too extreme, the workers will find that the samples exhibit many partial rings so that accurate cross-dating is questionable. They would then move to slightly less extreme sites. Once the general ecological niche for good cross-dating and high "sensitivity" is located, they sample at least two radii from 20 to 30 trees in a given location. The replication of at least two sampled radii per tree allows analysis of the variations within trees as well as among trees (Fritts, 1963). Additional replication of three or more radii is useful for dating and provides a wider selection of materials, but processing and analysis of more than two cores per tree is usually unnecessary at least for arid-site trees unless one is interested in evaluating the chronologies of specific trees (Fritts, 1969a). After returning to the laboratory, the scientists will examine their cores, cross-date them, and select approximately ten trees with the longest, most sensitive, and most complete ring-width records, as shown by the two most complete radii sampled from each tree. If the rings do not vary greatly in width or if correlation between trees is poor, replicated samples from 20 or more trees may be used to help minimize the nonclimatic "noise" and reduce the standard error.

Dating and screening of the specimens proceed after the cores are dried and properly mounted. Dating is accomplished by eye or by graphical techniques (Stokes and Smiley, 1968; Ferguson, 1970). It should be emphasized that dating *must* be accomplished to assure the recognition of the *annual* growth layers so that there is precise time control. The dendrolclimatologist *must* be certain that the year in which each ring was formed is properly identified before he attempts to reconstruct variation in past climate.

As each core is dated, the specimen is marked. At the Laboratory of Tree-Ring Research, a coding system is used in which the first ring beginning with each decade is marked with a needle prick, along with difficult areas where rings may be partial, absent, or hard to see (Stokes and Smiley, 1968).

The most sensitive and oldest trees are then selected, the width of each ring is measured, and the values are coded on IBM cards or written on magnetic computer tape. The entire set of data is first computer-processed through a preliminary clean-up routine. This preliminary processing serves to check for coding errors, includes calculations of ring-width variability, and involves construction of plots of 20-year average ring widths to assist in spotting and eliminating inconsistent data and in choosing the appropriate growth curve to be fitted to the data. After the computer output has been checked and the errors corrected, the data are resubmitted for final analysis.

Analysis may proceed in four basic phases:

1. An exponential growth function or a straight line is fitted to each measured radius by means of a least-squares curve-fitting technique (See Fig. 2.) (Fritts, Mosimann, and Bottorff, 1969), and ring-width values are converted to ring-width indices. These indices, unlike ring widths, generally range from a value of 0–2 and have an expected mean of one and a variance that is homogeneous through time (Fig. 2) (Matalas, 1962). The indices from all rings formed in each year are averaged to obtain a mean ring-width chronology for trees, subgroups, and groups (Fig. 2), depending on the sampling design.

Jonsson (1969), in Sweden, converts ring widths to natural logarithms, averages these data for all trees in a group, and fits a polynomial to the mean of the logarithmic series while simultaneously taking into account the effects of climate. The mean index value for each year is then calculated by subtracting the value of the fitted polynomial curve, subtracting the standard deviation, and taking the exponent. His ring-width indices are similar to those obtained in North American studies, but they differ in that his indices include variances arising from differences in individual growth curves among replications and among trees. Also, the polynomial curve could remove significant long-term climatic information if the climatic input was not known. His method is well suited for forest yield studies, where the climate is known, but would have limited application to studies of past climatic change. Nevertheless, such an approach has merit in studies where a function other than the exponent must be fitted to obtain ring-width indices. Sometimes moving averages have been used as growth functions but these data remove all long-term climatic change and in some applications introduce oscillations into the series. In studies of arctic trees, little change occurs as a function of tree age. In such cases, it may be appropriate to divide each ring width by the mean ring width for some interval of time common to all trees (Rampton, 1971).

2. Measures of statistical characteristics for the indices of each series are made. They include the mean, standard deviation, mean sensitivity, and at least the first-order autocorrelation. In all series of two or more radii, the standard error, standard deviation, and variance for each year of the chronology are obtained. Finally, if a correlation study and analysis of variance are appropriate, the necessary computations are made (Fritts, 1963).

3. The defining of the climatic "window" and response function, that is, the calibration of the ring-width series with existing weather or hydrologic data, may proceed in a fashion appropriate to the particular investigation. As stated earlier, a multiple regression analysis has been employed in some studies to predict the yearly growth indices as a function of the meteorologic variables (Fritts, 1962a,b; Serre, Lück, and Pons, 1964; Schulman and Bryson, 1964; Hustich, 1948; Julian and Fritts, 1968).

A more efficient technique involving extraction of eigenvectors from monthly temperature and precipitation values has proven highly successful (Fritts *et al.*, 1971). The eigenvectors are designated in matrix notation as ${}_mE_p$, where the subscripts preceeding and following the matrix symbol indicate respectively the number of rows and columns in the matrix. They are often referred to as principal components and represent uncorrelated modes or patterns of behavior of the original data assemblage, ${}_mF_n$. The subscript m is the number of variables, such as temperature and precipitation for the months prior to and including the period of growth, as shown in Fig. 9, n is the number of observations (years), and p is the number of important eigenvectors where $p<m$. A new set of uncorrelated variables or multiplyers of the eigenvectors called amplitudes, X, can be created by multiplying the eigenvectors and the original data,

$$ {}_pX_n = {}_pE'_mF_n \qquad (3) $$

where the prime denotes the transpose of a matrix, and n and p are the same as above (see Fritts *et al.*, 1971).

It is customary to discard those eigenvectors and their amplitudes that explain a very small percentage of the original data and use only the p-eigenvectors and amplitudes that represent the most important components of the data. Thus, principal component analysis is used to reduce the number of variables and to transform the data into orthogonal (uncorrelated) variables. Because they are orthogonal, stepwise multiple regression (Fritts, 1962a) is an efficient estimator of the tree-growth and climate relationship. The ring-width indices, ${}_1P_{31}$, are estimated from the multiplyers of the eigenvectors in the following manner,

$$ {}_1\hat{P}_n = {}_1R_pX_n \qquad (4) $$

where ${}_1\hat{P}_n$ is a row vector of estimates of ring-width indices, ${}_1R_p$ is a row vector of significant multiple regression coefficients (all insignificant ones are assigned a value of zero). Substituting ${}_pE'_mF_n$ in Eq. 3 for ${}_pX_n$ in Eq. 4 we obtain

$$ {}_1\hat{P}_n = {}_1R_pE'_mF_n \qquad (5) $$

Thus, the original climatic data can be transformed into estimates of tree-ring width via regressions on the multiplyers of eigenvectors. This transform is a transfer or response function

$$ {}_1T_m = {}_1R_pE'_m \qquad (6) $$

The response function is a row vector with elements that represent the magnitude of growth response to each climatic variable

(Fig. 10). The same eigenvectors may be used to derive response functions for several tree-ring chronologies in a given region, because only the regression coefficients vary.

It may be desirable to take into account the lag in response or autocorrelation by including in the regression analysis ring-width indices for prior years (Fritts, 1962a) (Fig. 10). This removes the correlation of the residuals arising from autocorrelation and allows a more precise determination of climatic or hydrologic parameters (Julian and Fritts, 1968). Certain species such as *Pseudotsuga menzesii* and *Pinus aristata* are favored for dendroclimatic research because there is low autocorrelation in the ring-width chronolgy and climatic information for each year is largely confined to a single ring. When autocorrelation is high, climatic information for a given year must be obtained from a number of consecutive rings.

Another approach, suggested by Stockton and Fritts (1968), involves the joint occurrence of climatic classes and tree-ring indi-

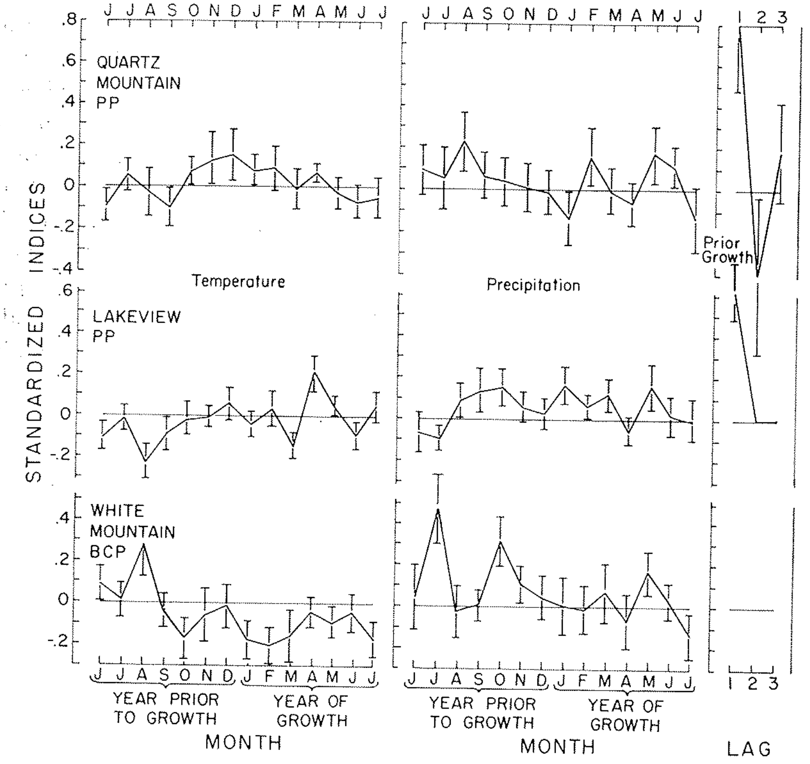


FIG. 10. Three diverse response functions T (not scaled by standard deviations as in Fig. 9) for three stands of semiarid site trees: Ponderosa pine at Quartz Mountain in northern Washington, Ponderosa pine at Lakeview, Oregon, and Bristlecone pine in the White Mountains, east-central California. Temperature is frequently inversely related to growth at low latitudes (i.e., the elements of the response function have negative signs), but temperature is directly related to growth at high latitudes or high altitudes, especially during the winter season. Precipitation is generally directly related to growth except at high latitudes or altitudes in midwinter, in April, and late in the growing season, when high precipitation is associated with conditions detrimental to growth. Prior growth up to lags of 3 years are correlated with current growth of the Quartz Mountain Ponderosa pine but prior growth is not correlated with current growth of the White Mountain Bristlecone pine.

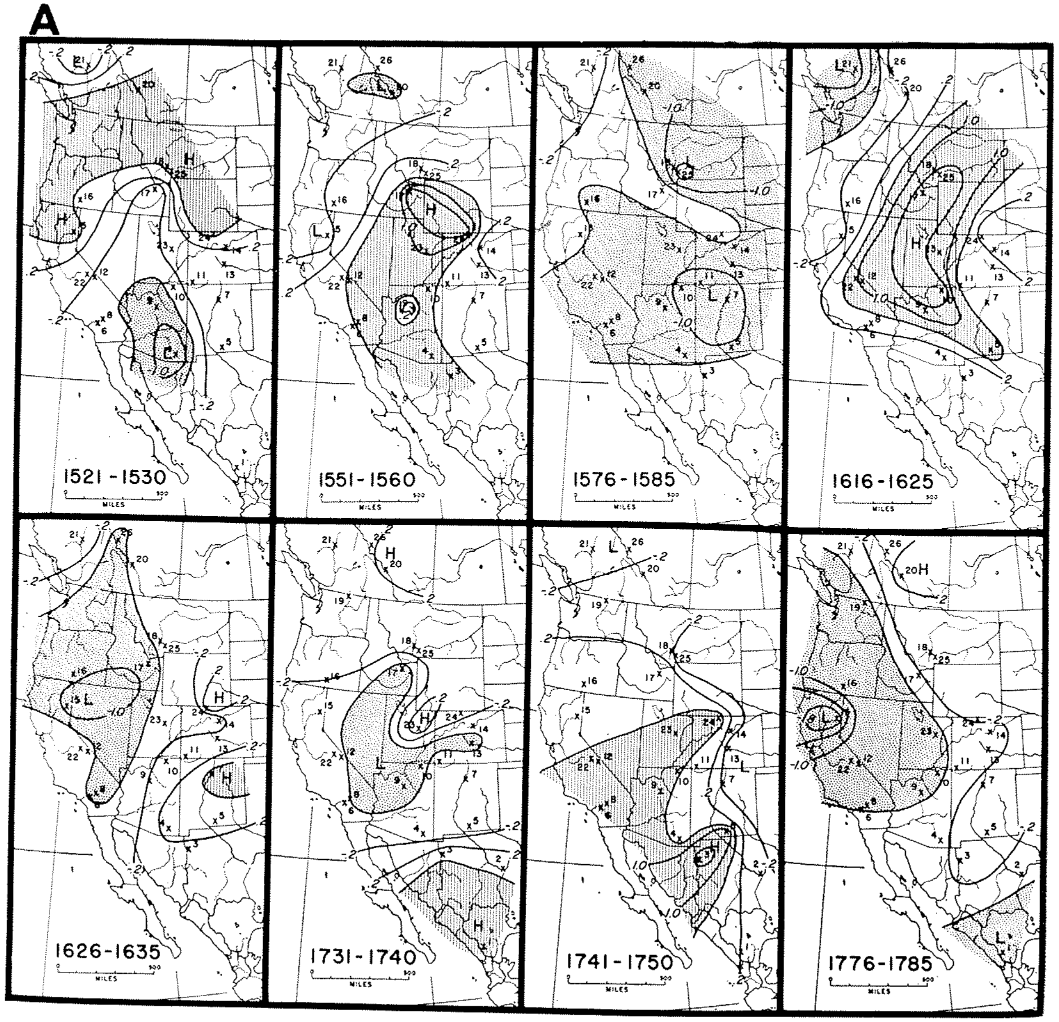
ces converted to standard normal form. The probabilities of each climatic class, given a specific tree-ring class, are obtained by the joint occurrences during the period when data for both climate and tree rings exist. These probabilities are applied to making statements about the climate during years for which only the tree-ring record exists.

4. Further analysis may be undertaken after the tree-ring data are evaluated and the climatic relationships assessed. In the past, it has been a common practice to select a group of chronologies over a wide geographic area which have a similar climatic response. It is then permissible to normalize each annual growth index by subtracting the mean and dividing by the standard deviation for a given period. These normalized values may be averaged for pentads or decades, plotted on maps and contoured to show anomalous variation in past growth (Fig. 11) (Fritts, 1965). If the chronologies have been calibrated with climate, it is then possible to infer what climatic variations have occurred by observing the areas and periods of high and low tree growth (Fritts, 1965).

Multivariate techniques have been used that involve eigenvector and canonical correlation analyses to reconstruct regional and hemispheric variation in past climate. For example, a current study by the author and others (Fritts *et al.*, 1971) involves a canonical correlation and regression of pressure anomalies during 1900–1962 for half of the Northern Hemisphere extending eastward from 165° east longitude to 5° west longitude and lying between 65° and 25° north latitude as compared to 49 tree-ring chronologies from western North America. Maps of past atmospheric circulation are reconstructed for the period when there is a tree-ring record, but no climatic record exists (Fig. 12). This new development provides a potential tool for deriving a series of transfer functions which can be used to reconstruct directly from tree rings the anomalous patterns of global atmospheric circulation (pressure anomalies). Maps of these anomalies (Fig. 12) may be used in studying past climatic change. Multivariate methods have the added advantage in that they can assess and utilize tree-ring chronologies of diverse climatic responses. Other dendroclimatic evaluation and calibration studies employ power and cross-power spectral analyses, digital filters, and a variety of other statistical techniques (See Jenkins and Watts, 1968; Mitchell, Dzerdzeevskii, Flohn, Hofmeyer, Lamb, Rao, and Wallen, 1966.).

Stockton (1971) has extended stream-flow records backwards in time by using tree rings. Separate replicated tree-ring samples were obtained from trees on widely scattered sites throughout two watersheds. These were calibrated with stream-flow and precipitation over the watersheds. Multivariate relationships of both spatial and temporal variation of ring widths are obtained which allow reconstruction of the runoff record from the tree-ring records of the sampled sites for years where ring-width measurements are available but no hydrologic records exist.

Stockton and Fritts (1971) used similar techniques to extend back to 1810 the water level record for Lake Athabasca, Canada. The water levels in channels, sloughs, and minor depressions within the Peace–Athabasca delta are directly related to the water level of the lake. The ring widths of White Spruce, *Picea glauca*, growing along the waterways were calibrated with water levels of Lake Athabasca for three periods during each year, using a 33-year record. The calibrations were utilized to reconstruct the water levels prior to 1935. The variations in water levels, especially those early in the season, were found to be considerably higher in the reconstructed record than in the 33-year calibration period. If the long-term variance had been estimated from the



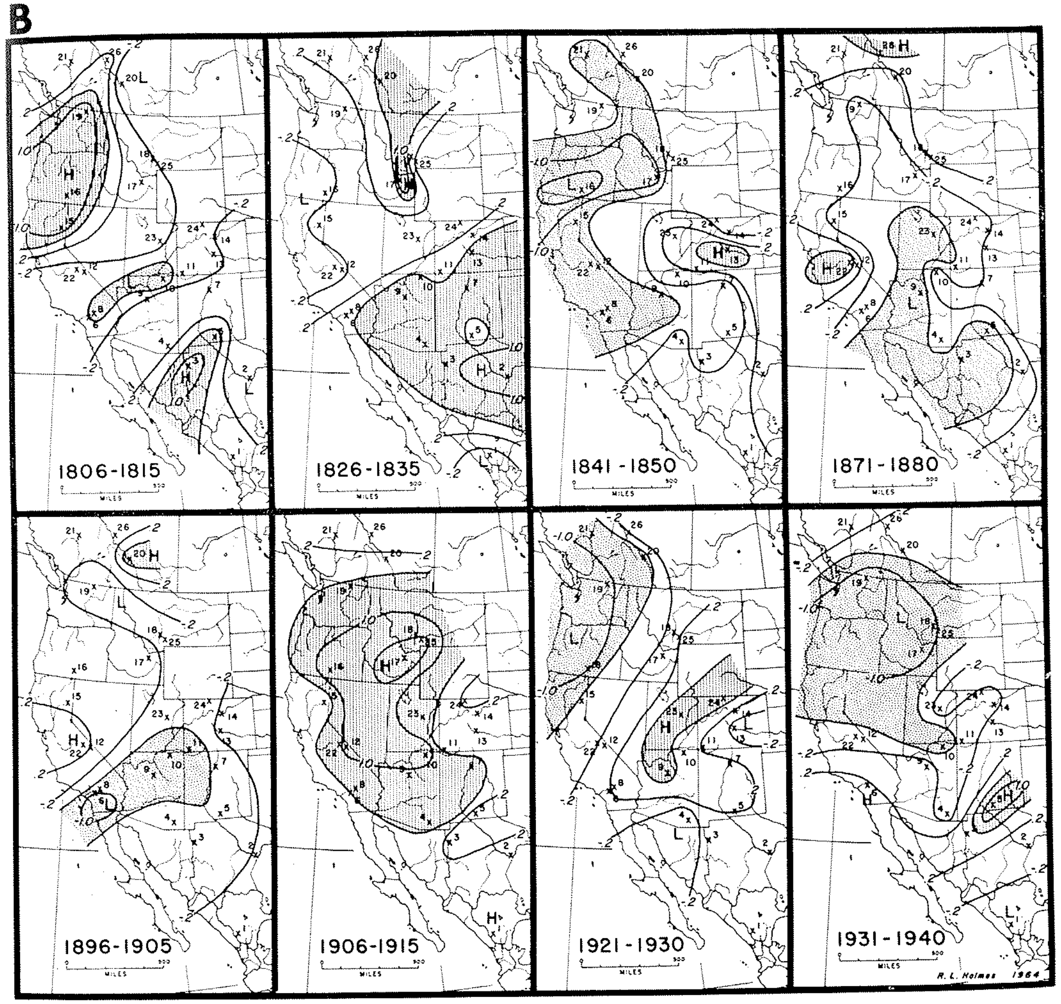


FIG. 11. Selected maps for western North America showing large-scale anomalies in tree growth for 10-year intervals of time from 1500–1940. Positive departures of high growth (H) indicate moist and cool anomalies in climate while negative departures of low growth (L) indicate dry and warm anomalies in climate. Shaded areas designate a mean anomaly exceeding 0.6 standard deviation which was calculated for the period common to all tree-growth chronologies, 1651–1920 (Fritts, 1965).

short, 33-year period, the variance of the early spring lake levels would have been only one-third the variance estimated from the reconstructed data for the period 1810–1967.

LaMarche and Fritts (in press) utilized several statistical techniques to examine tree-ring data for possible relationships with solar variation represented by sunspot numbers. They were unable to establish that any significant relationship existed and concluded that a further search for empirical associations between tree-ring indices and the record of sunspot numbers is likely to prove unrewarding. However, they noted significant periodicities in many tree-ring records at frequencies of approximately two years, and 22 through 29 years.

It is also possible to statistically anlyze for significant departures in tree-ring data (Julian and Fritts, 1968) or to map mean growth departures for a particular subperiod as compared to longer-term period for which the tree-ring chronology is available (Fig. 13). If the climate that has limited growth has been anomalous for the subperiod, then the mean anomaly in tree rings will reflect the anomalous variation in climate (Fritts, 1969b) (Fig. 13).

LaMarche and Fritts (1971) compared eigenvectors of 49 North American tree-ring chronologies for 1931–1962 with eigenvectors of precipitation (Sellers, 1968). They also compared the tree-ring eigenvectors for 1931–1962 with eigenvectors derived from the same chronologies for 1700–1930. They found that the tree-ring eigenvectors resembled the precipitation eigenvectors and that the three most important eigenvectors of tree growth were similar for the two periods. However, the fourth eigenvector differed between the two sets of tree-ring data. They concluded that the precipitation anomaly patterns which had dominated during 1931–1966 were reflected in tree-ring data and the first three patterns seem to have persisted for at least 260 years, and are thus likely to maintain their

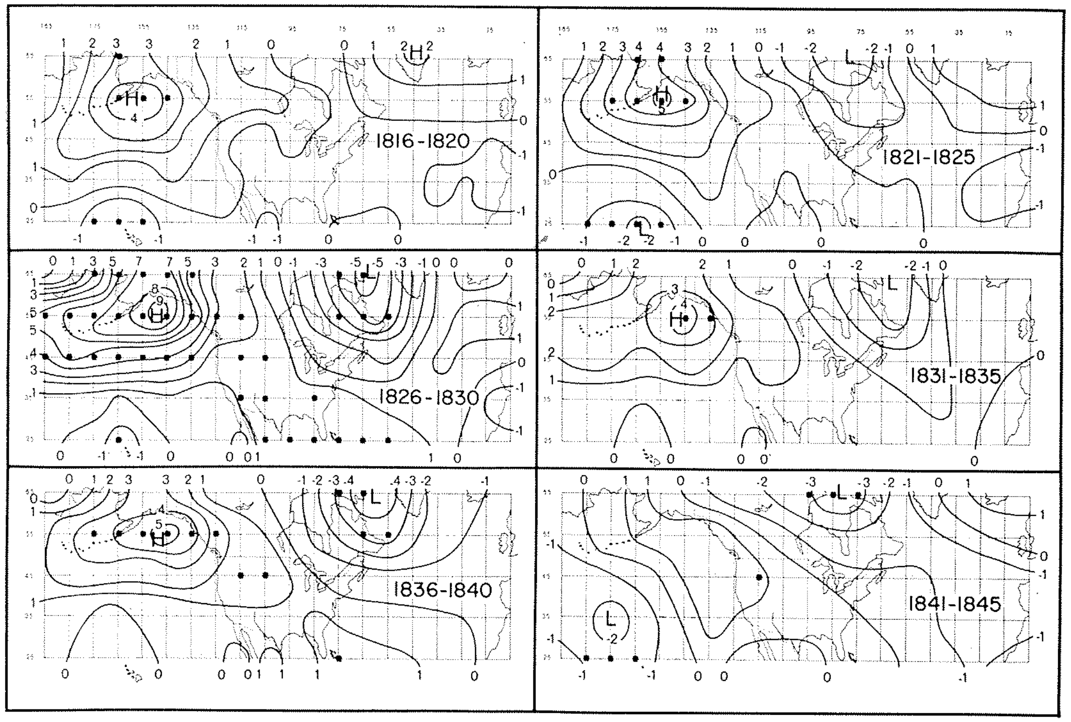


FIG. 12. Anomalous pressure variation during winter that persisted from 1816–1845 A.D. as reconstructed (predicted) from anomalous variations in the widths of tree rings (units are calculated as millibar departures from the mean pressure for 1899–1939, 1945–1962 and averaged by pentads). Square dots mark those departures that are twice the residual standard error. The period from 1816–1830 is characterized by a weakening of the Aleutian low (higher than normal pressure) and a weakening of the high over the subtropical Pacific, 25° N latitude. There is a strengthening of lows over Newfoundland and Hudson's Bay in 1826–1830 and again in 1836–1840. The anomalies are less marked in 1816–1820, 1831–1835, and 1841–1845.

importance during, at least, the immediate future.

Robinson and Dean (1969) utilized archaeological tree-ring chronologies to map and study the decade changes in climates in northern Arizona and New Mexico and southern Utah and Colorado during prehistoric times. Others such as Eklund (1956), Hustich (1949), Siren (1961), Schulman (1956), Douglass (1914), Weakly (1950), and Giddings (1941), to mention only a few, have utilized standardized tree-ring records from which they inferred the climatic conditions that have occurred in the past. LaMarche and Mooney (1967) use tree-ring dates from dead standing trees and remnants above the present timberline to establish and date the presence of an elevated altithermal timberline.

THE PROMISE AND POSSIBLE FUTURE OF TREE-RING ANALYSIS

There is little doubt that in arid and cold environments, tree-ring analysis will become an increasingly important tool for climatic and ecologic research. Data aquisition has been greatly facilitated by the computer so that chronologies can be developed more objectively and efficiently. Many new chronologies have become available recently, and old chronologies have been extended further

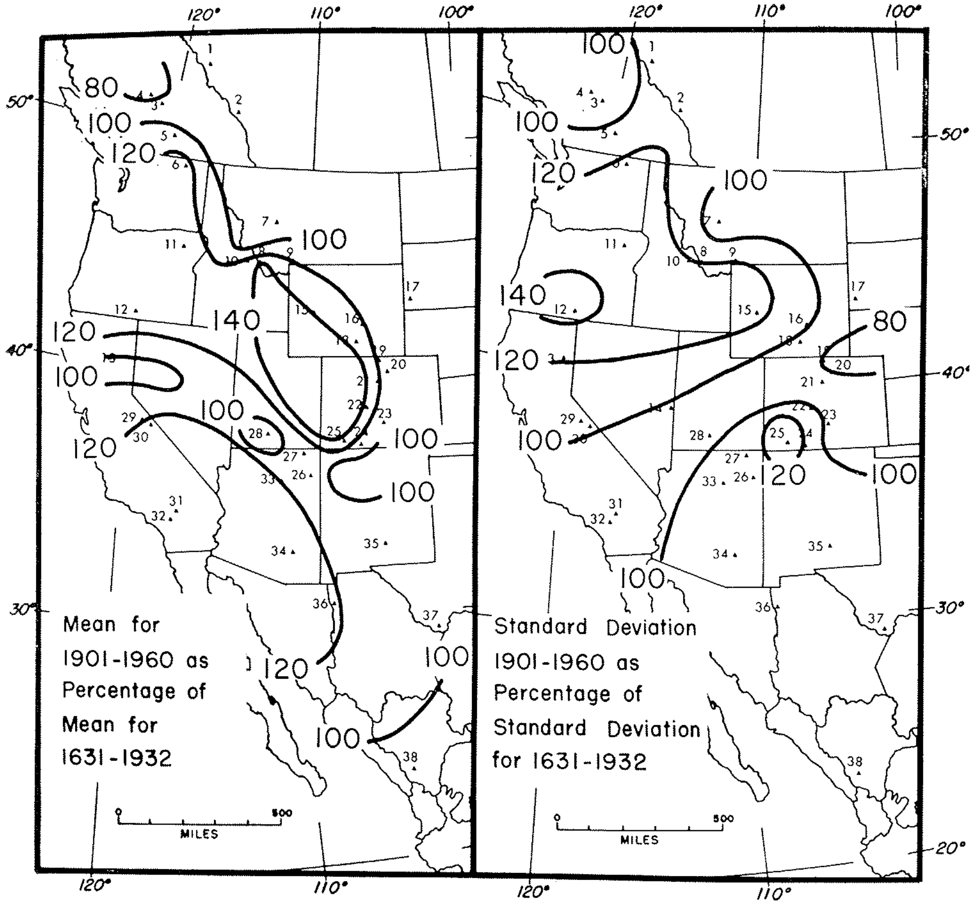


FIG. 13. Analysis of tree rings can detect potential anomalies in climatic data. The means and standard deviations of 38 tree-ring chronologies for 1901–1960 A.D. are divided by the means and standard deviations for the longer period 1631–1962 A.D. Contours show the areas of major departure in percentage of mean and variance for the subperiod, during 1901–1960 A.D. The mean growth, and by inference the moisture supply, has been anomalously high in the entire Southwest, along the western slope of the central Rocky Mountains, and in the Pacific Northwest during the recent normal period. The standard deviation has been high in the Northwest and locally in southeastern Colorado (Fritts, 1969b).

into the past. The scientific basis of the discipline is now accepted.

Trees from sites in temperate environments will undoubtedly receive more attention as populations increase and greater demands are made upon our natural resources. The rings from trees on the most arid and cool sites in temperate regions will yield some information on moisture and temperature at certain times within the year. However, few virgin forests are left, and the trees that are now available will be relatively young and growing in dense forest stands with a complicated history of use. Nonclimatic factors may have been limiting to growth for long periods so that the potential information on climate contained in the rings will be subject to large amounts of statistical "noise." However, with careful stratification, replication, and cross-dating of sampled material and the proper use of objective computer processing and analysis, a significant climatic "signal" may be extractable, even from data containing a large amount of nonclimatic "noise."

On the other hand, some ecological studies dealing with past history of the environment may find useful information in what the dendroclimatologist may regard as "noise." The statistical characteristics of tree rings can be applied to nonclimatic analyses of physiological gradients within trees, to the ecological differences among sites (Duff and Nolan, 1953; Fritts, *et al.*, 1965; Fritts, 1969a), and to phenological differences between apparently genetically different populations of trees (Fritts, 1963).

The structure of the cells throughout the ring may contain a number of features that may be related to climatic conditions (Serre, Lück, and Pons, 1964). Recent advances in X-ray techniques and wood-density studies (Polge, 1970; Parker and Meleskie, 1970; Jones and Parker, 1970) already point to radically new ways of quantifying such features. As these techniques are developed, they should make possible the rapid and objective measurement of ring structures which can be calibrated with appropriate environmental variables (Parker and Henoch, 1971). Such data on wood density appear to be independent of ring-width variation in at least some instances and should provide significant information on the variability of past environments. It appears that wood-density data from trees of temperate regions may contain more information on past climate than the measurements of ring widths (Parker and Henoch, 1971).

Dendroclimatic analysis continues to have considerable potential in such diverse fields as archaeology, forestry, geology, history, and hydrology, as well as in biology and climatology. Analysis of ring-width changes in semiarid environments will remain especially relevant to problems in water-resource development, while studies of ring-width changes in polar regions will be increasingly applied to problems of forestry and agriculture in environments where low temperature is limiting (Eklund, 1956; Hustich, 1949).

For example, scientists will turn more frequently to tree-ring data for augmenting and correcting anomalies in short climatic and hydrologic records (Gatewood, Wilson, Thomas, and Kister, 1964; Julian and Fritts, 1968; Schulman, 1945, 1947; Stockton, 1971; Stockton and Fritts, 1971). Studies of productivity in the natural communities of arid lands and cold regions should include dendroclimatic analysis. Estimates of dry-matter production for highly variable and marginal environments made over relatively short time periods ought to be compared with and adjusted for the long-term variances and means of past productivity and reproduction. Since productivity estimates are bases upon some measure of volume growth which is related to ring widths, the use of tree-ring analysis to correct for anomalies in measured productivity would be an especially suitable tool.

Many exciting possibilities exist for dendroclimatic applications to the assessment and analysis of past climatic anomalies and atmospheric circulation controlling climate. Progress has been reported in developing ways to relate tree-ring variance directly to meteorologic factors such as precipitation, temperature, pressure, indices of circulation, and frequencies of circulation types. There are also other types of proxy series of climate besides tree rings (Kutzbach, in preparation). As these data become sufficiently well-dated to be used along with tree rings, they can be entered into a multivariate analysis with tree-ring data and should improve the estimates of past climate.

As more research focuses on man's alteration of the environment, there will be an increasing need to rely on tree rings to reconstruct conditions prior to alteration and to assess the magnitude of man-induced changes. For example, tree rings are being used in an assessment of weather modification and as a measurement of the degree of air pollution. Dated tree-ring samples from a treated forest-stand can be compared to a control-stand to test whether there has been any significant changes in tree growth, and, by inference, any significant effect due to the altered environment (Polge, 1970; Vinš and Tesař, 1969).

As dendroclimatic techniques are extended to new species and new regions of the world, and some of the newer techniques become more widely used, tree-ring studies will be increasingly employed as a climatological and ecological tool. At present, they provide the most precise estimates of year-by-year environmental changes occurring prior to man's measurement of climate.

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