METHODS OF DENDROCHRONOLOGY - I

PROCEEDINGS

of the Task Force Meeting on
Methodology of Dendrochronology: East / West Approaches
2-6 June, 1986 • Kraków, Poland

Editors:

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Papers presented at the Task Force Meeting on

"METHODOLOGY OF DENDROCHRONOLOGY: East/West Approaches"

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FOREWORD

In a continuing effort to bring together specialists in dendrochronology[*], forestry and related fields, the International Institute for Applied Systems Analysis (IIASA), in cooperation with the Systems Research Institute of the Polish Academy of Sciences in Warsaw and the Agricultural Academy of Kraków) hosted a Task Force Meeting on *METHODOLOGY OF DENDROCHRONOLOGY: East/West Approaches* which was held in Kraków, Poland (2-6 June, 1986)

The Task Force Meeting was successful and met its goals: to establish the state-of-the-art of dendrochronological methods in East and West, to facilitate the establishment of a network on regional and transregional chronologies aiming to assess past growth conditions and present trends as base line data in order to evaluate anthropogenic impacts on forest decline as well as to improve the long-term prognosis mechanims using climatic background fluictuations to evaluate future ecological sustainability of biospheric systems (i.e., forest, agriculture and aquaculture).

Some thirty five participants from 13 eastern and western countries participated in a stimulating week of discussions; following the recommendations made at the Workshop, it was decided to publish the papers presented by the participants and, in addition, to write a book on the different approaches currently being employed by dendrochronologists in East and West. This book should reach an informed, but not expert, audience in environmental science as well as policy makers, and those who are not specialists in the different fields.

In a continuing effort in this innovative field of science, a further meeting will be held on a related topic "Forest Dieback and Reproduction: Regional and Global Consequences", again in Kraków, Poland (March 23-31, 1986). The Workshop will will be hosted by IIASA, together with the Systems Research Institute of the Polish Academy of Sciences as well as the Agricultural Academy in Kraków. The goals of the Workshop will be obtain a consistent picture of forest decline and to identify the choices that international organizations, the forestry community, governments and industry must face, to avoid further forest decline and facilitate the sustainability of the forest sector.

<div style="text-align:right">

Robert E. Munn
Leader
Environment Program

September 1986

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[*]Dendrochronology: the method of dating events and variations in the environment by a comparative study of tree rings.

ACKNOWLEDGEMENTS

CONTENTS

1. INTRODUCTION

1.1 PURPOSES AND OBJECTIVES

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Dendrochronology, the method of dating events and variations in the environment by a comparative study of tree rings, is usually used to study the historical trends in climatic fluctuations. During the last decade, this science has become very important for early indications of forest dieback due to anthropogenic pollution. There are also attempts to use dendrochronology to solve large-scale regional problems, including the sustainability of water supply, prediction of agricultural crops, adoption of silvicultural measures for ecological changes, etc. More speculatively, dendrochronological methods are also used for indications of the possible increase in biospheric carrying capacity due to the CO_2 increase.

Such a wide range of applications of modern dendrochronology beyond its traditional field can be expressed by the particularities of this science. Methods of modern dendrochronology enable a precise dating of events and to distinguish between the impact on the ecological systems caused by natural environmental background (climatic) fluctuations and those that are anthropogenically induced. This new field of application of dendrochronology is very important from a methodological point of view because both anthropogenically-induced and natural changes in the global biosphere have a simultaneous impact on some basic ecological processes. Assessing and dealing with this process is no easy task.

Dendrochronology (establishing past growth conditions and present trends as base line data) can be of vital assistance in obtaining an early assessment of new processes. Deviations from the master-chronologies (base lines) can then be used to document the beginning and extent of decline in tree growth and can be compared with known changes in atmospheric chemistry. Such deviations from a base line can be used to assess ecological sustainability of biospheric subsystems (forests, agriculture, water, etc.) and to forecast future outcomes.

Within the Environment Program at the International Institute for Applied Systems Analysis (IIASA) projects are being carried out on "Ecological Sustainable Development of the Biosphere", "Acid Rain", and "Climate Impacts", among others. Several methodological themes span across these projects and applications have been initiated:

— environmental monitoring;
— ecologically sustainable/unsustainable regional development; and
— dendrochronology and applications.

These themes span across the three above-mentioned projects and involve both methods of dendrochronology and dendroclimatology for dendroindications of natural and anthropogenic impacts.

It was for this reason that IIASA organized the Task Force Meeting on "Methodology of Dendrochronology: East/West Approaches" which was held in Kraków, Poland in June 1986, in cooperation with the Agricultural Academy of Kraków and the Systems Research Institute (Warsaw), of the Polish Academy of Sciences. Different methods are currently being employed in countries of East and West and thus IIASA used its resources to assist in bringing eastern and western scientists together to clarify these differences and to establish, unify or calibrate common approaches. An agreement between the Laboratory of Tree-Ring Research in Tucson, Arizona (USA), IIASA and the Commission for Dendroclimatology of the USSR Academy of Sciences in Moscow (USSR) was reached.

The following issues were discussed at the Task Force Meeting:

- geographical, biological, and ecological bases for field samplings;
- data processing and intercalibration methods;
- establishment of modern regional and transregional chronologies;
- application methods, particularly for early indications of forest dieback based on changes in atmospheric chemistry; and
- approaches and methods for estimating future probable outcomes.

The Task Force Meeting was designed to achieve the following results:

1. To establish the current state-of-the-art of dendrochronology methodology, especially common aspects and differences in eastern and western approaches.

2. To facilitate the establishment of a network on regional and transregional chronologies aiming to assess past growth conditions and present trends as base line data in order to evaluate anthropogenic impacts (pollution or CO_2) on forest decline.

3. To improve long-term forecasting mechanisms using climatic background fluctuations to evaluate future ecological sustainability of biospheric subsystems such as forests, agriculture, and aquaculture.

4. To draft and international review on the rationalization of dendrochronological sampling and on the analysis of methodologies, particularly the unification of eastern and western approaches as a basis for a multi-author international book to be published at a later date.

5. To work towards the successful outcome of the III International Conference on Dendrochronology (Seattle, USA; 1987) and an International Workshop on the Application of Dendrochronology in Forestry and Ecological Forecasting (Vilnius and Irkutsk, USSR; 1987) as well as to further development and worldwide cooperation in this scientific field.

Some 35 scientists from 16 eastern and western countries (see the List of Participants in the Appendix) attended the Kraków Task Force Meeting at which 26 papers were presented and have been included in this publication.

1.2 SOME PROPOSITIONS OF DENDROCHRONOLOGY

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1. Introduction

I would like to talk about some propositions (or
principles) of dendrochronology that could be important in the
five days of discussion we have before us. For some
propositions, we may wish only to articulate them clearly. For
others, we may be more concerned with specific applications.
In hopes of stimulating discussion, I offer the following
thoughts on a few tentative propositions. The topics are not
necessarily listed in order of importance.

2. Crossdating

Tree-ring data from one measured and dated stem section
can be regarded as a time series of annual values that in
themselves provide relatively noisy estimates of environmental
factors that have directly or indirectly limited growth in each
year (Fritts, 1976). In order to use tree-ring data in a
rigorous fashion, such as in time series analysis, it is
proposed that a number of trees be sampled, and all rings
should be crossdated before they are used in the analysis. Is
DENDROCHRONOLOGICAL crossdating the only reliable method
available today that can assure that the ring is dated to the
exact year of formation? Are there any situations to which
this proposition does not apply? If crossdating is not used,
can other dendrochronological methods such as standardization
and calibration be applied? Should studies of undated
materials be considered as the domain of dendrochronology?

There are a variety of approaches to crossdating. Most of
them involve at least six logical steps that I will attempt to
describe in a simple and straightforward fashion. I am by no
means the most qualified person in this room to be discussing
this particular topic, because of my limited experience with
crossdating. However, I will present this list just to get a
discussion started.

Basic Steps in the Procedure of Crossdating

1) Visual and statistical comparisons are made of
the ring characteristics through time that can be observed

on collected specimens. These involve features such as:
width of the ring, width of the earlywood, and width of
the latewood. Wood density or other related differences
in structure are commonly used. Often plots of one or
more ring features are utilized and some computations made
to assist the dating operation.

2) If one and only one ring is formed in a year, the
chronology of ring characteristics over a particular
period of time is generally synchronous between
neighboring trees as long as one begins with the same year
when making the comparison. If a ring is absent in one or
more trees, or if two layers of latewood are formed in one
year (sometimes called a "double" or "false ring"), the
chronology from that tree may match the chronology in
other trees up to the location of the absent or false
ring. Beyond that location the chronologies will appear
to be one year out of phase unless there are other
problems in other trees that compound or compensate for
the discrepancy.

3) Crossdating utilizes the presence and absence of
synchrony in ring characteristics from different cores and
trees to identify where rings may be locally absent, where
extra latewood bands make a ring appear double, or where
there is simply a misinterpretation of ring structure.

4) Knowledge of cell growth, ring structure, and
chronology is used to correct the sequence by entering
zero values for locally absent rings, combining the widths
of double rings, and adjusting for miscounting or any
other discrepancies within the ring sequence.

5) The comparison, checking, and correcting are
replicated many times using specimens from different
trees. The time period spanned by the rings must include
some growing seasons when climate had been sufficiently
limiting to produce a visible growth reduction. The
replication of crossdating continues until no further
errors can be identified. If the dating is correct, no
additional effort can change the over-all dating, although
the dating of some specimens may still be in question.
Specimens with such problems usually are not used to
develop the site chronology. Computer programs have been
developed that analyze the statistical crossdating of
tree-ring series (Aniol and Schmidt, 1982, Baillie, 1982;
Holmes, 1983). These programs are most useful for
checking the dating of samples that have a relatively
small number of errors. They are also valuable as a
routine check of dating quality. The programs should not
be considered as substitutes for the dating procedure but
rather as objective guides for making crossdating
decisions.

6) The final step in crossdating involves checking
the site chronology against independently dated
chronologies from other species and from trees in other

sites. This last step may not be absolutely necessary
because of the internal consistency and rechecking that
has already been built into the crossdating of trees
within the sampled site. If step 6 is included, it serves
as an additional confirmation that the chronology dating
is accurate to the exact year of ring formation. Step 6
can always be used at any time it might be necessary to
evaluate the dating of another chronology.

3. Stratification, selection of site, and averaging

Most of us emphatically acknowledge that a variety of
environmental factors can limit growth. Over the decades
dendrochronologists have developed ways of reducing the
noisiness of the data attributed to multiple factors by
sampling all trees for a particular analysis from a given
species, age class, and a narrowly defined site. After these
rings have been dated, their characteristics can be averaged in
different ways to combine the results from many trees and
sometimes different sites. Noisiness can be reduced further by
standardization, filtering (smoothing the data), and by
combining a number of different standardized chronologies to
obtain a wider coverage. More complex techniques of
multivariate analysis, principal components, and Auto
Regressive Moving Average (ARMA) also help to reduce the
noisiness if they are applied correctly. Are there more
techniques that can be listed?

4. The signal to noise ratio

The percent variance that is common to all sampled trees
from a particular site can be regarded as the signal. The
remaining variance not in common to all trees can be considered
the noise. My climatological friends sometimes criticize this
definition of the signal because they would like the term
"signal" to include only the climate response. My definition
of signal includes the effects of all variables that appear to
influence the sampled trees in the same way.

The signal is hypothetically the same for one tree or for
the mean of many trees representing a site chronology. The
noise, however, diminishes in size like the average values of
random numbers. As more and more measurements are averaged
together to form a chronology, the noise diminishes but the
signal remains the same size. The ratio of signal to noise
(s/n) increases reflecting the relative strength of the signal
compared to the noise. Thus, any operation that reduces the
amount of error variance (the variance not in common to all
sampled trees) reduces the noisiness of a tree-ring record.
Fritts (1976) developed empirical methods for estimating the
signal and noise and showed how these results can be used to
evaluate the effects on a chronology of changing the sample
size.

Wigley, Briffa and Jones (1984) developed the statistical
proof for the empirical methods of Fritts and derived the
statistical equations for estimating the signal and noise from

a particular sample. They objected to the s/n because it is a
ratio, and derived a substitute, which they call the "expressed
population signal." It is approximately the s/n divided by
[1 + s/n]. They also derived an equation to compute a minimum
sample size below which the correlation of the expressed
population is too low. However, like Fritts's computations,
there is no theory to help one choose the minimum correlation
to use. How can we decide what is a meaningful threshold
correlation coefficient or lower limit to the s/n? Is there an
upper limit in the number of rings (the number of cores or
trees) needed to obtain a high-quality chronology? At what
point does increasing the sample size become prohibitively
costly? If we hope to extrapolate our tree-ring results to
various environmental problems, it will be extremely important
that we thoroughly understand how much information is in in our
tree-ring data, and how we can sample or manipulate data to
enhance the s/n. It is proposed that in addition to more
mathematical analysis of our procedures, modeling and
simulation studies could also be an aid in studying questions
of this kind.

5. Standardization

Standardization is often but not always necessary. It
can transform non-stationary ring measurements into indices
with more or less stationary means and variance over time. It
can be regarded as another s/n enhancement technique. Several
promising and innovative methods of standardization exist
today, but some have not been thoroughly tested on tree rings
from different species and regions. The International Tree
Ring Data Bank is an obvious source of data that could be used
for such testing.

6. Evaluating chronology quality

Certain standard statistics of tree-ring chronologies can
be compared and interpreted as indicators of particular
chronology qualities (Fritts, 1976). It is proposed that a
minimum set of statistics should be calculated and published
with every chronology to facilitate comparisons. As new
procedures and insights develop, new statistics can be added to
the information published with our chronologies. For example,
when computers were first used for standardizing, it was
customary to publish the standard deviation, mean sensitivity,
and first order auto-correlation. Later the percent variance
that was common to all trees was added along with other useful
statistics. Ed Cooks new program, ARSTAND, provides a host of
new statistics. It also calculates the standard deviation,
mean sensitivity, and first order auto-correlation for
comparison. The ITRDB already archives a large array of basic
statistics along with the original measurements and derived
chronologies.

7. Characterising the time-series analysis

New techniques of time-series analysis can provide
powerful tools for dendrochronological research. Sometimes

chronologies that are transformed by these techniques have the same or more information in them than was obtained using the older methods for standardization. If the new transformation is clearly demonstrated to be superior, it can be safely substituted for the earlier version and submitted to the ITRDB. However, sometimes the new transformations such as the "prewhitened" chronologies from ARSTAND can actually have less information than the normally derived chronology. If this is a possibility, both the untransformed and transformed ("unwhitened" and "prewhitened") chronologies can be published and contributed to the ITRDB (Stahle et al., 1985). In other words, new techniques may provide new approaches to certain problems, but the results may not be advantageous in other studies. It may take time to establish the limits of new technologies. Until the new methods are shown to be clearly superior to older methods, it is judicious to preserve and use the results from both technologies.

8. Calibration

Calibrating the growth response. There are at least two basic types of calibrations. The first can be called the response function. Climatic data are the predictor variables and a tree-ring chronology the predictand variable. The principal objective is to obtain a set of regression coefficients that can be interpreted as the growth response to each variable of climate (Fritts et al., 1971). The original response function (using program RESPONSE) was calculated using principal component regression, but now there are a several approaches to the response function problem (Hughes et. al.,1982; Fritts and Wu. in press).

Recently, Cropper (1985) applied simulation results to different approaches to the response function problem. His results show that the confidence limits of the principal component regression versions are underestimated by about 40%. He proposed that ridge regression was a suitable alternative. Some of the differences in several response function programs are discussed by Fritts and Wu (submitted).

Transfering the tree-ring signal into estimates of climate. The second type of calibration relates climate to tree growth in such a way that the yearly chronology values can be transfered to estimates of climate. Transfer functions are obtained that range from simple regression using individual tree-ring chronologies as predictors to canonical regression where large arrays of climatic data can be related to large arrays of tree growth data (Fritts et al., 1971; Fritts 1976). Much discussion has revolved around the question of which type of multivariate model is best (Hughes et al., 1982; Stockton et al., 1985). It might be fruitful to use the various transfer function techniques on widely different data sets and then evaluate from known data the relative merits of each transfer function approach.

9. Simulation Modeling

I have changed the direction of my own work to focus on development of two simulation models in hopes that they may help resolve some important dendrochronological problems and lead to new environmental applications. One model will attempt to simulate the response function by modeling the processes of cambial division, cell enlargement, and cell differentiation as they are affected by the physiological-environmental coupling system on the tree sites.

Figure 1 is a simplified diagram of the model entitled "Response Generation Subsystem" (RGS). The most important part of the model is the "PHYSIOLOGICAL RESPONSE SIMULATOR" (shown on the right) that estimates a well replicated chronology from a given climate input by operating on daily climatic data and mimicking the physiological linkages between the climatic regime and the processes of "Cell Division, Cell Enlargement, and Cell Differentation." These last three processes are already modeled in a program, ARBOR, described by Stevens (1975). A file of synthetic cells is created which will resemble the naturally occurring cellular features across the ring when the model is in working order. A Densitometry Simulator converts the characteristics of this cell file into simulated width and densitometric measurements in OUTPUT B.

The left-hand portion of the diagram is the RESPONSE FUNCTION SIMULATOR. The input for this part is also Daily Climatic Data that are converted to monthly values. These are multiplied by the response function coefficients to estimate the annual width, density measurement, or any other feature that had been calibrated in the response function work. The result, OUTPUT A, serves as one type of control for the "Physiological Response Simulator" shown on the right.

Outputs, A and B, are compared, the structure of the functions of the PHYSIOLOGICAL LINKAGE is varied, and the results are compared over a period of time, perhaps 50 years at first. If the structure appears satisfactory, the values of the parameters of the equations are varied using an iterative procedure that chooses the direction of variation that reduces the error in the result. This type of model can also be used using field measurements of the environment conditions and some of the important plant processes affecting growth (Fritts, 1976).

It is hoped that the RGS model will provide new insights the various environmental interactions affecting the cell division and cell development processes. It should assist the testing and development of improved response function techniques, and provide a way to separate the effects of climate on growth from other possible sources such as pollution and other human impact.

A second simulation model is called the "Generalized Ecology Generation System" (GEGGS) (Figure 2). The figures represent the the tree-ring or the tree-ring state. The underlying world.

Response Generation Subsystem

START

RESPONSE FUNCTION
SIMULATOR

Input Daily Climatic
Data for n Years

PHYSIOLOGICAL RESPONSE
SIMULATOR

New
Response
Function
?

No

Yes

Another
Iteration
?

No

Yes

STATISTICAL LINKAGE
Apply Response
Coefficients to
Monthly Climate

PHYSIOLOGICAL LINKAGE
Climate Driver and
Plant Process Interface

RING RESPONSE
Width and Density
Other Parameters

GROWTH SIMULATOR
Cell Division
Cell Enlargement
Cell Differentiation

Accumulator:
Yearly Ring
Response

Accumulator:
Cell File
Structure

Densitometry
Simulator

OUTPUT A
Width/Densitometric Variations

OUTPUT B
Width/Densitometric Variations

COMPARISON
Similarities and
Differences

If
Satisfactory

No

Modify
Structure
or
Adjust Parameter
Values

Yes

STOP
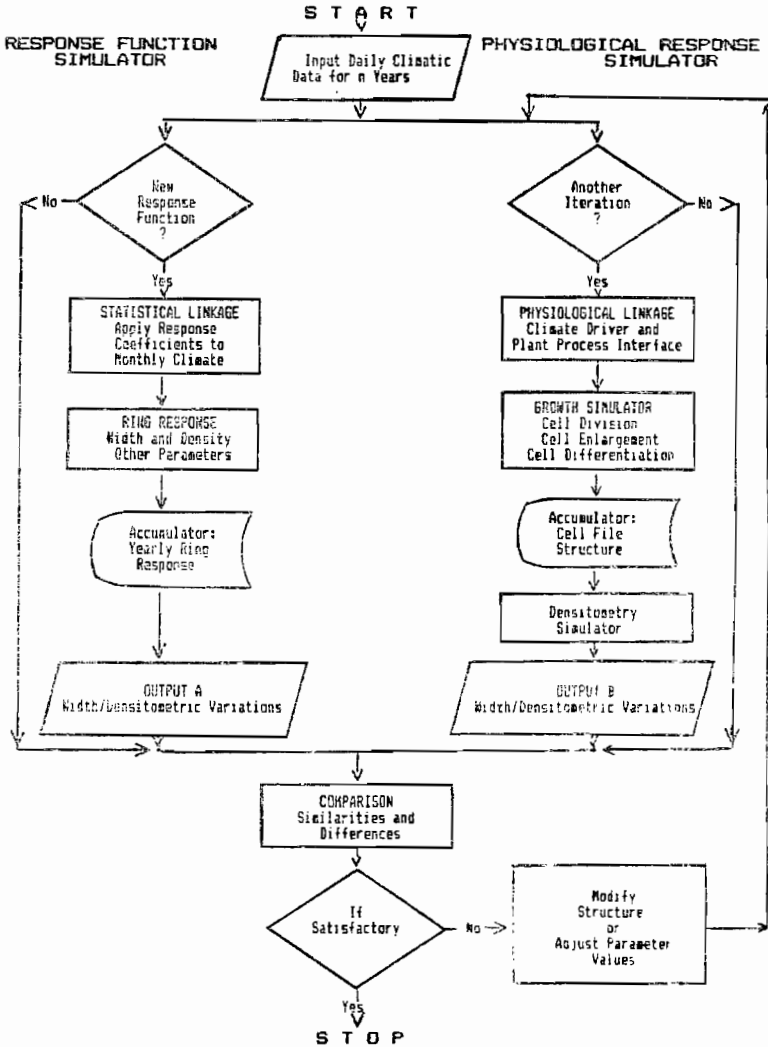
Use Subsystem to Analyze Response Problems

FIGURE 1   The Proposed Response Generation Subsystem.

Generalized Climate and
Chronology Generation Subsystem
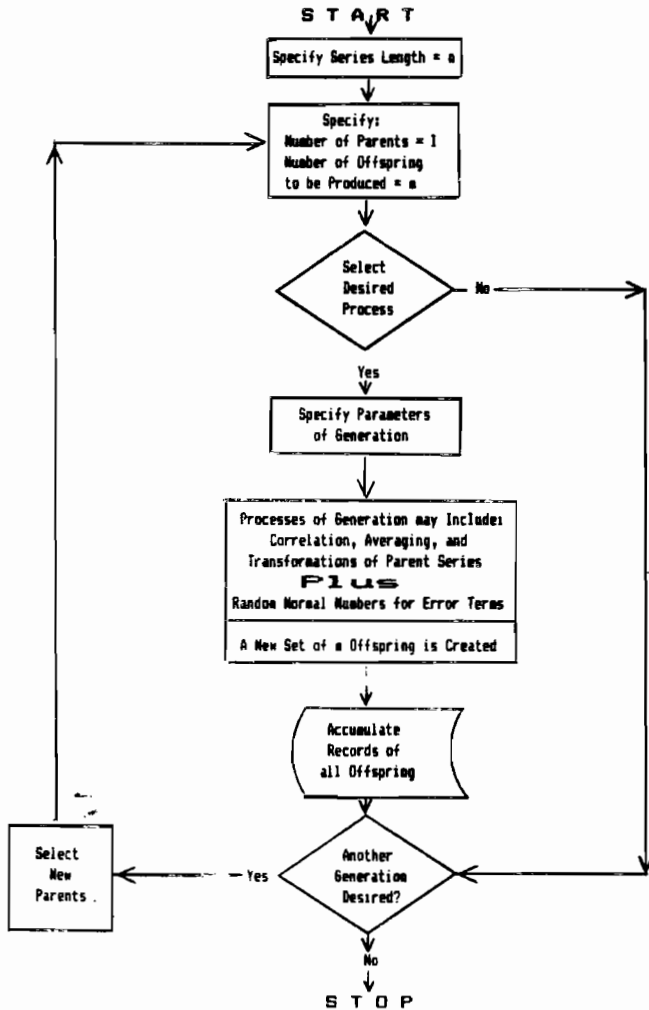
FIGURE 2   The proposed climate and chronology generation
subsystem.

can then be analyzed by transfer function techniques to see how
well different transfer functions recover the original climatic
data. A large number of replicate data can be generated from
random numbers to check whether the probability estimates from
current methods are correct.

For the time being the model will use random normal
numbers to synthesize large or small spatial arrays of climatic
data with specific time series characteristics including
nonlinearities and trends. Increasingly complicated climatic
patterns are generated by first creating one or more sets of
random numbers to represent uncorrelated modes of climatic
behavior. These "parent" series are treated by one or more of
7 different modules that convert the "parent series" to a new
"offspring" data set. These become the data of new "parents"
which are passed through the model again, this time using other
modules to generate new "offspring" with still other
characteristics. Synthetic tree-ring chronologies with a great
variety of characteristics can be derived from synthetic
climatic data which also can have a variety of characteristics.
Random Normal Numbers are added in a way to reflect noise and
both intrinsic and extrinsic stand influences. The module
functions are: 1) generate an "offspring" series of purely
random normal numbers, 2) generate an "offspring" that is
correlated with a "parent" by a specified amount, 3) generate
an "offspring" that averages together the weighted effects of
two or more "parents", 4) introduce a nonlinearity into a
"parent" series to form the "offspring", 5) introduce
autoregressive and moving average process, 6) generate a trend
using a specific function or character string that is added to
the "parent" data to form the "offspring", and 7) add a mean
and generate a specified standard deviation in the offspring.

These two subsystem models allow us to examine both
biological and statistical systems that are involved in forming
a tree-ring chronology. Eventually we hope to join these two
subsystems, as the output from the modeled processes in
Figure 1 can become the input for the statistical series
created in Figure 2.

10. Verification on independent data

Goodness of fit measurements made for the calibration
interval usually overestimate the reliability of a
reconstruction estimate. For transfer function work
independent climatic data should be set aside, and the success
of the reconstruction tested using a variety of verification
statistics. Unfortunately, different statistics are used by
different workers, and there is always the temptation to
publish only those statistics that look good or are most
convenient to calculate. Could there be some agreed upon
reporting criteria including the specific independent
statistical tests that appear to be most useful for
verification? This is one simple way we could make
dendrochronology a more objective science.

11. Reconstruction

Backward forcasting, backcasting, or reconstruction are terms sometimes used to describe dendrochronological work. Generally it concerns conditions in the past and applies Hutton's Uniformitarinism Principle (Fritts, 1976) to deduce past conditions based upon the observed and reco. Jed conditions of the present. In such cases, tree growth values for a particular set of years or seasons have been used as surrogates of past climate, because climate and growth are linked by a complex set of known cause and effect relationships. Other phenomenon may be linked simply because they are correlated with causally linked factors. Such correlated linkages can be used in reconstruction work, but care must be taken to prove that the correlation was not a circumstantial result somehow due to chance variation. Verification with independent data is one good way to demonstrate that the reconstruction is a real effect.

Statistical forcast (involving some future time) is also proposed and most certainly will be discussed at this meeting. Here the tree is not only a proxy of climate at a particular time but also an indicator of what the future will bring. We will need to review very carefully the biological as well as the physical evidence for a forcastable system involving the tree-ring response. Is there also empirical evidence for a forcastable effect? If there is, rigorous statistics are needed to assure the effect is stable through time. Reliable calculations of degrees of freedom are needed, especially for the low frequency information, because few complete cycles are available for a test. Since tree-ring chronologies often yield very long time series with well-behaved statistics, they are especially valuable for testing forcast models of low-frequency effects. I have had limited exposure to this type of analysis and look forward to learning more about this type of work.

12. Forest decline and other related problems

Dendrochronology has already made a number of unique contributions in the field of ecology (Fritts and Swetnam, in press). Crossdating provides the precise time control, and the dendrochronological time series estimates are relatively stable. Differences between the highly variable effects of climate and the slower action of possible pollution changes have been resolved in a number of dendrochronological applications (Cook, in press; Eckstein et al., 1984; Kienast, 1982, 1985; Schweingruber et al., 1978). La Marche et al. (1985) report a possible enhancement of growth of high elevation trees in arid western North America that could be responding to rising levels of CO_2. There are many more applications that could and should be mentioned in a complete review of forest decline work.

At this particular meeting we are asked to review the important methodologies dealing with environmental problems and to discuss differences in our perception of the science in an attempt to arrive at a clearer understanding. We have a marvelous opportunity as well as an obligation to build bridges of understanding between the East and West and to begin a truly international effort.

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2. SITE SELECTION AND SAMPLING

2.1 SITE SELECTION AND SAMPLING STRATEGY

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1. INTRODUCTION

Practically every dendrochronological study states the locality from which
the material is taken and the number of tree—rings contained in the samples
and chronologies, but only in dendroecological papers are the principles of
selection described (e.g., MUELLER-STOLL, 1951; JAZEWITSCH, 1961; FRITTS,
1965). LAMARCHE, COOK, and BAILLIE (1983) pointed out the potentials and
limits of dendrochronological studies in historical and ecological fields.
The present paper focuses on the aspect of site in sampling strategies for
various spheres in dendroecology.

2. SITE SELECTION

The results of dendroecological studies stand or fall with the selection of
the sites and trees. Consequently the technical dendrochronological work
begins in the forest. In order to minimize variability within local tree—
ring chronologies, the following principles must be observed in all
studies:

- The homogeneity of the sites determines to a large extent the quality of
  the chronology.
  A site chronology should only be constructed from trees from the same
  class of site. In fortunate cases it is possible to find sufficient trees
  within a small area. Often, it is necessary to group together trees from
  different places but the same site conditions in order to obtain a chro-
  nology. The units of collection are best identified by means of phyto-
  sociological relevés or at least floristic descriptions. These surveys
  also permit the relationship of ecological conditions on sites far
  distant from each other, which is not possible on the basis of topogra-
  phical—geological descriptios alone.

- Stand development affects cambial activity.
  Wherever possible, only trees of the same social statues (dominant, co-
  dominant) should be grouped into a site chronology. The variability due
  to competition is thus reduced, although it cannot be completely elimina-
  ted, particularly not in intensively managed forests, where a number of
  silvicultural operations are conducted within a relatively short time.
  If, on the other hand, the study concerns stand development, then all the
  trees should be included, although once again, the single curves are not
  grouped together to give mean curves.

— Growth varies within an individual tree.
The variability is greatest at the foot of the stem and smallest in the crown region. In order to obtain the longest possible ring sequences with a minimum of individual variability, samples are taken at breast height. Where stem discs are available, it is possible to exclude all the irregularities (compression wood, tension, wood, abrupt or localised changes in ring width, wound tissue). However, samples are usually obtained with an increment borer. With two cores per tree a large part of the individual variability can be eliminated through averaging.

For our own studies, we select the following points for coring:

— not in the vicinity of a wound;
— not in the vicinity of reaction wood; between buttresses, parallel to the slope or a forest margin, or halfway between the luff and lee sides. The absolute compass direction does not appear to be of any great importance.

In studies on slope or snow movements or on the influence of wind, attention must be paid to the side of the trunk with compression wood in conifers or tension wood in broadleaves.

— Not all irregularities are predictable.
Consequently, it is best to sample a few more trees than necessary, so that anomalous curves may be discarded.

— Individual variability decreases with an increasing number of samples.

For this reason, several trees are cored on each site. For densitometric studies 2 cores from each of 12 trees are sufficient. For ring width analysis, a sample number of 2 cores from each of 20 trees is recommended. Studies on individual features such as frequency of wounding or abrupt growth changes require samples from more than 20 trees.

— In densitometric studies, variability due to technical processing can be greatly reduced by taking the cores as nearly perpendicular to the fibre orientation as possible. This requires the use of a support for the increment borer.

The more carefully and appropriately the sites and trees are selected, the fewer the trees which have to be sampled an thus the less the work involved.
     It should be borne in mind that coring injures the tree. Even with careful work, a bore hole is left; this usually becomes sealed and overgrown within a few years. In the case of conifers, treatment is seldom necessary. Broadleaves, however, react physiologically, the result being radial, disc-shaped discolourations around the bore hole. Furthermore, fungal infection often follows; as a minimum preventive measure the hole should be plugged with wax, so as to prevent the entry of spores. Opinions on the effectiveness of further treatment vary.

At least the following characteristics should be recorded for each site:

Date	Tree cover %	Tree height in m
Place (local, regional)	Shrub cover %	
Latitude and longitude	Herb cover %	
Height above sea level	Moss cover %	
Exposure	Tree/shrub/herb species	
Slope inclination	.	
Geological substrate	.	
Species sampled and number	.	
of trees/cores	(if not all, then at least the most	
	important)	
Collector's name	Special features of individual trees, e.g.,	
	broken top, old wound with resin.	

Brief description of the site, for example: old pine stand with earlier pasturage, with dense undergrowth, on deep brown soil, on gentle, south-facing slope. Stand possibly planted.

Aim of the study or reason for sampling, e.g.:

- site for coring in a climatological sampling network - maximization of the effects of precipitation;

- studies on previous May bug epidemics;

- can the date at which the site was abondoned be determined? (only old trees sampled);

- comparison with samples from another site. Drier? More pointer years?

- comparison of ring growth with present density of needles.

3. SAMPLING STRATEGY

The sampling strategy depends on the aims of the study, which in turn decide the methods to be applied.
    Every study begins with a search phase. At this stage, the optimum information should be obtained with the least effort. To that end those features of the core which are easy to identify visually are examined, e.g.:

- Mean ring width

- sensitivity (frequency of visually recognizable pointer years)

- frequency and date of abrupt changes in ring width

- rot, wounds, compression wood

- relationship between growth and density of needles.

The final definition of the aims and the selection of the sites are made in the course of this work.

During sample collection the basic assumptions are tested by visual inspection of each core. Aberrant cores are discarded, since it is usually possible to detect what feature of the tree or the site caused the abnormality. This phase of selection is often ignored once the samples reach the laboratory, with the result that good results may be obscured and the amount of work is increased. Many statistical misfits could be recognised as such in the field. As a rule, samples collected previously are unsuitable, since they have been taken with different aims in mind. Equally unsuitable are samples from rigid networks, as the sites are generally not homogeneous and fail to meet the criteria for a valid ecological study.

Dendrochronology can be applied in a wide spectrum of fields, and the range of sampling strategies is correspondingly broad. The basic principles are illustrated in the following with three examples.

3.1 Dendroclimatology, continental networks

FRITTS (1965), KUTZBACH and GUETTER (1980), and LAMARCHE (1982) have shown how ring width chronologies from ecologically different sites in the western USA and the Southern Hemisphere can be analysed statistically in order to obtain reconstructions of the climate with varying quality. Our strategy is somewhat different, as is also our objective: reconstruction of previous conditions of temperature and precipitation for given areas and years.

Selection of sites and trees: Through selecting well-grown trees at the limits of vertical or horizontal areas, it is possible to maximize particular ecological factors in the tree-rings. Trees growing near the northern or upper timberline contain most information on temperature, while those growing near the lower, arid timberline provide more information on precipitation.

The density of sites within a network can be increased within a study area by including local extreme sites. In deciduous forests, for instance, sites in hollows with cold air masses are climatically more raw than those on the surrounding normal sites; and at the upper timberline in arid areas only those trees growing on north-facing slopes with deep soils contain worthwhile information on temperature. In every case, phytosociological findings indicate the special features and suitability of a site. Through strict application of this ecological principle of selection it is possible to eliminate diffuse ecological effects, particularly those which are not limiting every year, and emphasise those that are.

Methods: Densitometry is practically the only suitable method for the reconstruction of summer temperatures in the Northern Hemisphere. Determination of maximum density allows year-by year reconstruction for large areas. For the reconstruction of precipitation, ring width may also be used (KIENAST, 1985). Araucariaceae, certain Cupressaceae, and five-needled pines are less suitable for densitometric analysis.

3.2 Dendroecology

Aim: determination of the year-by-year interplay of relationships between climate (absolute measurement), site (phytosociology, soil science), and tree growth (various ring parameters).

Selection of sites and trees: definition of the programme on the basis of climatological, topographical, and geological characteristics assessed from maps, aerial photographs, and field inspections. identification of typical sites in terms of site characteristics, and selection of typical trees.
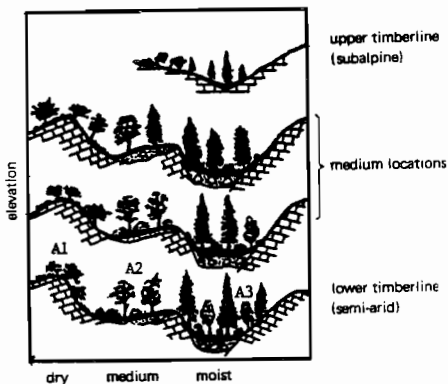
Fig. 1

Ecological site selection in mountain forests.

Method: since this is a new field in dendrochronology, simple methods whould be used at first, e.g., registration of pointer years (skeleton plots of total ring width and latewood width, and identification of pro- nounced density fluctuations within the rings) as well as long-term growth changes (onset and duration).

Measurements of ring width and density can naturally also be used; this, however, involves considerably more work and the results, at least at first, are not significantly better than those obtained with simple methods.

3.3 Pollution research

Since dendrochronology is practically the only discipline which can provide the long-term historical dimension in pollution research on terrestrial ecosystems, the range of applications is very wide and, in almost every case, of political importance.

The following main problem areas can be investigated:

local: damage to trees and forests in the immediate vicinity of an emission source. Damage to and state of health of trees in cities.

regional/national: comparison of the state of health of forests in areas with different population densities or exposed to different natural hazards.

continental/hemispheric: investigation of ring growth in relation to climatic and environmental changes (CO_2, acid rain, nitrogen oxides, etc.).

Of the many problems, the example below deals with a question relating to forest decline and of current interest in Central Europe.

Aim: assessment of growth behavior of individuals and forests on ecological well described sites and regions.

Selection of sites and trees: selection of trees of different species but with the same social status (16 per species and site) on homogeneous sites. Selection is based primarily on ecological criteria: dry to moist, acidic to basic, low to high elevation, outside and inside inversion layers, close to or far from suspected emission sources.
    The question as to the representativeness of the results in terms of forestry can not be decided until the ecological conditions under which damage is manifested in tree-rings are known.
    In all such studies it is necessary to compare a large number of trees and sites. The several hundreds usually analysed are not sufficient.

Method: This last requirement dictates the use of the simplest, least time-consuming method. The classic skeleton plot or the shortened version with pointer years is used to determine the onset, duration, and intensity of abrupt growth changes (fig. 2). Such changes are in themselves manifestations of ecophysiological changes and can at most indicate anthropogenic environmental damage. It is difficult to understand such growth changes because we are missing many knowledges about carbon translocation and fixation in different parts of the tree. It is known that heavy pollution reduce cambial activity. But it is not sure that minimal longtime pollution cause abrupt growth reductions.

4. CONCLUSION

The basis of every good dendrochronological study is the selection of samples according to biological–ecological criteria. The first important step in the somewhat lengthy process of dendrochronological analysis therefore takes place in the forest itself. Neither the most accurate measurements nor the most sophisticated statistical treatment can compensate for errors made here. The selection of trees, sites, and methods should primarily be made according to the aims of the study. One case may involve the use of complicated methods for the detailed analysis of one single tree, while another may require simple observations on 5000 trees. Dendrochronology today offers many methods, and it is important to decide which is the most appropriate for the task in hand.
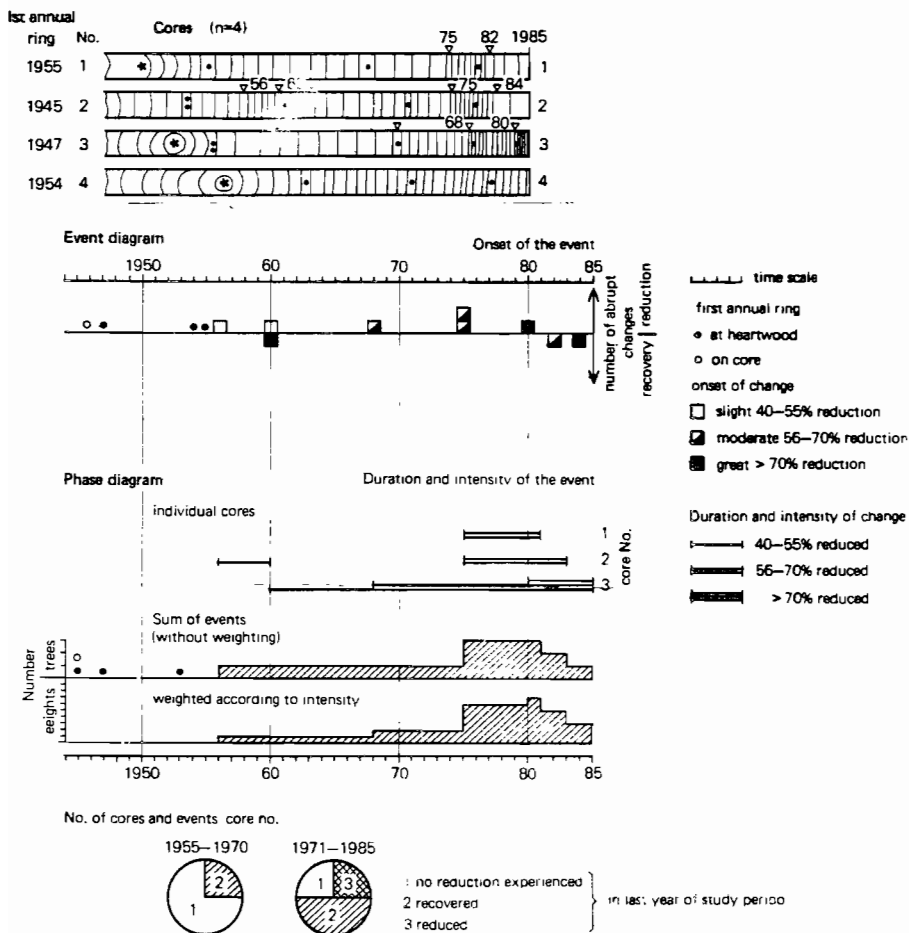
Fig. 2

Recording and presentation of abrupt growth changes.

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2.2   SAMPLING IN TIBET

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1. INTRODUCTION

The Tibet (Qinghai-Xizang) Plateau, known as the "world's
roof", plays an important role in the formation and fluctua-
tion of the general atmospheric circulation over the Northern
Hemisphere. As geoscientists, we are engaged in the research
of climatic change during the historical time and have been
aware of the importance of the plateau, which is a treasury
of information on long-term climatic variation.

With a multi-discipline expedition, we started the study
on climatic change over the plateau in the early 1970's.
There are only a little historical literature recording some
weather or climate phenomena and a few short-term meteorlo-
gical stations in Tibet. Thus, dendroclimatological approach
has been adopted as one of main methods to obtain available
proxy data for the climatic change study.

Although the forest area in Tibet is smaller, human's
activities are not frequent as those in densely populated
region. Compared with the Eastern China, the Tibet plateau
has not been influenced by human being. That may be another
reason we chose the plateau as one gap to develop dendrocli-
matology in China.

It has been proved that tree-ring width variation is a
kind of data for understanding the changes of air temperature
and precipitation during the last hundreds years of Tibet,
when some speciamens are collected and analysed successfully.

2. TWO KINDS OF SAMPLING SITES

Based on Prof. H.C.Fritts (1976) who has described the
basic principles of site selection, dendrochronologists must
apply the law of limiting factors and the concept of ecolo-
gical amplitude when they obtain their research materials.
in order to assure selection of trees which will give them
the information they desire. Thus, we have selected two
kinds of regions for sampling over the plateau (Wu and Lin,
1978; 1981).

2.1. Driest sites

It is obvious that the ring width of trees growing in
the driest sites is most likely to have been limited by
drought. The experience with sampling in Arizona state,
USA and other driest sites has proved the positive relation-
ship between variations in ring width and variations in
precipitation.

Most areas in Tibet are quite dry, the annual precipita-
tion is less than 500 mm, except a small region located in
the southeastern Xizang, where the annual precipitation can
be over 800 mm. According to the Penmen's formula, we have
calculated aridity the ratio of potential evaporation and
precipitation over the plateau and find the aridities of
most sites are heigher than 2.0, even larger than 20.0 in
desert (Lin and Wu, 1981). It can be said that the Tibet
plateau is one of the driest areas in China.

The annual average total precipitation in the most sites
we have collected samples is near 400 mm, even 300 mm a year
in a few sites, according to the observed records of the
nearest meteorological stations. For example, the annual
rainfall is 470 mm in Qamdo county town, 30 km distant from
the tree site. In Lhunze county town, 150 km distant from
the tree site, the rainfall is 270 mm a year.

In these driest areas, the forests are limited in small
scope and are quite sparse, excepting some woods located by

lake, river. If the trees are far from the waters, the most
of them may be useful samples for reconstructing the past
precipitation.

It should be emphasized that the rainfall in Tibet is
mainly caused by monsoon. When the Southwest Monsoon (Indian
Monsoon) is set up in early Summer, it brings much moisture
into the plateau and the rainy season begins from the south-
east through the northwest gradually. With the monsoonal
circulation withdrawal, the dry season comes instead and there
is almost no rainfall during the winter half year. The rain-
fall is, of course, concentrated in the summer half year.
Normally, the rainfall during May through September occupies
80% or more of the annual total precipitation. Taking Lhasa
as a sample, the three months' rainfall (June, July and August)
is 80% of annual precipitation there, and the five months'
rainfall reaches 97% of total. It is so concentrative that
the distribution of seasonal rainfall is different from that
in the East Asia monsoon area. In addition to this, the rainy
season does coincide with warm season. Although the air tem-
perature raising from cold winter is favourable to tree grow-
ing, the decisive factor making the cambial initiation in the
stem might be onset of the rainy season. Besides, the ring
widths of trees will rely upon the length and rainfall of the
rainy season, which is called "intensity of monsoon".

2.2. High altitude sites

The other kind of sampling region could be limited near
upper tree line with high altitude. The Tibet plateau is
famous for high altitude and cold climate. The upper limits
of most plants in the plateau are higher than those in plains
and hills. Generally speaking, the upper tree line in the
plateau can stretch into 4,000 m or more, even 4,500 m or
more. Compared with other areas in the world, this high
location growing some trees is seldom to be found. The air
temperature by the altitude is quite low, annual mean is near
$0^{o}C$, the warmest month(July) mean is often below $15^{o}C$ and

the coldest month (January) mean could be lower than -10°C
or more. That means the days of daily air temperature below
0°C would last more than half a year. The precipitation,
meanwhile, by this altitude would be more than that at the
foot and hill, because the maximum precipitation height
might be closed the altitude of upper tree line.

Based on our study (Wu et al., in press), there is a
maximum precipitation height at each site over the plateau.
With closing to the height, the rainfall has more or less
increasing. The height is different with topography and
environment, but the maximum precipitation height is generally
located by 5000 m above sea level at the north slopes of
the Himalayas and it is about two to three km a.s.l. at the
south slopes. It should be noted that the trees growing at
upper tree line can get more water supply not only from
rainfall but also from melted snow or glacier than those at
low land or in valley. Thus, we can be sure that the ring
width of trees growing at the upper tree line is most likely
to have been limited by cold rather than drought. And it
has proved the positive relationship between variations in
ring width and variations in air temperature.

3. DISTRIBUTION OF SAMPLING SITES

We have collected a great deal of specimens in Tibet
since 1974. The total sites are 31 and the distribution of
sampling sites is shown in Figure 1. It's obvious that the
distribution is not even enough because of the limitation
of forests in the plateau. The most forests and distributed
mainly over the south edges of the plateau, the Himalayas,
and the east edges of the plateau, the Hengduan Mountains,
and the Yarlung Zangbo River valley. The landscape in the
Southern and Western Tibet is almost desert or alpine
steppes without any forest.

Among those 31 sites shown in Fig.1, 15 lie on dry area
where tree growing responds to rainfall variation and 16
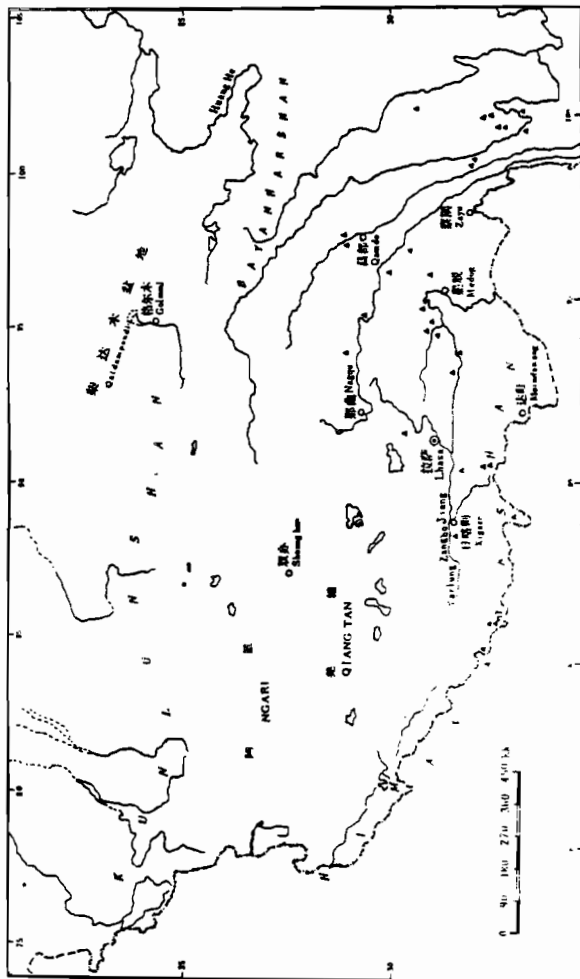by the frigid tree line zone where tree growing responds to

Fig.1 Location of 31 Tree-ring chronology sites in Tibet

temperature variation.

In arid area, we has noted that the tree-ring characte-
ristics from forest interior through forest border vary with
increasing aridity. There is a small forest (Pinus densata)
in Nangxian County with 3500 m a.s.l.. We sampled from the
border through the interior of the forest and buil⁺ four
tree-ring chronologies which had 100-meter interval between
each two, marking with No.1, No.2, No.3, and No.4. Some
statistical characteristics of each chronology are calculated.
They are mean tree-ring width (x), mean sensitivity (MS),
standard deviation (SD) and correlation coefficient (R) related
with the annual precipitation in the nearest meteorological
station. The results (Table 1) support H.C.Fritts' deduction
that the rings in forest interior are wide and "complacent",

Table 1.   Some statistical characteristics of
           four chronologies

Series	x (mm)	MS	SD	R
No.1	1.9	0.38	0.56	0.86
No.2	2.1	0.36	0.42	0.60
No.3	2.4	0.24	0.37	0.53
No.4	2.3	0.22	0.35	0.41

and there is little correlation in the ring-width variation
among trees or between ring widths and climate, meanwhile
the rings near forest border are narrow, mean sensitivity and
standard deviation of the chronologies are high, and there
is a high correlation of the chronologies among trees and
with climate. For ring width (x), No.1 is 1.9 mm, and it
is narrower than others. For MS and SD, No.1 has highest
values, 0.38 and 0.56 separately, but No.4 has lowest values,
0.22 and 0.35. In particular, the correlation coefficient
(R) between ring and rainfall near the forest border reaches
0.86, and it is quite low, 0.41 in the forest interior.

On the Tianbao hill, the Hengduan Mountains, a scattered
Liax spiciosa forest, 3700 m a.s.l. was noted. Some trees

stand on the hill with a slope of 35°, and the hill is covered by flowstone, so that every tree we got cores from is surrounded with stone. Under the layer of stone there is a shallow layer of soil with poor capability of storing water.

Based on analysis for some cores sampled from these trees, the tree ring variation could be used to indicate the local annual precipitation variation.

With collecting near upper tree line, it should be notable that the trees are located near a maximum precipitation height, where the high humidity causes rot inside some trees, particularly for old trees. When we sampled in Gyirong, Zhangmo and other sites in the south slope of the Himalayas, it took us much time and spirit to reach at the upper tree line. However, it was difficult to find a few ideal trees as our specimens because rot was popular and serious over there. The number of ring that could be identified by longer cores was only several decades. The trees lay in the overwet highland are not ideal as dendroclimatological samples.

It is necessary to find out the laws on the topographic climate over the sampling site, especially on the vertical distribution of seasonal precipitation. Using both of observed meteorological data and investigation, we could know more or less situation before climbing any hill, and it could avoid wasting much time and spirit.

In addition, there is temperature inversion in some mountain areas. The phenomenon occurs in the Himalayas and the Hengduan Mts., but it is only during the winder and can not influence on tree growing.

4. CHARACTERISTICS OF SAMPLING IN TIBET

Compared with sampling on plain or hilly land, there are a few specific problems in Tibet. They might be caused by the specific plateau climate and topography.

Two kinds of dendroclimatological specimens, responding to precipitation and temperature, could be sampled with in short distance. In the arid area of the Himalayas and the

Hengduan Mts., it is easy to see a few high peaks which may
be over 4,500 m a.s.l. and the straight distance could be only
ten km and more, or only a few kilometers, from the arid forest
border to the cold upper tree line. For example, we have got
the specimens to reconstruct the past annual precipitation by
the towns of Qamdo and Nyingchi, about 3,500 m a.s.l., while
lots of cores could be collected near the upper tree lines,
10 km or so distant from the towns. The upper tree lines, of
course, are near 4,500 m. ⤳ In Zhongdian County, the Hengduan
Mountains, the straight distance is only one km or two for
sampling both two kinds of dendroclimatological samples (Wu
and Lin, 1983).

The false ring and missing ring in Tibet are of rare occur-
rence. It may be because the Tibetan climate is dominated by
the monsoon regime that has an obvious seasonal variation, and
the warm season happens to the rain season in Tibet. The
cambium and differentiating xylem of the conifers in Tibet can
produce the earlywood and latewood during the summer half
year. We have not found any false ring or missing ring on the
cross sections which were collected as dendrochronological
samples from the Northern Himalayas and inside the plateau.
A few trees contain false rings or missing rings and they
come from the Southen Himalayas only. The reason of causing
the difference should be discovered in the future.

Selection of species is another decided factor for building
dendrochronology. Based on our experience, the species which
could be considered fro dendroclimatic analysis in Tibet are
as follows: Pinus densata, Liax spiciosa, Abies ferreana and
some species belonged to the genus Sabina. Especially, Sabina
saltuaria and Sabina wellichiana grow at high altitude and
their growth speeds are very slow. All species of Sabina is
one of the slowest growth in the conifer trees of Tibet. We
have collected many specimens of Sabina near upper tree line,
and these trees' age could reach 300 or 400 years with breast
diameter 35-40 cm. The age of a tree (Sabina saltuaria) from
Saqila Mountain, Nyingchi, is 483 years old, but its breast
diameter is only 38.4 cm and the height is 9.6 m. Another

tree was located near a glacier in Baxoi County, 710 years
old and breast diameter 58 cm. It was said that there would
be some trees with thousand years old in the Northeast Tibet.

The cores of all species mentioned above have clear rings
and larger sensitivities, and most of them have suited to
be in master chronologies. Of course, we have tried to use
other species, such as Picea spinulosa, Picea likiangensis,
Cupressus gigantea, et al. for dendrochronological analysis,
but the results have been less effective than those using
the species mentioned in last section.

How to consider the response of tree to climate in Tibet
would be more difficult. A few meteorological observed
stations lie scattered over the plateau, and most of them are
located in river valley. One station is, sometimes, separated
from others by high mountains or rivers. The distance between
two stations would be quite far, decades or hundred km. When
the correlation coefficient or response function between the
ring widths and the climatic factors recorded by the nearest
station from tree site are calculated, the results may be be-
yond expectation because of the different micro-scale climatic
regimes. In addition to this, the length of climatic data
each site has seldom lasted 30 years. It is not eough for
the claibration and verificiation between tree ring chronology
and climatic series. In this case, we prefer a chronology
that has been properly dealt with strict sample and rigorous
cross dating to the statistical results. Of course, we must
try to use an additional proxy data to check the chronology.
And one kind of proxy data is documentary information.

To use more reliable documentary data may be another way
to improve the tree ring chronological reliability. When
sampling in Tibet, we have been paying attention to collecting
other kinds of proxy data, including documentary record during
recent hundreds years. With History Archives and other units
in the Xizang Autonomous Region, we are editting a series of
books from the local historical files. in Tibet on disaster
records. And the Volume one "section of snow damage" has been
published. Other literal record concered with weather and

climate are also useful, such as the record in Tibetan calendar, personal diary, etc.. Here are two examples to describe the relationship between the tree ring widths and some documents. Accoding to the Tibetan calendar in 1937, an anomalous drought appeared in Summer around Lhasa through Xigaze and many poor peasants and herdsmen became beggars in street. The ring width in corresponding year indicated very narrow within some tree chronologies. The other example is from the diary of a former top officer to Tibet in Qing dynasty. According to his diary, it was anomalous cold in Lhasa in 1905, the ice was still remained in ponds by the end of April, the wadded garment could not been taken off in Middle May, the climate was cool at the beginning of July and it looked like in Middle Autumn, and it began freezing on the road in Lhasa in the first decade of November. That means it is much colder in 1905 than other years of the early 20th century and the modern time. We also find a narrow ring in the chronology built by trees near the upper tree line.

Excepting calibration or verification, the documentary data could be combined with tree ring chronology to reconstruct the past climatic variation. Authors have been doing the reconstruction in Tibet plateau (Wu and Lin, 1981).

5. CONCLUSION

Due to the high altitude and complicated topography, the dendroclimatic sample in Tibet could have some specific circumstances, which should be worthy of brief mention here.

In some small areas, there exist two kinds of trees as samples of dendroclimatological analysis. One is the trees growing in arid land, the other is the trees near upper tree line. Their distance could be only a few kilometers, though they express responses to precipitation and air temperature separately. It should be noted that taking suitable samples with local conditions will be most important.

The false ring and missing ring within the plateau are ot frequent. And several species of trees, the genus Sabina,

Pinus densata and other Tibetan conifers, have been sampled
and proved their dendrochronological potential. All is a
preliminary study based on our experience. Until all kinds
of Tibetan species are tested and analysed, futher speculation
is unwarranted.

The documantary data can be used to complement the tree
ring chronologies either checking or combining each other.
It is more available for past climatic reconstruction in
Tibet.

In a word, we have tried to provide an overview of the
potential and progress of dendroclimatological collection in
Tibet plateau. Considering the plateau character and little
man's impact, we believe that dendroclimatic research in
Tibet is likely to have a broad and great potential.

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3 MEASUREMENT AND DATING PROCEDURES INCLUDING DENSITOMETRY

3.1 MEASUREMENT AND DATING PROCEDURES IN DENDROCHRONOLOGY

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INTRODUCTION

Dendrochronology is concerned with wood coming from different sources: living trees, construction timbers, panels of paintings, archaeological excavations or subfossil finds. The annual growth of trees can be analyzed with regard to its width, its density and structure, and to its chemical composition. Which of these features are best to be used depends on the questioning. The appropriate technical procedures vary from a pure ocular observation of tree-ring characteristics to highly sophisticated methods like x-ray densitometry, automatic image analysis, or mass spectometry. In the following I will concentrate on tree-ring width, since densitometry and histometry as well as the chemical analysis of wood are dealt with in separate contributions within this Session.

MEASUREMENT OF TREE-RING WIDTH

The most simple and oldest measure to extract information from
a piece of wood and convert them into a time series is the
skeleton-plot technique. The specimen is examined with a hand
lens, and a vertical line is marked on a strip of graph paper
at each interval where a narrow ring occurs; the narrower the
ring, the longer the line, average rings are not marked (Fig.
1).

This sort of representation is mostly applied on conifers from
extreme sites. In all other cases, above all for deciduous tree
species, all rings are absolutely measured in order to receive
the most possible information. This can easily be done using a
magnifying glass with a built-in scale, particularly if
measurements have to be taken on site. It is much better,
however, to make the measurements in the laboratory. The
sample, viewed through a stationary binocular microscope
furnished with crosshairs is mounted on a travelling stage, the
movement of which can be red off to one tenth or one hundredth
of a millimeter (Fig. 2). The ocular lenses can also be
replaced by a TV-camera and the image of the sample be viewed
on a TV-screene what enables the operator to work in a more
relaxed attitude. In principle, the tree-ring widths could be
determined fully automatically, but then the expenditure of
time and care for the sample preparation as well as for the
examination of the data and for the detection of errors would
probably be counter-productive.

TREE-RING PECULARITIES

Since the essence of dendrochronology is to establish the exact year in which a tree ring was formed and since all further deductions depend on this, much care has to be concentrated to reliably recognize the tree-ring borders. Some pecularities are to be mentioned (Fig. 3). In conifer trees so-called false or double rings sometimes occur, they are latewood-like bands within the earlywood. In conifers as well as in diffuse-porous deciduous trees missing rings are another problem. Since missing rings cannot be seen, there is no way to directly detect them. Sometimes, however, it is possible to recognize a ring just disappearing. Even ring-porous trees sometimes contain ring anomalies, for example, a series of extremely narrow rings. All these anomalies can lead to serious mistakes. The ring pattern in the case that one to several rings are missing or were overlooked or were erroneously measured more than really present will run out of phase with the time-scale. Much experience is necessary to overcome these difficulties. The final check, however, is the crossdating procedure which will be demonstrated further down.

MEASURING PROGRAMS

In the early 60's Fritts (1963) began to use computers for tree-ring analyses. But it was only few years ago that the measuring set-ups were directly linked to minicomputers and microcomputers. This step became possible with the development of interactive programs providing the necessary interaction with the data, in particular in cases of doubt or of ring pecularities. Various computer programs are in use, one of them being developed by Aniol (1983a), which stands as an example.

It is called Catras (Computer aided tree-ring analysis system)
and consists of several programs performing the different steps
of the of tree-ring analysis. Its structure is shown in Fig. 4.
Around the data bank various programs are indicated. The outer
ring symbolizes the interface between user and program. The
user enters his orders which the system translates into orders
the machine can understand. The processes are optimized with
respect to time and storage. The user can fully concentrate on
his research without being distracted by the operating of the
computer; no knowledge of EDP is necessary. Catras has several
programs to input measurement data. A powerful algorithm
facilitates synchronization of the series. It plots tree-ring
series on graphic video display, line printer, or plotter. With
different methods and algorithms mean curves are calculated.
Series can be manipulated with the help of an editor. A table
of contents of the data bank can be supplied. Catras can be
used for data exchange if the format, which the Laboratory of
Tree-Ring Research in Tucson/Arizona has proposed, is adhered
to.

The result of the measurement is a time series where the annual
values vary in relationship to time. This variation contains
the information one is interested in (=signal), but it also
includes portions caused by other influences (e.g. aging,
microsite etc.) (= noise). The signal usually can be enhanced
by a careful selection of trees. For example, trees growing on
shallow soils free from the influence of groundwater most
likely record variations in precipitation; trees from a
polluted site record the pollution history; the influence of
periodically occurring insect attacks can be traced in tree-
ring series by sampling in appropriate areas, etc. For further
details I would like to refer to the Session on Site Selection.
The enhancement of the signal is furthermore achieved through

replicate sampling in order to average out the random differ-
ences within and between individual trees. The number of trees
that should be sampled is 10 at minimum and should be increased
to 30 or more per site if necessary.

CROSSDATING

It is common practice to visualize tree-ring series as curves
either on a linear or on a logarithmic scale. The logarithmic
scale amplifies minima and damps maxima of the curves. In the
two tree-ring series of Fig. 5 the ratio between the widths of
consecutive rings are the same at corresponding positions. The
similarity between both series can be recognised more easily in
the logarithmic presentation.

Any dendrochronological study involves the establishment of
crossdating between tree-ring patterns. In the case of a dating
exercise crossdating is the final goal, in all other appli-
cations of dendrochronology it is an absolute necessity before
the proper analysis can be continued. There are various ways.
The early American work relied almost exclusively on visual
observation of the timber samples and skeleton plots. But
mostly the whole tree-ring pattern has to be considered. The
subsequent crossdating either of the skeleton plots or of the
whole pattern can be done visually: the ring patterns match
ring-for-ring up to the year where a ring is missing in one of
the samples (Fig. 6), the ring count is one year off after this
point, unless correction is made by inserting a "ring" at the
proper place in the sequence.

Crossdating can be performed among the radii within a stem,
among different trees, and different sites. If crossdating can

be achieved there is evidence that there is some environmental information common to the sampled trees. There are examples known that even within a large region all collected trees had a ring missing in one and the same year. Verification could only be obtained through an independent sampling in a neighbouring region. Visual matching and crossdating is the method of choice when living trees are dealt with where the date of sampling is known. With historical and prehistorical samples a trained dendrochronologist can find the correct matching positions visually as well, but it is a matter of saving time and of avoiding subjectivity to use some mathematical quantification of the similarity. Huber (1943) introduced a measure to check visual agreement. Since he worked in the pre-computer era this measure must have been simple. He counted the number of cases where two tree-ring curves under comparison increased or decreased together and converted this figure into a percent value. For two curves at random position one expects 50% agreement or disagreement, respectively. The standard deviation for this mean value depends on the length of the overlap of two curves under comparison (Eckstein, Bauch 1969), for example, the standard deviation for n = 100 is ± 5%. Even with the availability of computers, this kind of checking a visual agreement is still in use, although more powerful statistics can now be applied, so for example, correlation calculations (Baillie, Pilcher 1973). But before a correlation calculation can be performed the possibly occuring trends in the tree-ring series have to be removed in order to avoid pseudo-correlation.

The elimination of trends out of tree-ring series is a problematic field. It can be done simply by hand, as in earlier times, or using moving averages or mathematical functions as an exponential, a polynomial, or a spline function, respectively. Details will be dealt in the Session on Standardization.

There is still another feature to be mentioned, the so-called significant years, indicator years, or pointer years (Eckstein, Bauch 1969). Pointer years are such years where external influences on the growth of trees are particularly strong. Consequently the tree-ring width in many trees out of a population becomes larger or narrower. In order to recognize a year as a pointer year one needs of course many trees. In a pointer year more tree-ring series agree in their upward or downward direction than the greatest possible number of agreements that would be expected to occur by chance. For example, out of 20 trees 18 must agree or out of 50 trees 37 must agree that a year be acknowledged as a pointer year. Once such a chronology is established it is a good tool to crossdate series of unknown age. In addition, pointer years are interesting years for climatic considerations.

FUTURE DEMANDS

From a dendroclimatic point of view it would be very helpful if more tropical tree species could be tested for their tree-ring characteristics. Some tree species are already known to have some potential for dendroclimatology (Eckstein et al. 1980). But new dating methods are necessary for this problematic field; e.g., stable carbon isotope ratio variations could be appropriate for such complacent trees.

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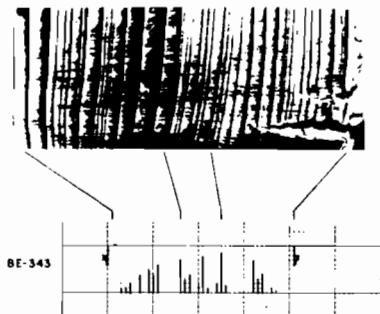dating. Univ. Chicago Press, Chikago-London, 1968, 73 pp.

Fig.1   Skeleton-plot technique (Stokes, Smiley 1968).

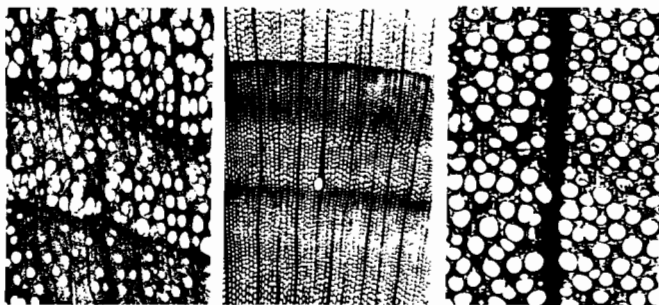Fig.2   Equipment for tree-ring measurement.

Fig.3   Examples of complicated tree-ring structures:
disappaering ring in a beech tree (arrowed, left; mag-
nification 30x); false ring in a spruce tree (arrowed,
middle right; magnification 30x); sample of oak with
extremely narrow rings (right; magnification 13x)
(Eckstein et al. 1984).
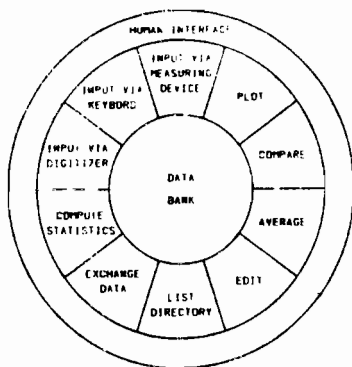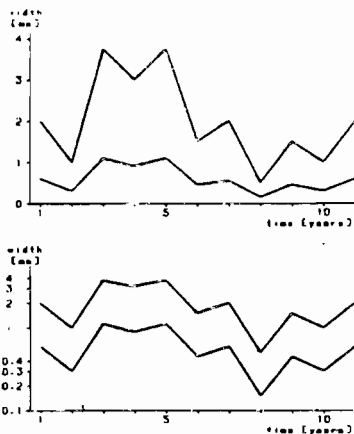
Fig.4 Structure of Catras (Aniol 1983a).

Fig.5 Two tree-ring series where the ratios between widths of consecutive rings are the same for both series at corresponding positions. Above: plotted on a linear scale; below: plotted on a logarithmic scale (Aniol 1983b)
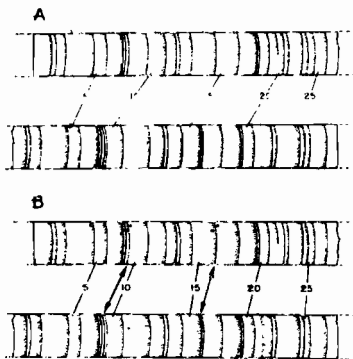

Fig.6 The procedure for cross-checking wood samples and tree-ring series for missing and false rings (Fritts 1976).

3.2 HISTOMETRIC ANALYSIS OF TREE RINGS IN ECOLOGICAL AND DENDROCHRONOLOGICAL RESEARCH

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The data on trees rings structure are being applied now-days more and more intensively. The fact is accounted for by the creation of the corresponding methods and devices for this kind of analysis (Polge, 1966, 1978; Schweingruber, 1983; Vaganov, Terskov, 1977 et al), by the vast volume of ecological-ly-based information concerning woody plants growth and also by a more precise interpretation of this information on the basis of regressive models describing the interrelations bet-ween the annual rings structure parameters and some climate factors and conditional factors for trees growth.

Indirect physical indices of trees rings structure (such as density and its distribution, porosity, the flux of incident or transmitted light) possess quite distinct struc-tural basis, i.e. they integrate the anatomical differences of cells in intraseasonal zones. For instance - the changes in density as well as incident light or porosity changes in conifers are practically defined by the ratio between the size and width of tracheids walls in different parts of the tree ring. In other words histometric heterogeneity of xylem results in differences of physical parameters of the annual rings structure.

The aim of the article to consider the original semiau-tomated methods dealing with the histometric data analysis, to discuss some main problems concerning the relationships between the kinetics parameters of seasonal growth and the structure of trees rings, to estimate the ecological factors (climate ones first of all) influencing the formation of rings' anatomical structure of conifers and to evaluate the possibilities of dendroindication of growth conditions on the basis of histometric data. The case with conifers (pine and larch mainly) in different growth conditions has been inves-tigated. Radial sizes of tracheids have been analyzed as the principal characteristic.

Method of tracheidograms. Tracheidogram represents a discrete curve of changes in cells radial size (tracheids) in a separate radial row on the annual ring cross-section (Fig. 1). In order to obtain tracheidograms a special automatic device including a microcomputer has been developed. It pro-vides a simultaneous measuring of the tracheids radial size and the initial data processing in accordance with the ope-rative programme. The set of applied programmes includes:
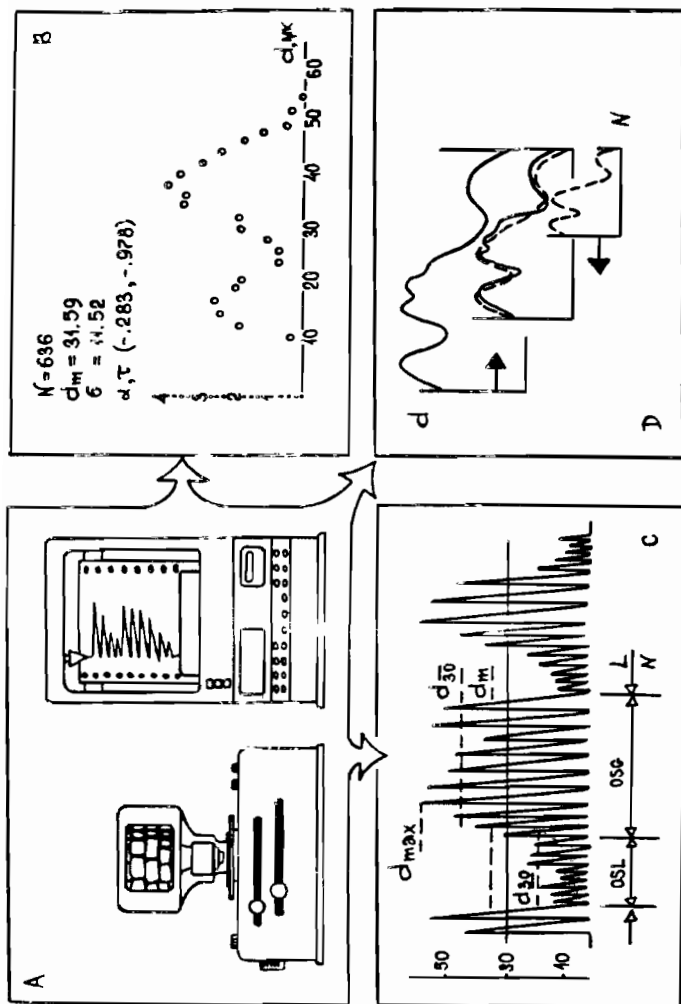
Fig. 1. Semiautomated device for obtaining and processing of the data on the conifers annual rings structure (A) and some methods of processing: obtaining and analysis of the histogram statistical parameters (B), the estimation of quantitative characteristics of trees rings tracheidograms (C) and tracheidogram standardization (D)

1. Cells radial sizes measurements, building of histogram showing cells distribution in size and the estimation of the main statistical parameters of the distribution curve.
2. Standardization of tracheidograms. Since the annual rings in one and the same tree and in different trees contain the various number of cells and differ in width the comparative analysis of their structure becomes difficult. Standardization "compresses" or "streches" the initial tracheidogram along the absciss (making it fit the standard - in our case 30 cells) leaving the ordinate invariable, thus simplifying the comparison of the annual rings.
3. The calculations of tracheidogram quantitative indices: the number of cells; the width of the trees rings; maximal (d_{max}), average (d_m) and minimal size (d_{min}) of cells; the average sizes in intraseasonal growth zones ($d_{\overline{ao}}$, d_{ao}) and the value of these zones in a ring (OS_c, OS_L), the relative state of cells size maximum in a ring (ON_M) and some other derivative parameters.
4. Separate measurements of the early and late wood zones (by visualization of boundaries) and the calculation of the increment curves, the percentage of late wood and the indices of the increment in relation to the "sliding" norm or the approximating function.

The operating features of the device are characterized by the following: the measurement of 500-600 cells or 300 tree rings (in the measuring regime of early and late wood increment) as well as the processing of the data obtained according to the assigned programme become possible in 30 minutes period. The data concerning the analysis of the average tracheidograms of the trees rings obtained while unifying the measurements of 6 cells rows in every annual ring are reported.

Tracheidograms in the analysis of growth mechanisms and seasonal differentiation of xylem cells. As it is known the cell produced by the cambial zone consecutively passes through the phases of cell wall enlargement and bulging completed by the formation of the cell; the subsequent changes in size practically do not occur. The mature tracheids of conifers, forming in different intervals of seasonal growth appreciably differ in size and cell wall width. Therefore if the number of cells and the annual rings width account for the seasonal increment on the whole, then the anatomical indices, radial sizes of tracheids in particular, can be used for a more detailed characterization of the seasonal growth process and hence for the determination of the factors affecting the growth rate in different seasonal intervals. However it demands the solution of some problems. First of all it is necessary to clear out what kinetic parameters determine the final size of the cells. Secondly, since the tracheidogram is the sequence of cells sizes it is important to establish the seasonal terms in the course of which the given cell passes the maturing phases, i.e. reflects the environmental influence to some extent. And finally, as the result - what is the mechanism of influence of the environmental factors and growth phase upon the cell radial size?

The special investigations of seasonal growth kinetics and annual rings formation of trees with different growth po-
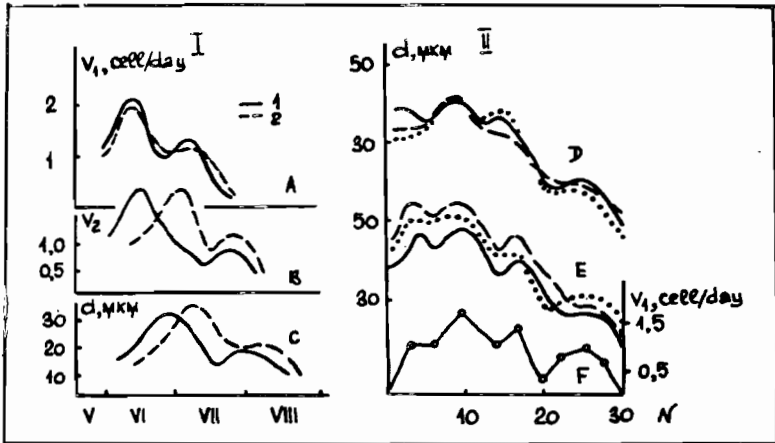
Fig. 2. Seasonal dynamics of cells production rate (A), the rate of transition to enlargement (B), the average cells size in the enlargement zone (C) in fast (1) and slow (2) growing specimens, cells production rate comparison (F) with tracheidograms of fast (D) and slow (E) growing pines

tential carried out in field conditions in the region of the Angara river in 5 year period allowed to obtain the following results. The growth kinetics of the cells number in trees of different growth potential in one and the same year is identical. The growth kinetics of wood layer width increment differs (Fig. 2). The produced cells of slow growing trees get into the zone of enlargement with some delay in time. That is why the cells of one relative disposition in a ring become enlarged in fast and slow growing specimens in different seasonal intervals, but nevertheless they have the same enlargement period and don't differ in size. The duration of cells production of slow and fast growing trees in one and the same year doesn't practically change. The increase in the total production is conditioned by the increase of the proliferative zone i.e. cambium so long as a positive correlation ($r = 0.6-0.7$) exists between these kinetic parameters.

The additional information on the ratio of cells production and their enlargement can be obtained from the analysis of the "instant" tracheidograms, i.e. the ones obtained on the forming annual ring in certain seasonal terms. The formation of the local maxima and minima of cell size changes within the ring is well observed. These changes prove to be "tied" to one and the same ring zones, though the cells forming them in the annual rings in slow and fast growing trees are urged not simultaneously.

The above stated results allowed to suppose that the final size of tracheids depends on the kinetic characteristics

which change during the season in fast and slow growing trees identically and simultaneously. The analysis of the experimental data shows that the final size of tracheids is determined at the earliest stages of cells differentiation - at the level of changes in production rate. Really the tracheidograms of the formed annual rings reflect the specificity of growth rate curves of cells quantity (Fig. 2). The similarity of rates curves of cell production in annual rings of different trees accounts also for the observed likeness in tracheidograms of different trees annual rings of one formation year (Fig. 1D, Fig. 2).

The analysis of ring seasonal formation kinetics and its structure leads to the conclusion important for dendroclimatology: since the production season is far shorter in duration than the season of growth and xylem maturing, the correlation between the histometric characteristics of trees rings (cells number, annual ring width, average cells size etc.) and weather conditions should be searched for the production season only and the period preceding it. The amount of cells in cambial zone is determined at the beginning of the season, the cambium assigning the total cell production for 80-90% and the annual ring width for 60-70 %. The current changes in production will depend on the conditions of this period (e.g. 2-2.5 months in our case). Therefore the establishing of close relationships between any histometric characteristics of the annual rings and weather conditions in the periods following cells production completion is hardly useful.

The data on the dynamics mechanism of the annual ring formation and on the relationship between the kinetic and morphological characteristics of a xylem are described in terms of a simple computerized model, allowing to reconstruct the dynamics of seasonal course of cell production and wood increment. The following statements are in the basis of the model:
1. Proportionality in cell size and relative rate of production.
2. The existence delay in time between the loss of cell ability for division and the transmission to enlargement (8-10 days in accordance with the experimental data).
3. The kinetics of cells enlargement of early and late wood in conformity with the equation of monomolecular reaction with similar kinetic coefficients.

The comparison of the calculated and experimental data for various material, including the one not used in the construction of the model, showed them to be in a good agreement not only with a quantitative estimation of cell production, enlargement and wood increment but also with the dynamics of the "instant" tracheidograms. It is not only the indirect provement of the model initial premises correction but an immediate indication of close relation of intraseasonal growth rate to cells size in conifers rings. The practical result the model yields is the possibility to confront every cell with a certain seasonal interval, which conditioned its size. For example, Fig.3 presents the seasonal dynamics of temperature and precipitation in compliance with changes in cell size of pine in a given year. As it is seen the fluctuations of cell sizes in the first seasonal half "follow" temperature fluctuations. Precipitation deficiency at the end of June caused soil
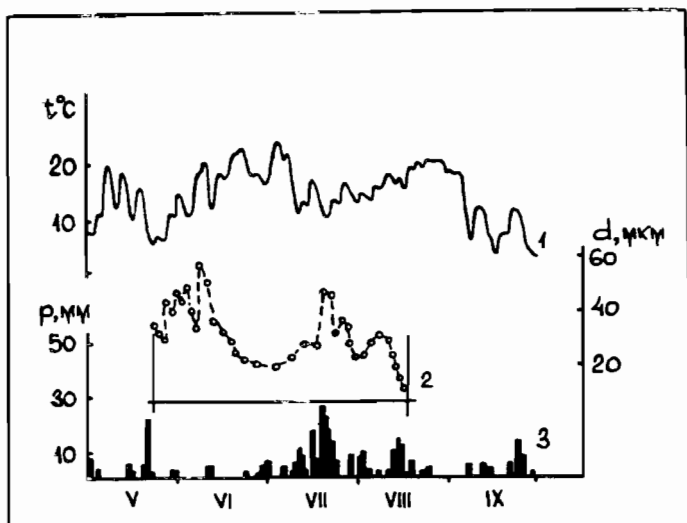
Fig.3. Comparison of cells size changes in pine annual ring (2) with the temperature dynamics (1) and precipitation (3) during the season.

drought and a sharp decrease in cells production rate and their size,and only the rains in July reinforced the increment and promoted the increase of cells size (feebly marked "semi-false" ring was formed). Thus,the model is applicable in different aspects. The possibility appears,firstly,to fix tracheidogram in time (i.e. to mark the temporal scale on the tracheidogram); secondly,the direct comparison of the annual ring growth rate with meteorological factors was made,thus permitting to clear out the reasons of intraseasonal growth changes. And thirdly, the establishment of the quantitative relations between the increment and the main medium factors is possible. It is of paramount importance for the interpretation of dendroclimatological information.

Tracheidograms use in the analysis of weather conditions influence upon the seasonal growth rate and cell size. The annual rings comparative analysis in trees of one stand,but of different growth potential showed their analogy (Fig.2). Standardised tracheidograms are more suitable for the obvious comparison. Their likeness testifies to one type of the increment reaction in different trees in response to the dynamics of the external conditions (weather ones,first of all) in a given year. This uniformity manifests itself in a high degree of synchronism of changes in tracheidogram quantitative indices.

But the annual rings tracheidograms of trees even of the same region differ greatly. For instance, the annual rings of pines from dry site reveal a clearly expressed zone transition

from early to late wood. The transition to the formation of
late wood cells is observed at the more and more earlier parts
of the annual ring,the moisture deficiency being increased in
the first half of the season.

Let's consider the case of tracheidograms application in
quantitative evaluations of the relationship between the cells
size and weather factors in the course of the growth season.

TABLE 1. Correlation coefficients of indices in trees rings
tracheidograms of pines and larches growing in different lo-
cations.

Index		N	d_m	d_{max}	OSI	ONM	d_{30}	d_{30}
N	1	1.0						
	2							
	3							
	4							
d_m	1	0.386						
	2	0.345	1.0					
	3	0.765						
	4	0.506						
d_{max}	1	0.297	0.735					
	2	0.607	0.685	1.0				
	3	0.759	0.949					
	4	0.435	0.700					
OSL	1	-0.253	0.300	0.011				
	2	0.080	-0.629	0.155	1.0			
	3	-0.686	-0.725	-0.642				
	4	-0.242	-0.714	-0.460				
ONM	1	-0.094	-0.639	-0.672	-0.232			
	2	0.329	-0.007	-0.145	0.038	1.0		
	3	-0.273	-0.151	-0.255	-0.094			
	4	0.060	0.400	0.330	-0.490			
d_{30}	1	0.578	0.802	0.447	-0.510	0.206		
	2	0.371	0.788	0.747	-0.031	0.01	.0	
	3	0.605	0.514	0.793	-0.431	0.13		
d_{30}	1	0.156	0.316	0.097	0.336	0.114	0.467	
	2	0.406	0.529	0.512	-0.083	-0.053	0.519	
	3	0.521	0.783	0.667	-0.597	-0.074	0.345	

1,2 - larch growing in dry and moderate moistured locations,
correspondingly; 3 - pine of dry locations; 4 - larch growing
at the northern forest boundaries.

Table 1 presents the correlations of the annual ring structure
indi ces for the trees of different locality. Depending upon
the cinditions (dry,humid) the correlation between the same
indices may be different in sign. The conditions,limited in
temperature or moisture make one of the factors influence
prevalently on the growth rate thus ennancing the correlation
between the annual rings structure. The annual increment of
cells number is in agreement with the increase of the average
or maximal cell size in a ring and also correlates with the

increase of the average cell size in early and late zones.
This correlation isn't occasional since the production inhibi-
tion also affects the intraseasonal dynamics of growth and
cells size. Important is the fact that the correlation between
the relative width of late wood zone and cells production and
their average size is negative on the whole,i.e. growth acce-
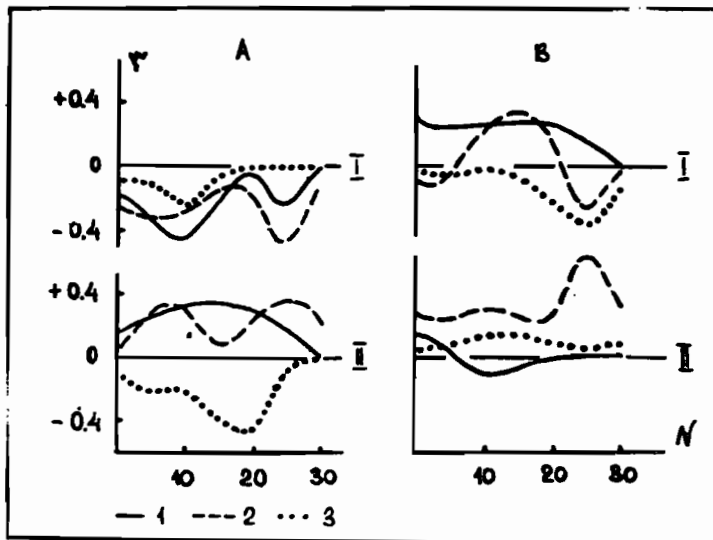leration deteriorates wood technical characteristics.

Fig.4.Correlation in cells size of pine (A) and larch (B) an-
nual rings from different moisture locations with the average
summer months temperatures (I) and precipitation (II):1 - May,
2 - June,3 - July.

Apparently the cells sizes in different parts of the an-
nual ring in trees from dry and humid sites would react upon
the temperature regime and some months precipitation in dif-
ferent ways. The data presented on Fig.4 illustrate the case.
The temperature increase adversely affects the cell size of
pine growing in dry conditions,May and June temperatures ap-
preciably influencing the cells size. The dynamics of the
correlation coefficient shows the positive relationship bet-
ween the cells size and the precipitation in May and June and
the negative relationship between the cells size of transition
and late zones and the precipitation in July.
Quite other dynamics of correlation coefficient of cells
size and weather conditions is observed for a larch growing in
moderate humidity conditions. E.g. the increase in May tempera-
ture positively affects the cells size of the early and tran-
sition zones. The temperature in June accounts for the cells

size increase only in the central part of the ring forming
mainly during this month. The temperature of July influences
the cell size only in the late zone. The changes in May and
July precipitation practically have no effect on cells size in
different zones. The increase of rains in June results in the
size increase of the cells completing the early and confronting
the late zones. The same conclusions are supported by the re-
sults on the correlation analysis of quantitative indices of
the annual rings tracheidograms and weather factors (Vaganov
et al.,1985).
    The correlation analysis of rings structure parameters
and weather factors leads to the conclusion that changes in
weather conditions of certain months in different locations
anequally influence the cells size and morphology,the cells
being formed in tree growth rings in different seasonal terms.
    Annual rings tracheidograms in the reconstruction of
weather conditions. The analysis of the data obtained showed
the cells size and seasonal growth rate of the trees from the
conditions with some factor (humidity or temperature) constant-
ly limiting the growth rate to be essentially influenced by
the conditions preceding the growth beginning and the ones of
the first half of the season. On the contrary,the woody plants
from morefavourable climatic locations are more sensitive to
current conditional changes. The indices of seasonal rings
structure depend on different factors and weather conditions of
different months influence these indices value. So the con-
nection between the weather factors and seasonal rings struc-
ture indices is "multiple" in general case. This "multiplici-
ty" makes it possibile for dendroclimatological reconstruc-
tion to use the methods of multiple regression,where trachei-
dograms indices are presented as variable sings and the weather
factors as the dependent ones. The preliminary correlation
analysis and the quantitative estimation of weather conditions
influence of certain months on cells size in different ring
parts promote in carrying out the regressive analysis and
making it more purposeful. Fig.5 presents the instrumental
values and the values obtained from the equations of linear
multiple regression of some weather factors on the basis of
the data on annual rings fine structure. The given example
demonstrates the unique abilities of dendroclimatological
reconstruction in accordance with tracheidograms: one ring
only provides the evaluation of several weather factors most-
ly influencing the trees seasonal growth in certain condi-
tions.
    Still more perspective is the usage of histometric in-
formation in weather conditions reconstruction with the help
of "differential" tracheidograms. Tracheidograms has its
own peculiarities for every concrete year. If the standardi-
ged tracheidograms of many growth years are plotted on one
graph then the spread in values of cells size in one and the
same parts of seasonal rings would be considerable. Moreover,
the standardized tracheidograms serve as the summarized
estimate of seasonal growth conditions,whatever weather con-
ditions and season duration were. In this sense the standar-
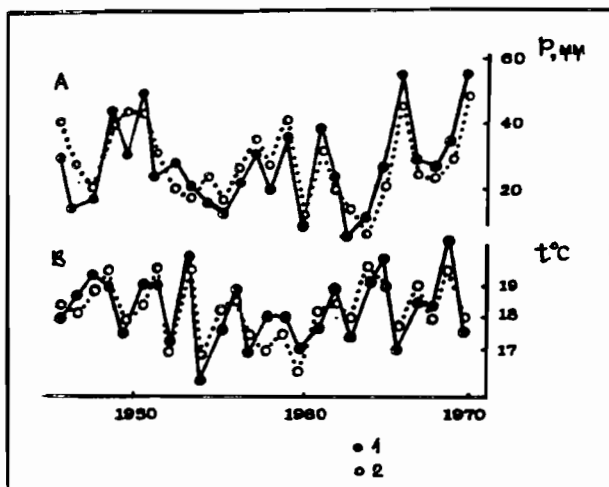dized tracheidogram can be considered as the "ecological

Fig.5. The example of reconstruction of average monthy precipitation of May (A) and July temperature (B) in accordance with the tracheidograms parameters: 1 - instrumental data, 2 - the data calculated from the equation of a multiple linear regression.

equivalent" of growth season. Unifying the stadardized tracheidograms of many years one can obtain: firstly, the maximal tracheidogram of the whole growth period under study, and it will correspond to the maximal possible cells growth by the optimal combination of moisture and temperature conditions. Secondly, the "differential" tracheidogram for the definite year can be derived and it will show how much the certain tracheidogram cells size is smaller than that of the maximal on in different seasonal intervals. "Differential" tracheidogram of trees growing in abundant moisture locations will show the differences in temperature and optimal conditions. Differential tracheidogram of trees growing in dry locations will summerize the growth deviations from the optimal ones in temperature and in moisture. If both differential curves are brought in line for the certain growth year then one can judge which of the factors was limited and in what seasonal intervals (Fig.6). E.g. in 1963 and in 1964 the seasonal growth of pines in this locality was limited only by temperature (differential curves practically coincide); in 1967 and in 1969 the lack of moisture was noticeable, but nevertheless the fluctuations in cells size and growth rate are mainly conditioned by temperature. But 1965 and 1966 years reveal the essential difference in curves, the fact showing the influence of a strong drought upon the pine growth in those years.
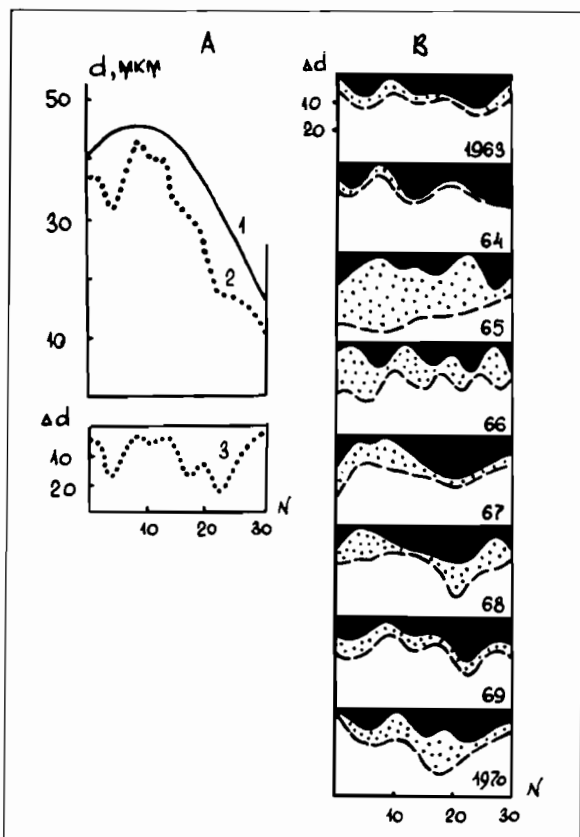
Fig.6. The method of obtaining the differential tracheido-
gram (A) from the maximal (1) and the real (2) one; and dif-
ferential tracheidograms (B) of pine annual rings of the
same calendar years from moistured and dry locations.

The application of differential tracheidograms provides
a quantitative characterization of weather conditions speci-
ficity and help to clear out which of the factors is mainly
responsible for the variations in cells size and growth rate
changes. One of the peculiarities of the differential trache-
idograms is their ability to reflect tree's reaction not only
on the changes in current conditions but also on the prece-
ding ones. Moisture deficiency can be different at the begin-
ning of the season, it can be compensated for a short period
at the expense of precipitation, and can show no display at
all during the season, in case the initial moisture is high,
precipitation is abundant and uniformly distributed. The de-

crease of cells size and growth rate can be ascribed to the
moisture deficiency in some cases and in the others to the
considerable decrease in temperature. Differential tracheido-
grams allow to distiquish between these cases.

In conclusion it is necessary to note that the above
considered applications of histometric data in the analysis
of trees seasonal growth mechanisms and of the trees rings
formation contribute valuably the dendroclimatology,develo-
ping the method's biological principles of the use the an-
nual rings structure. The possibility of creation and appli-
cation of new approaches and new kinds of analysis in dendro-
climatological reconstructions also arises.

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3.3   X-RAY DENSITOMETRY AND IMAGE ANALYSIS AS METHODS IN DENDROCHRONOLOGY IN CANADA AND THE UNITED STATES

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1.   INTRODUCTION

Although the recorded observation of the relationship between time and the diameter growth of trees dates back at least two millenia to Theophrastus, the student and successor of Aristotle (Studhalter 1959), it was not until the 20th Century, through the work of A.E. Douglass (1919, 1929, 1935, 1937), that dendrochronology developed as a recognized and continuing field of scientific investigation. During the first half of this century, the *width* of annual rings in trees has proven to be very useful for dating archaeological samples and for relating tree growth to climate. In addition to the published works of Douglass, a number of other authors have provided useful descriptions of the techniques and applications of dendrochronology using ring-width data. These are, for example, Schulman (1956), Bannister (1963), McGinnies (1963), Stokes and Smiley (1968), Ferguson (1970), and Fritts (1972, 1976).

2.   MECHANICAL-OPTICAL METHODS OF MEASURING TOTAL RING WIDTHS

Instruments that measure total ring width have been in use for many years (Douglass 1943, Eklund 1949). The usual technique is to observe ring boundaries on the transverse surface of a tree-ring series under a low-power microscope. Some of these instruments have been computerized and automated, so that digital ring-width data are recorded directly on magnetic tape or disc; or ring-width plots are produced as a sample is being measured. Total ring-width values can be produced accurately by these instruments if the operator is skillful. However, the instruments are not very accurate for measuring earlywood or latewood components separately. The transition between earlywood and latewood is very gradual on some wood samples and these instruments rely on the subjective judgement of an operator to make decisions on boundary location.

One advantage of using a system of X-ray densitometry to obtain ring-width and ring-density component (earlywood and latewood) measurements is that an operator is not required to make a judgement on earlywood-latewood or latewood-earlywood boundary locations of each ring. Density levels can be chosen for these boundaries and the system can be programmed to "trigger" automatically at these points. The decision as to what density levels are to be used may be a subjective one made by an operator, but the boundaries located during sample scans will be consistent and objectively located by the instrument. The electro-mechanical scanning densitometer is faster than traditional operator-controlled ring-width measuring instruments, because the scanning densitometer can make a rapid and continuous traverse of a sample without stopping at every ring boundary.

3.   THE INTRA-RING DENSITY PROFILE

During the past three decades methods have been devised to rapidly and accurately measure aspects of the annual ring other than total ring width. For coniferous species, the annual tree ring can be broken down into earlywood and latewood components. The major constituents of the xylem are the longitudinal tracheids. These cells progress, as viewed in cross section, from pith to bark in a radial direction, from large diameter with thin walls to smaller diameter with thick walls. This aspect makes the rings discernible and usually gives them the appearance, in the transverse cross section, of having two distinct bands per year: earlywood and latewood.

The changes in cell diameter and cell-wall thickness from the first-formed tracheids to the last-formed, result in density differences. This general progression from lower-than-average density to higher-than-average

density can be measured and expressed as the "intra-ring density profile." This profile is the basis for techniques, such as X-ray densitometry, that measure both the width *and* density aspects of both earlywood *and* latewood. This intra-ring density profile is shown in Figure 1. Figure 2 presents some of the width and density parameters that can be derived from it.

4. DEVELOPMENT OF X-RAY DENSITOMETRY

In 1973, when the status of radiation densitometry of wood was reviewed by Parker and Kennedy (1973), there were about ten institutions active in this field. Smith (1977) reports that there were 24 laboratories throughout the world using the technique of X-ray densitometry of wood in 1976. Evertsen (1980) lists 30 laboratories in 18 countries engaged in radiation densitometry of wood by 1980.

Various radiation, light and mechanical techniques have been developed to study the within-ring density variations in wood samples (Cameron et al. 1959, Marian and Stumbo 1960, Green 1964, 1965, Green and Worrall 1964, Harris 1969, Kawaguchi 1969); but perhaps the most successful method, X-ray densitometry, was pioneered by Polge (1963, 1965a, 1965b, 1965c, and 1966) during the 1960's.

The basic technique of X-ray densitometry is to produce a radiograph (negative image) of a transverse (or radial) cross section of a wood sample by transmitting X-radiation through the wood onto a sheet of X-ray sensitive film. The film is then developed and scanned on a densitometer that converts the film density of the wood image to an analog signal. This signal represents the intra-ring density variations and the width components of the annual rings.

Particular aspects of the techniques employed vary from laboratory to laboratory. For example, some laboratories radiograph cylindrical increment cores, while others cut the wood samples to a uniform thickness before they are radiographed. Some laboratories use a stationary technique, with the X-ray generator positioned several meters from the film and wood sample. Other laboratories use an in-motion technique for making the exposure.

Techniques in radiography of wood samples have been extensively developed during the past 20 years. Beta-ray and X-ray absorption have been used to obtain detailed measurements of intra-ring density. These methods have certain advantages over previously devised techniques for measuring intra-ring density.

Very high-resolution radiographs of wood samples can be produced by X-ray techniques, particularly if the samples are of uniform thickness and in-motion radiography is used. Large quantities of accurate and detailed intra-ring density data can be obtained from radiographs of wood samples with a scanning densitometer, particularly if it is interfaced directly with an on-line computer. These intra-ring density data provide new and useful information for fields that deal with the forest environment or the structure and properties of wood.

Many laboratories began using radiography during the last twenty years incorporating new electro-mechanical instruments (microdensitometers) with digital computers. X-ray densitometry is undergoing a stage of experimentation and development in tree-ring analysis and many innovations and improvements may be added. The next stage should be one of extensive use of intra-ring density data in practical application

5. COMPARISON OF X-RAY DENSITOMETRY WITH OTHER TECHNIQUES

5.1. Beta Radiation Method

Beta radiation was used in England during the late 1950's to produce intra-ring density data by the radiographic technique (Cameron et al 1959, Phillips 1960, Phillips et al. 1962), but most workers engaged in this type of research since then have used X-ray densitometry.

The beta-ray and X-ray methods have been compared (Harris and Polge 1967) and it may be concluded from the evidence presented that the X-ray technique is superior, in that it produces more accurate and detailed data in a shorter time period because of the higher intensity. In defending the beta-ray technique, Phillips (1968) presented some detailed intra-ring density chart recordings, but admitted that the disadvantages of this technique are slow scanning time, and the need for very thin sections.

5.2. Gamma Radiation Method

Direct scanning was used by Woods and Lawhon (1974), soft gamma radiation being the radiation source. Differences in gamma absorption by latewood and earlywood were translated into measures of relative wood density, radial growth, and percentage earlywood and latewood. This modification was progressive in that the intermediate steps of film exposure and processing were omitted. A limitation of the technique is that relative ring width and density were determined instead of absolute width and density.
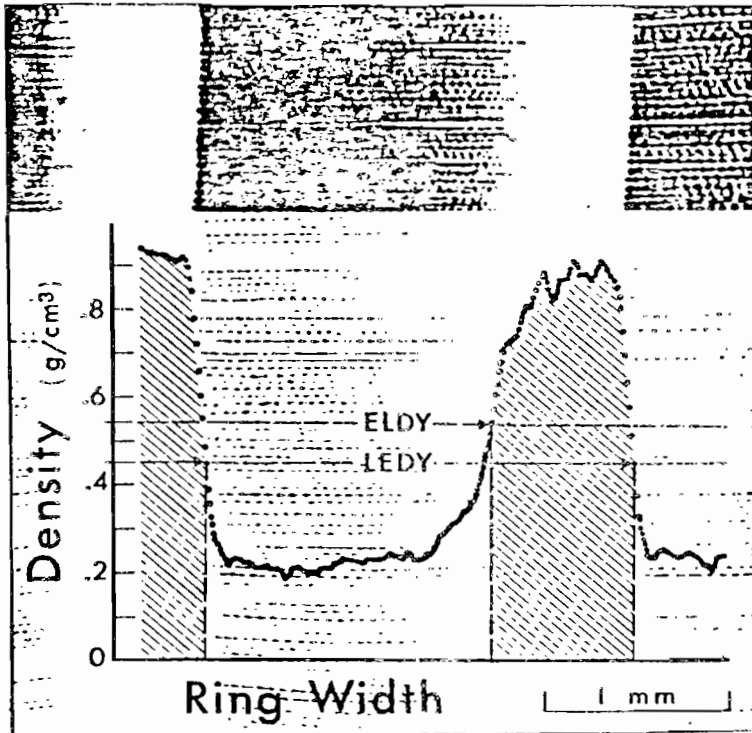
FIGURE 1   Intra-ring density profile of annaul ring superimposed on a negative radiographic image
(intentionally faded on one side for the purpose of illustration only). The density levels or
"triggering levels" for the earlywood-latewood (ELDY) and latewood-earlywood (LEDY)
boundaries are shown for this Douglas-fir sample (Parker et al. 1980)

5.3. Photometric Methods

Very detailed intra-ring density plots have been produced by scanning photometric instruments
pioneered in Canada by Green and Worrall (1964), and Green (1964, 1965) Elliott and Brook (1967)
used an improved technique to record cell wall/lumen ratios These methods involve measurements of light
transmitted through transverse microtome sections. A scanning microphotometer is used to measure trans-
mitted light, while intra-ring density data are plotted on a chart recorder and also may be converted to
digital form and recorded on tape for computer analysis. The limitations of these techniques are that the
preparation of microtome sections is very time-consuming and, also, it may be difficult to obtain the same
degree of opacity in the staining of each sample, leading to errors in intra-ring density determination.

5.4. Gravimetric Methods

Gravimetric methods for measuring density on relatively large whole samples are generally rapid
and accurate, but these methods are impractical for large-scale intra-ring density determinations because
they are extremely time-consuming However, limited data have been obtained from serial tangential

	YEAR	RSX	RW	EW	LW	RD	ED	LD	MND	MXD
a	1900	151.64	1.60	1.19	0.41	.4543	.3524	.7502	.2808	.9373
b		.4421	.3897	.3627	.3481	.3409	.3332	.3373	.3271	.3755	.3197
		.3181	.3136	.3109	.3101	.3076	.3090	.3093	.3060	.3026	.2983
		.2981	.2993	.3017	.2935	.2900	.2863	.2821	.2830	.2858	.2877
		.2974	.3021	.3106	.3134	.3141	.3131	.3149	.3151	.3126	.3239
		.3240	.3255	.3260	.3276	.3334	.3367	.3398	.3376	.3405	.3422
		.3477	.3559	.3591	.3673	.3699	.3754	.3770	.3824	.3865	.3954
		.4031	.4124	.4212	.4353	.4375	.4400	.4433	.4502	.4722	.4922
		.5050	.5242	.5448	.5671	.5855	.6069	.6271	.6658	.7075	.7390
		.7705	.7935	.8342	.8634	.8891	.8965	.9161	.9274	.9342	.9230
		.8859	.8441	.7918	.7219	.6561	.6152	.5721	.5292	.4737	.4328
a	1901	153.24	1.31	0.93	0.38	.4888	.3841	.7451	.3379	.9006
b		.4095	.3770	.3673	.3580	.3514	.3498	.3449	.3471	.3449	.3478
		.3427	.3473	.3475	.3428	.3466	.3437	.3460	.3419	.3420	.3381
		.3411	.3419	.3457	.3428	.3460	.3469	.3402	.3429	.3401	.3434
		.3424	.3470	.3467	.3522	.3530	.3586	.3586	.3651	.3711	.3690
		.3740	.3730	.3773	.3769	.3825	.3830	.3863	.3907	.3886	.3919
		.3923	.3977	.4025	.4047	.4101	.4143	.4188	.4248	.4306	.4389
		.4464	.4549	.4668	.4734	.4847	.4918	.5101	.5207	.5299	.5509
		.5632	.5862	.6048	.6333	.6582	.6928	.7209	.7368	.7667	.7887
		.8146	.8430	.8679	.8842	.8923	.8942	.8978	.8984	.8883	.8760
		.8420	.8041	.7665	.7096	.6623	.6270	.5727	.5327	.4840	.4334

FIGURE 2   Form of data produced by the Vancouver, British Columbia densitometer system, using the Tree-Ring Input Program (TRIP), (Parker et al. 1980).

 a. RSX = distance from pith (mm); RW = ring width (mm); EW = earlywood width; LW = latewood width; RD = ring density (g/cm³); ED = earlywood density; LD = latewood density; MND = minimum ring density; MXD = maximum ring density.

 b. 100 intra-ring density profile values for each ring (g/cm³).

microtome sections from which micro-specific gravity was subsequently determined (Ifju et al. 1965, Kennedy 1966). Gravimetric methods are best suited for measuring large samples and provide a good means of calibrating systems using X-ray densitometry, but the X-ray technique is superior for measuring intra-ring density.

6.   AN EXAMPLE OF AN X-RAY DENSITOMETRY SYSTEM USED IN CANADA

  At the Western Forest Products Laboratory (now Forintek Canada Corp.), Vancouver, British Columbia, an X-ray scanning machine and a tree-ring scanning densitometer with a computerized data-acquisition system (Parker and Jozsa 1973, Parker et al. 1973, 1980) are used to produce intra-ring density measurements of wood samples. The X-ray machine can be used to make conventional radiographs of wood samples from a distance of up to 7 feet (2.13 m), but the density values are obtained by using an in-motion radiographic technique. Air-dry, 2-mm-thick transverse wood samples, usually extending from pith to bark, are used. These samples are prepared from 5- or 16-mm diameter cores or from wood blocks that are glued between two mounting sticks (Parker 1970) and machined to a smooth and uniform thickness by a twin-blade saw (Kusec 1972). Paper calibration wedges made from Douglas-fir mechanical pulp are placed on the bare (without paper envelope) X-ray film. A collimated beam of X-radiation (20 kVp and 2 mA) is emitted through a 0.33-inch-wide (8.38 mm) slit onto a tree-ring sample and film that are located 12.5 inches (31.75 cm) below the 0.3 mm focal spot of the X-ray generator. The specimen and film are supported by a 4-foot-long (1.22 m) carriage that travels at a uniform speed beneath the X-ray unit. A hydraulic system is used to provide constant-speed and vibration-free carriage traversing during a scan. The usual scanning speed is 2 inches (5 cm) per minute. The X-ray beam penetrates a tree-ring sample at the desired perpendicular angle, even for samples from large-diameter trees, when this narrow-slit scanning technique is used. The X-ray generator can be positioned at the desired angle if the cells in the tree-ring sample are not properly aligned.

A fine-grained, high resolution film (Kodak Type-R single-coated industrial X-ray film) is used An X-ray exposure is made in total darkness, but a safelight (Kodak Series 6B brown filter with a 25-watt bulb) is used for film loading and developing. Film is processed with Kodak liquid X-ray chemicals and developed in a tank with automatic temperature controls and nitrogen-burst agitation.

The radiographs are scanned on a computerized densitometer. Intra-ring density and ring-width data are produced by the data-acquisition system. Density values for each 0.01 mm radial increment on tree-ring samples are produced in analog form on a chart recorder; or in digital form by a computer system that includes a mini-computer, a disc drive, a printer, a magnetic tape unit, and an X-Y digital plotter. The system can be programmed in a number of ways to produce intra-ring density plots, or integrate the data to derive values for such factors as earlywood width, latewood width, total ring width, minimum, maximum or total ring density, total sample density, mean latewood density, ring mass, etc.

A scanning densitometer was designed and fabricated specifically to scan radiographs of tree-ring samples and has the following useful features: (1) a xenon-arc lamp and regulating unit for very bright and stable illumination of the film image on the density-measuring photodiode and viewing screen; (2) an optical and light-intensity measuring system that permits the measuring of very small areas of tree-ring image on film (routinely 0.01 x 0.0625 mm or 0.05 x 0.0625 mm); (3) a viewing screen that allows an operator to monitor a 10 X image of a tree-ring sample during the scanning operation; (4) a stepping motor and film-transport system that moves film in exact 0.01 mm increments, in both forward and reverse directions, at speeds of 4 to 300 steps per second or at one step at a time.

An on-line computer makes the system very versatile. An operator can choose programs or select options to produce data in a variety of forms. Also, a computer can be used as a calculating instrument for comparison of tree-ring data and other data, such as weather records, hydrological data, silvicultural treatments, etc.

7. DIRECT-SCANNING X-RAY DENSITOMETRY

In X-ray densitometry of wood it is possible to bypass the use of X-ray film by a direct-scanning technique. The tree-ring sample is irradiated with a collimated radiation source and the radiation that penetrates the wood is measured by an X-ray scintillation detector or some other device. This technique has been used successfully by Robert Megraw for Weyerhaeuser Company in Seattle, Washington since the early 1970's (personal communication). It also has been used by Cown and Clement (1983) at the Forest Research Institute, New Zealand Forest Service, Private Bag, Rotorua, New Zealand.

A good-quality direct-scanning system is now being used by M.D. McKimmy, College of Forestry, Oregon State University, Corvallis, Oregon. This system is interfaced with a micro-computer and intra-ring density data (Fig. 3) are produced rapidly and accurately.

8. IMAGE ANALYSIS: THE POTENTIAL

The technique of image analysis may prove to be the next important advancement in methodology in dendrochronology. It has the potential for producing intra-ring density data and may have some advantages over techniques such as X-ray densitometry.

R.L. Phipps, T. Yanosky and C. Robinove are experimenting with an image analysis system to analyze tree-ring samples at the U.S. Geological Survey, National Center, Reston, Virginia. The system uses a video camera and a micro-computer to produce digitized images of wood samples on a video screen. Tree-ring characteristics, such as the ratio of cell-wall area to lumen area can be measured, processed, stored and reproduced.

An advanced image analysis system has been purchased by the Oak Ridge National Laboratory, Oak Ridge,Tennessee for the purpose of tree-ring analysis. It is expected that images of annual rings, such as reflected images of the wood itself, microtome slides or radiographs, all could be processed by this system. Computer programs for processing the digitized images need to be developed as well as new sample-preparation techniques.

If images of tree rings, such as those shown in Figure 4, can be produced for the full length of the tree-ring sample, an image analysis system would provide an excellent means of obtaining high-quality intra-ring density data. A major advantage of this type of system would be that the percentage of cell-wall area, i.e., density, could be measured for any designated area of the image of the transverse cross section.
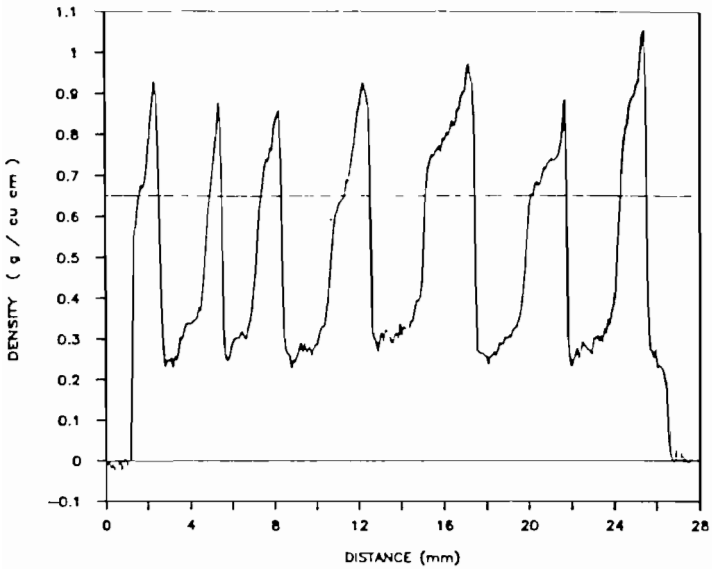
FIGURE 3 Intra-ring density profiles of seven annual rings produced by a direct-reading X-ray densitometry unit at the College of Forestry, Oregon State University, Corvallis, Oregon.
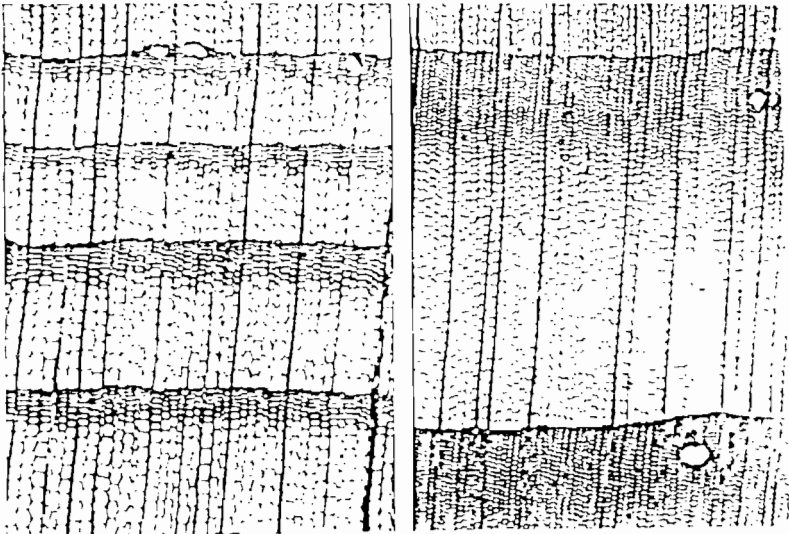

FIGURE 4 Photographic images of microtome slides of transverse sections of coniferous wood

9. DISCUSSION AND CONCLUSIONS

9.1. Advantages of Using both Width and Density

Some of the advantages of using both width and density data are illustrated by Figures 5-8. Figures 5-7 are taken from a fertilizer and thinning study of Douglas-fir trees from Vancouver Island (Parker et al. 1976). A more detailed understanding of silvicultural treatments is possible if both width and density are examined in this manner. Some treatments may increase ring width but reduce ring density. Measuring both width and density also is useful in assessing the effect of air pollution or elevated levels of carbon dioxide on trees.

The ring mass data shown in Figure 8 were produced at the Oak Ridge National Laboratory from ring width and density data derived from an increment core from a British Columbia Douglas-fir tree. For some studies, ring width data are sufficient, but for other studies ring density data are useful in themselves or to be used to calculate ring mass.

Both ring width and ring density are useful for providing proxy climatic data. It has been observed that the correlations between tree-ring variables and climate depend on the enironment of the trees studied. Generally, ring widths relate best to early summer precipitation in dry areas while maximum ring density relates best to late summer temperature in cold areas. The annual ring components of earlywood and latewood and of width and density respond differently to the various climatic factors. Therefore, environmental factors can be more accurately assessed if both width and density are measured.

9.2. Recommendations

For some studies, simple ring counts are sufficient. For other studies, ring-width measurement is adequate. However, for many research projects, such as those designed to provide proxy climatic data or assess the effects of environmental influences, *both* ring width and ring density should be measured.

Techniques should be developed and utilized that provide the most efficient means of producing tree-ring data for the particular job required. These methods should be coordinated on a world-wide basis to facilitate the exchange of information that can be used to solve mutual problems.

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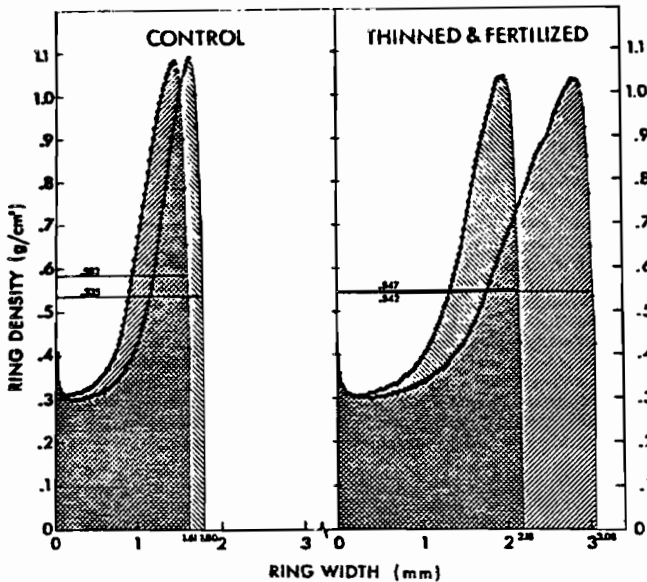
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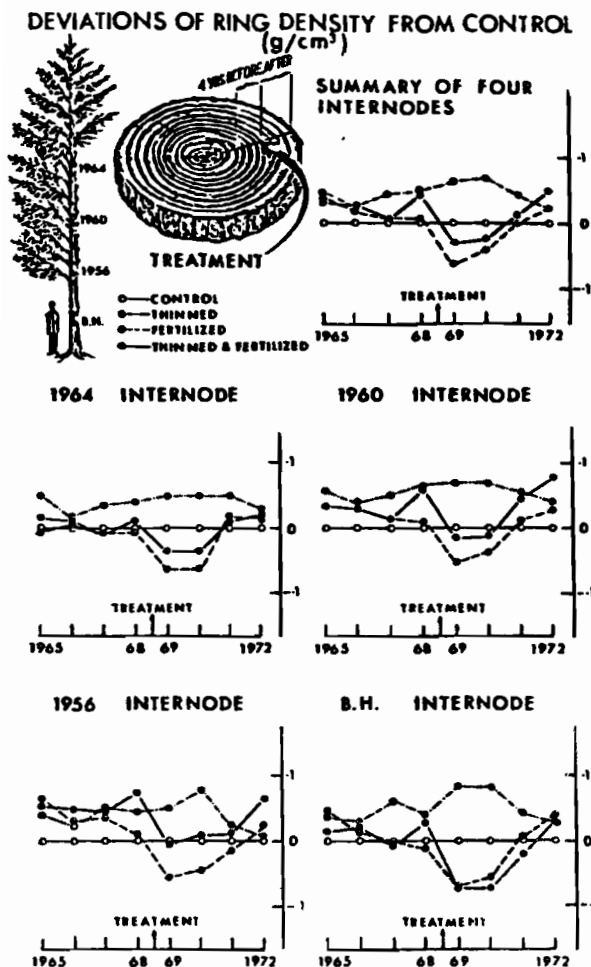
FIGURE 6   Year-to-year variation in ring density as affected by silvicultural treatment. This method also is useful to study the effects of air pollution or elevated CO_2 on trees.

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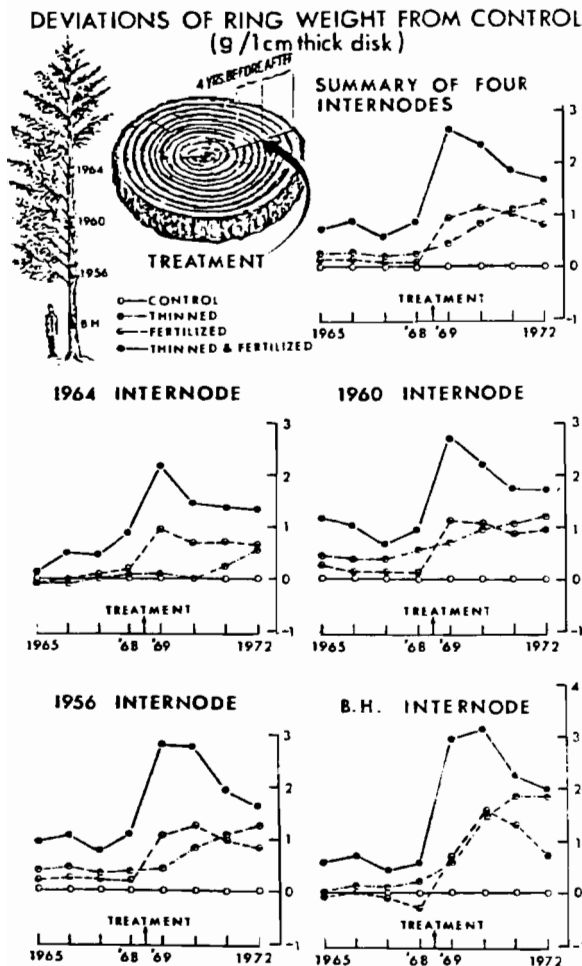
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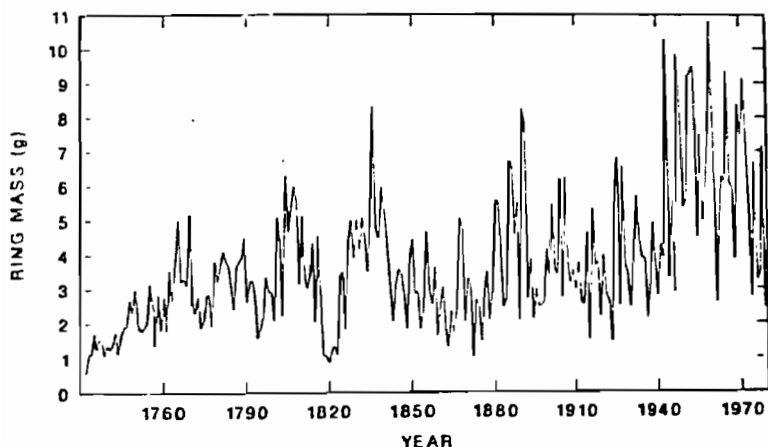
FIGURE 8   Time series of ring mass calculated for a single increment core from a Douglas-fir tree from British Columbia.

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4. STANDARDIZATION AND THE PREPARATION OF CHRONOLOGIES: SOME CONTRASTING APPROACHES

4.1 TOWARDS AN OBJECTIVE APPROACH TO STANDARDIZATION

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ABSTRACT

This paper is a review of tree-ring standardization methods. A generally applicable definition of standardization as a frequency-dependent means of noise reduction is proposed. The rationale and concepts underlying various approaches are discussed and the various techniques are described under three general categories, deterministic, time series modelling and filtering methods. The general applicability and the strengths and weaknesses of these methods are outlined. Consideration is given to how standardization success can be gauged. The importance of and methods for assessing chronology confidence are also discussed. Simple rules are suggested for defining good standardization.

1. INTRODUCTION

1.1. What is standardization?

In tree ring research, standardization is an integral part of chronology construction. Standardization is used to enhance some data characteristic by removing part of the variance that is thought not to be (or to be weakly) associated with the required characteristic.

This leads to the concepts of signal and noise: essentially signal is variance associated with what we're looking for, noise is all other (unwanted) variance. The only signals that we can identify are those that are manifest to some degree in <u>all</u> individuals within a group of trees. There are a number of different signals: those due to climate, to ageing, to pollution, etc., determined by the researcher's particular interest. Signal to one investigator will be noise to someone interested in some other aspect of tree growth. Because the possible signals may reflect growth influences operating on a variety of different time scales, standardization in general, should be considered as a frequency-dependent method of noise reduction.

Standardization was initially developed in dendroclimatology as a prelude to the averaging of individual tree ring series. In this context, it is employed as a method for removing non-climatic variations, primarily ageing effects, which would not otherwise be efficiently cancelled out by the averaging process. Because standardization has been used mainly in dendroclimatology it is usually assumed to mean the removal of some of the <u>low</u> frequency variance in tree-ring data. However, standardization could equally well refer to producing a time series that <u>retains</u> only the low frequency variance. The general underlying concept, therefore, is the removal of variance within a particular frequency band or zone from a tree-

ring time series. In other words, standardization is a spectrally specific noise reduction method.

1.2 How do we standardize?

Standardization methods can be grouped under three general categories according to the way in which a curve for the removal of unwanted variance is fitted to the raw tree ring data. The categories are

1. Deterministic standardization - using a specified function to represent the unwanted variance.
2. Standardization methods based on time series modelling.
3. Standardization methods based on digital filtering methods.

In some cases the distinction between these categories is rather blurred, and some specific methods could be considered as falling into more than one category.

2. METHODS OF STANDARDIZATION

We will use the term standardization for the method applied to transform individual time series. This generally involves two stages, the first being the fitting of a curve to be used for removal of unwanted variance and the second being the production of the final standardized series. The second stage may also incorporate some form of normalization (i.e. making the overall variances of the individual ring width time series comparable).

The second stage is far more straightforward than the first, so we consider it first. The basic principle involved is to produce a final series that is as near homoscedastic as possible. However, testing for homoscedasticity is rarely, if ever, done. High mean values in parts of raw ring-width series are invariably associated with high variability so some attempt must be made to equalize the variance in different parts of a tree-ring series (i.e. produce a more homoscedastic time series). For ring widths, in dendroclimatic applications, this is usually done by taking the quotients of the raw width values over the fitted values to produce the indexed series, rather than taking the residuals of the raw from the fitted values. However, this is not the only method. In general, having decided on a curve fitting method, the final standardized series may be produced using either a multiplicative or an additive model, i.e.

$$W_t = w_t / \tilde{w}_t \tag{1}$$

or

$$W_t = w_t - \tilde{w}_t \tag{2}$$

where W_t is the final standardized value, w_t is the raw value and $\tilde{w}_t$ is the fitted value in year t. In the dendroclimatic case, (1) is used for ring width standardization since ring width variability is often larger for wider rings. Equ. (1) therefore has the effect of removing the strong time-dependence of variance that often appears in width time series. An alternative approach would be to consider the logarithms of the widths, filter these using an appropriate method, and then produce the final time series using an additive model, exponentiated.

$$W_t = \exp(y_t - \tilde{y}_t) \tag{3}$$

where $y_i = \log_e w_i$ and $\bar{y}_t$ is the filtered value of y_t. For tree ring parameters other than ring width (e.g. density) the additive model (2) is generally used.

In applications other than dendroclimatology where we may be seeking to enhance the low frequency signal(s) neither steps (1) nor (2) may be required and $\tilde{w}_t$ may be the required "standardized" output. Let us now consider the three possible data transformation methods.

2.1. Deterministic approaches

Early workers searching for climate signals in the ring width series of old conifers, identified long-term growth trends in measured ring-width data which could confidently be attributed solely to tree ageing. In general, many factors can influence tree growth. However, by careful selection of long lived trees growing in highly climatically-stressed sites, early workers attempted to ensure that non-climatic growth influences such as competition and defoliation were minimized (Douglass, 1914). In this way, the selected trees hopefully had a strong potential climate signal and the ring width series were such that unwanted noise (resulting from tree ageing) could be unambiguously identified. In such situations a deterministic growth curve was appropriate for describing this unwanted noise. In 1945, Schulman stated:

> "To obtain a mean curve representing trees of various ages, the usual procedure is to ´standardize´ the individual tree curves by computing percentage departures from a trend line fitted to the curve and then to average the standardized values. Thus the large average growth rate of youth is reduced to conform with the slower growth of maturity and old age." (Schulman, 1945, p. 19).

Besides straight lines, early workers sometimes fitted simple curves to the data. This was done by hand, with the values taken from graph paper (Stokes and Smiley, 1968). Later workers adopted more "objective" least squares fitting procedures. Although the decision on what form of curve to fit was still a subjective one, the curves used were invariably of a simple deterministic form.

The development of dendroclimatology in the southwest U.S.A. based exclusively on coniferous species led eventually to a computer program for the deterministic standardizing of ring-width time series, INDEXA (Fritts, 1963; Fritts et al., 1969; Graybill, 1979, 1982). Primarily, this allowed the user to fit a curve based on the negative exponential

$$\tilde{w}_t = a\ e^{-bt} \tag{4}$$

Because this function was not able to fit the period of rapid growth often associated with the juvenile stage of tree development, it was suggested that these early sections of conifer ring width series should either be rejected or should be fitted separately as a linear trend (Fritts et al., 1969). It was also found that the simple exponential function, which tends to zero as t becomes large, was not adequate for modelling the average growth of old trees which generally reach a semi-constant mean growth rate in old age. To overcome this, the modified negative exponential was introduced (Fritts et al., 1969). This involved the addition of a constant to equation (4), i.e

$$\tilde{w}_t = a\ e^{-bt} + c \tag{5}$$

Fritts states that

> "...the exponential function has been found to be adequate for many
> North American conifers because it approximates the various parabolic,
> hyperbolic and logarithmic forms, and resembles the declining rate in
> the conifer growth function." (Fritts, 1976, p. 263).

Notwithstanding this, the INDEXA program also has options to default to a
linear trend of negative slope, zero slope or even positive slope. The last
of these is obviously untenable as a biological model of direct ageing
effects. Its inclusion merely reflects the fact that situations arise where
simple deterministic functions are not adequate to describe unwanted growth
variations.

This point is reinforced by the fact that the INDEXA program also
contains an "orthogonal polynomial" option. By allowing higher and higher
order polynomials to be added (under the control of a residual least squares
value) a much greater degree of flexibility of curve fit is attained. In
this way, more complex growth variations can be fitted than is the case
using simple functions. This option has been increasingly adopted for
situations where the noise to be removed in tree-ring series is clearly not
deterministic in nature. The theoretical justification and practical
expediency of this method is clearly reduced in such situations (Cook and
Peters, 1981; Briffa, 1984).

A variety of other deterministic functions have been used in various
aspects of tree growth studies and several modifications of the approaches
described above have been suggested. Braeker and Schweingruber have used
the 'Hugershoff' function as a standard means of processing the hundreds of
ring-widths and densitometric chronologies produced at the Swiss Federal
Institute of Forestry Research (Braeker, 1981).

Yang et al. (1978) describe a number of empirical functions that have
been proposed for describing average growth of trees and forest stands.
They also propose a modified Weibull-type function as a generally applicable
model of stand growth. Similarly, Warren (1980) has proposed a function
which can model the juvenile as well as the mature phase of mean tree
growth. These functions are valuable for investigations of stand volume
changes in forest productivity studies.

To model complex growth variations such as arise through competition
and release effects in dense forests, Warren (1980) suggests an extension of
his method where an aggregate function (representing a series of simple
functions) is fitted to a ring width time series. The constituent simple
functions are fitted by least squares. Somewhat dubious statistical signi-
ficance testing is then involved in deciding whether the measured series has
departed from one fitted function sufficiently to require the incorporation
of another function in the aggregate (see Cook, 1985, p. 16 for further
details). In common with the orthogonal polynomial, this method behaves in
practice as a filter (as judged by several examples shown by Warren). Its
spectral response, however, is not constant and varies with the length of
the base period used to fit the individual part functions. The spectral
response of this method may also vary with position in the series for any
given period.

Like the orthogonal polynomial option of INDEXA, this method is essen-
tially a pragmatic adaption of the deterministic approach to a situation
better considered stochastic in nature. Given the simple and more control-
lable spectral response of direct filtering (see later) Warren's method
offers little if any benefit in most situations.

Some workers have proposed that all individual ring-width series for a
given species at a particular site should be standardized with a single mean

growth function. A site curve is derived by averaging the logarithms of the measured ring widths of all trees matched according to cambial age. Some form of deterministic curve is then fitted to this average site curve and the residual indices computed (Jonsson, 1969; Jonsson and Matern, 1974; Kuusela and Kilkki, 1963). For the fitted curve, both polynomials and power functions (i.e. $\bar{w}_t = at^b$, b < 0) have been used. On purely geometrical grounds the form $\bar{w}_t = a/\sqrt{t}$ has something to recommend it. This method is probably only applicable to even-aged and relatively undisturbed stands of trees. If the trees are subjected to medium time scale random disturbances (such as can occur through competition, or through its interaction with windthrow or snow damage) the average site curve may be inapplicable to many of the individual trees and medium frequency chronology variations may be unreliably represented.

2.2. Strengths and weaknesses of the deterministic approach

In the rare situations where the growth signal under investigation is known to have a simple deterministic form, there is no doubt that the best approach is to describe the relevant signal with an appropriate mathematical function. This is the most concise and directly communicable way of describing and explaining the signal. Even in complex systems where a particular tree growth signal may be highly variable, expressing the data by means of a fitted function is often useful as a diagnostic or descriptive tool. The inherent, under-fit conservatism of a simple mathematical function may be an advantage in some cases.

On the other hand, assuming a mathematical function for describing tree growth signals may be unnecessarily restrictive. Problems increasingly arise when this approach is used in situations where tree growth signals are complex or where it is necessary to remove relatively medium or short time scale variation in tree-ring data. Functional growth equations are often too simple.

A more basic weakness of the method is that the goodness of fit varies with time. Thus, noise-related medium frequency variance may be retained in some parts of the series, yet removed in others. In addition, spurious medium frequency variations may be introduced into the standardized series.

The deterministic method is also conceptually unsatisfactory because, since least squares fitting is controlled by the overall variance of the raw series, the degree of fit at any one point of a curve can be influenced by data far removed from it. As a consequence of this, the fitted curve may change appreciably when additional data are added to the series. This means that if a tree-ring series is updated, re-standardization may alter all of the original indices.

With our definition of standardization as a spectrally-specific noise reduction method, the deterministic approach cannot be considered generally applicable. Deterministic standardization, especially when used to high-light what are essentially stochastic growth signals, can he arbitrary and largely unpredictable in its spectral response effects. In situations where relatively low or medium frequency signals are the ones under investigation, it is rarely practicable to describe the noise in terms of mathematical functions. In Figure 1, we illustrate the spectral response of three different types of standardization.

2.3. Time series modelling

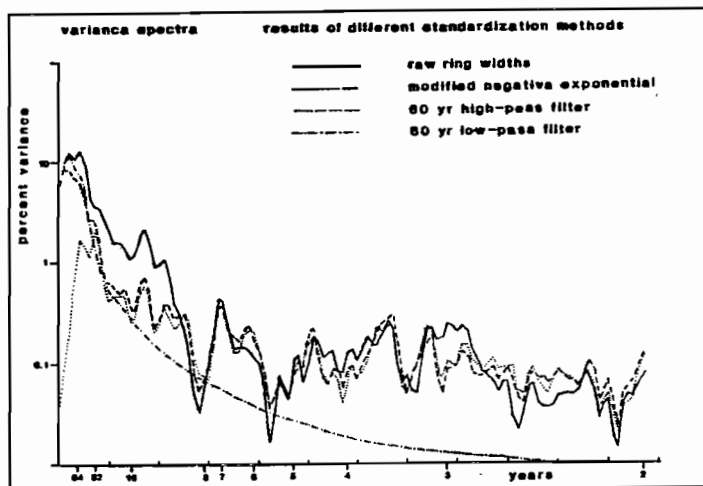Under this heading we consider the use of autoregressive (AR), moving

FIGURE 1 Variance spectra of a single core 351 years in length from
Riukuselka, Finland (68°28′N, 28°01′E), standardized by three different
means: modified negative exponential. 60-year high-pass filter and 60-year
low-pass filter. The three different variance spectra are compared together
with the various spectrum for the raw unstandardized data. Spectral
estimates have been renormalized so that the areas under the curves
represent the total retained variances.

average (MA) and combined schemes (ARMA). In all of these schemes the
fitted curve is of the form

$$\tilde{w}_i = \sum_{j=-J}^{J} a_j w_{i+j} \qquad\qquad (6)$$

where the coefficients a_j are determined from the data (some coefficients
may be zero). Note that the same form is used in the filtering method, with
the important distinction that, for filtering, the a_j are specified a priori
and are the same for each core.

The assumption behind the time series modelling approach to
standardization is that tree growth can be considered largely as an auto-
regressive and/or moving average process. Time series modelling is usually
applied after some other form of curve fitting. In other words, it is
assumed that the residual growth effects (i.e. those remaining after an
initial standardization) follow an AR and/or MA process. There is some
physiological justification for this. If linear carryover or feedback
effects exist, then it is easy to show that the spectral response to white
noise forcing must be red noise, i.e. an autoregressive output. Thus, AR
modelling would seem to be a logical way to remove these carryover growth
effects. When written in finite difference form, a simple linear feedback
model reduces to that for a first-order AR process, so low-order AR
standardization methods can be justified as a way of removing internal,

physiologically-caused feedback or carryover effects on tree-ring data. The
difficulty here is that the carryover effects may well be non-linear, e.g.
stronger in stressed compared with non-stressed periods.

In practice, time series standardization of a ring width series
involves the production of a series of annual residuals from the chosen AR,
MA or ARMA model fitted to the modified data. When the residual indices are
calculated using an AR model the data are said to be "pre-whitened". To
complicate the process, the pre-whitened data are often recoloured by adding
back in some average AR or ARMA process (see. e.g. Cook, 1985, and Guiot,
1986).

From the frequency-dependent noise-reduction viewpoint, complete pre-
whitening (i.e. removing all the AR structure in a tree-ring series) is
clearly inappropriate, since the whole idea of standardization is to empha-
size some frequency band or zone. Usually, however, dendroclimatic studies
tend to use low order processes which selectively remove the lower frequency
variance components, so that, before recolouring, the "pre-whitened" series
has a preponderance of high-frequency variance.

Recolouring, as used in dendroclimatological applications, re-
introduces low frequency variance in the hope this re-introduced variance is
climatological in origin. In other words, the assumption is made that the
AR structure of an individual ring-width time series is composed of two
parts, one that is common to all trees reflecting low frequency climate
variance, and one that is particular to the tree reflecting internal physio-
logical effects. If a tree is modelled as a simple, perhaps non-linear
feedback system forced by coloured noise, then it is clear that there is no
way that the different contributions to the colour of the output (i.e. the
input colour and the additional feedback-generated colour) can be easily
separated. The practice of recolouring requires more testing before it can
be accepted.

2.4. Strengths and weaknesses of time series methods

One of the strengths of the time series modelling approach, at least
for low-order AR models, is that it has some physiological justification.
More complex models, however, are more difficult to justify, and they are
really little more than ad hoc extensions of the simple case, introduced
mainly to improve the fit of the model to the data. In this sense, there is
a strong parallel with the extension from simple deterministic
standardization models (such as exponential or power-law forms) to more
complex deterministic models (polynomials, etc.).

An important weakness has already been noted, namely the difficulty in
separating out the physiological, internal causes of autoregressive struc-
ture in tree ring time series from the external causes that arise through
low-frequency aspects of external forcing. The recolouring method is based
on the idea that the former are tree-specific while the latter are common to
the stand. This requires testing.

Another weakness, potentially more serious, lies in the fact that the
time series coefficients tend to be unstable in time. Figure 2 illustrates
the variability in the lag-1 autocorrelation coefficient in a chronology of
Pinus sylvestris (Suojanperä, northern Finland) and one of Quercus (Forest
of Dean, U.K.). The raw Pinus data were standardized by dividing with a 60-
year low pass filtered curve. The Quercus standardization used a 30-year
filter. The r_1 value calculated over the whole length of the Pinus series
is 0.39. The running 30-year values vary between about -0.5 and 0.7. The
Quercus running values range from about 0.2 to 0.6 with an overall value of
0.32. Such large variability is just what one would expect on physiological

grounds.

In general, this sort of instability is manifest in the following way. If a time series model is fitted to one part of a tree ring series, the coefficients (particularly the higher order coefficients) may differ noticeably from those obtained if the model is fitted to another part of the data. Thus, if a single "best fit" model is used, based on all of the data, then false autoregressive structure will be introduced into the data series. This means that the spectral character of the standardized series may vary with time and may, for some parts of the record, be incompatible with the original data. This is clearly undesirable.

In any event, from a pragmatic point of view, ring width time series standardized using the time series modelling approach tend to differ only minimally from those produced by much simpler digital filtering techniques, and the onus is on the practitioners of AR, MA and ARMA methods to demonstrate the superiority of the methods, or to provide some better physiological justifications for them.

2.5. Digital Filtering schemes

Filtering schemes use equ. (6), but with coefficients that are pre-specified. Of course, such filters are moving averages, but this fact should not be confused with the time series moving average model where the coefficients are determined by fitting to the data. Although both deterministic and AR contributions to growth can often be recognized in series of tree-ring parameters, the overall dominance of physiological, ecological and climatological forces that are essentially random and unpredictable in nature suggests that a more flexible approach to modelling tree growth variations be used, recognizing the immense difficulty in prescribing the form of the growth "function", and concentrating on the spectrally-specific nature of the basic standardization process.
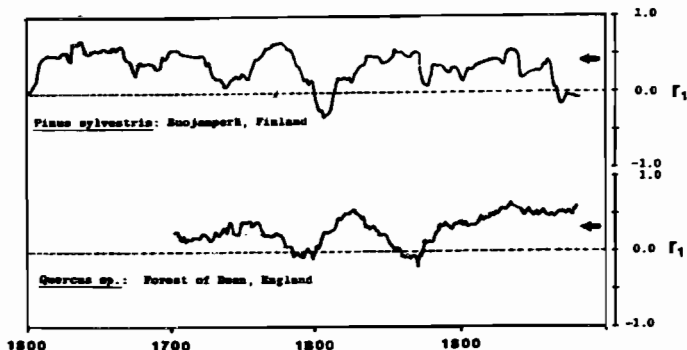
FIGURE 2 30-year running values of lag-1 autocorrelation (value plotted at the end of each 30-year period): (upper) Pinus Sylvestris, Suojanperä, Finland (69°19'N, 28°08'E), standardized by dividing the raw data by 60-year Gaussian filtered values; (lower) Quercus Sp., Forest of Dean, England (51°45'N, 2°50'W), standardized as for the Pinus but using a 30-year filter. Overall period lag-1 autocorrelation values (Suojenperä, 0.39; Forest of Dean 0.32) indicated by arrows.

Any time series can be characterized by its variance spectrum, and different parts of the spectrum of a ring-width or density series may be attributable to different causal factors. These factors can, to a varying extent, be distinguished by their spectral characteristics. Consequently, filters can be designed to remove parts of the variability from raw tree-ring series specified according to their spectral character.

Several workers have proposed the use of digital filtering schemes to estimate standardization curves in dendroclimatic studies. Bitvinskas (1968, 1974) has used simple unweighted moving averages of varying length. Such a crude filter is unsuitable because it causes phase shifts in the smoothed series and because of its flat spectral response curve (Mitchell et al., 1966). This can be overcome by weighting the ring widths to be averaged by an amount proportional to the ordinates of a Gaussian probability curve. Specific weights can be calculated which allow predetermined frequency variations to be removed or maintained at will. Other filters can be designed which have sharper response curves: for further details see Mitchell et al. (1966).

Digital filters have been used to standardize tree-ring series from coniferous (Parker, 1971; Parker et al., 1981) and deciduous (Briffs et al., 1983; Briffa, 1984) species. They have also been applied in the standardization of previously averaged ring width chronologies to isolate variations in specific frequency ranges, either to explore frequency-dependent relationships or to test hypotheses (Julian and Fritts, 1968; LaMarche and Fritts, 1972; LaMarche, 1974; Stockton and Fritts, 1971).

Cook and Peters (1981) have described an approach to ring-width standardization which is equivalent to the use of digital filters. They proposed fitting the raw data with a smoothing spline, a set of cubic segments joined smoothly at their ends passing through a series of defined points or knots. In their method, the level of fit of the spline is controlled by a parameter whose effect they quantify in terms of a specific frequency response. This means that the user can, just as with a digital filter, set a single parameter which controls the frequency characteristics of the variations to be removed from the raw data.

Another interesting variation on the general theme of filtering is afforded by Barefoot et al. (1974). In standardizing Quercus ring-width series from sites in southern England, specifically to produce a dating chronology, they used an exponentially weighted one-sided filter to define their standardization curves. This filter allows only a particular number of prior years to influence the level of fit of the smoothed curve at any point of the raw series. By altering the exponent which determines the exponential weights, the degree of smoothing can be controlled. Barefoot et al. subjectively chose a factor which allowed about 15 prior years to influence the fitted filtered curve at any one point. They give no details of the spectral response of this filter, nor on its phase integrity. However, it is essentially a high pass filter and seems to be well suited to isolating the variations in Quercus ring-width series that are optimal for archaeological crossdating.

This is also true of the method derived by Holstein (1975). He takes the first differences of the log-ed ring widths for all series, averages them, and fits a linear regression to this average series. Although first-differencing is in essence a high-pass filter, the linear regression aspect is actually equivalent to an exponential deterministic standardization method.

2.6. Strengths and weaknesses of filtering schemes

A major strength of this approach to standardization lies in its
flexibility, particularly in its general applicability in situations where
growth variations to be modelled reflect both deterministic and stochastic
processes. If we consider standardization to be a frequency—dependent noise
reduction strategy, then clearly the most appropriate approach is one with a
well defined spectral response. Another desirable characteristic of a good
standardization method is that it should pass required variations with
minimal alteration to their phase. These points argue strongly in favour of
using well defined filter schemes.
Filters are both predictable and consistent in operation and avoid
problems of changing curve fit when chronologies are updated and re-
standardized. Filtering also offers a method that can be applied equally
well to applications other than dendroclimatology. High or low frequency
thresholds can be set enabling the retention or removal of ranges of varia-
bility specified directly in the time domain. Band—pass filters may be used
to eliminate noise outside specified periodicity limits.
One drawback of this approach is that it cannot substitute for mathe-
matical formulae as means of summarizing underlying deterministic processes
controlling or influencing tree growth. Another problem with the use of
filters is that isolated abherent or anomalous extreme values in the raw
ring width series can deflect the fit of the smoothed curve in the area
adjacent to the anomalous value. However, compared to the potentially much
larger effect that such an anomaly would have on the fit of a deterministic
function, this is relatively insignificant.
A potentially greater problem with symmetric filters is the need to
"pad" the ends of the series to be standardized in order to prevent data
loss. J (see equ. (6)) terms must be added to each end of the raw data
series in order to obtain filtered values spanning the whole data record.
For low frequency filters, J may be relatively large. Depending on how the
padding is done, it can lead to end effects which may noticeably affect the
first and last (roughly) J/2 terms of the series. However, for the range of
filter lengths generally used in dendrochronological research, padding
effects are of minor importance, and the sensitivity of the results to
padding can easily be assessed by comparing different padding strategies.
The effects of padding are generally of greater practical importance at the
recent end of the data.
If filtering is used to remove unwanted low—frequency noise (e.g. the
growth curve), then there may well be low frequency aspects of the signal
(e.g. climate in the dendroclimatic case) that will be removed at the same
time. Furthermore, high frequency aspects of the noise will be retained.
These are the prices that must be paid in order to reduce the noise, prices
that apply with all methods of standardization.

3. AVERAGING STANDARDIZED SERIES

After standardization, the next stage in chronology construction is to
average the individual standardized series. Although we consider it
separately here, averaging may be viewed as an integral part of the overall
standardization process since it also is a noise reduction procedure, albeit
not spectrally specific. As noted earlier, prior to averaging, tree-to-tree
diferences in variability should first be removed by normalizing the data
(i.e. subtracting the overall mean and dividing by the overall standard
deviation), unless there is some a priori reason for expecting the strength
of the signal to vary appreciably from tree to tree.

Different averaging methods have been used. The simplest and most obvious is to use a simple unweighted mean of the normalized series. A more complex robust mean could be used (e.g. Cook, 1985), but the advantage of this added complexity has yet to be demonstrated; indeed, there are arguments for and against the use of a robust mean.

Another averaging method is to use the first principal component of the set of standardized series (Peters et al., 1981; Guiot, 1986). PC1 is essentially a weighted mean which maximizes the common variance in the constituent time series. If we are seeking to isolate some common signal, then this is a sensible procedure to follow. However, the PC1 time series is almost always highly correlated with the simple mean time series (see, e.g., Wigley and Tu, 1984), so the gains, if any, are likely to be small. A serious drawback of the PC "averaging" method is that, for practical purposes, all the series must be equal in length. Incorporating very long or relatively short series into a chronology is not straightforward. Principal components analysis may, however, be useful as an objective supplement to series aelection on the basis of visual crossmatching (although the correlation matrix is equally useful in this respect).

4. JUDGING THE SUCCESS OF STANDARDIZATION

All evaluations of standardization methods must consider the final product, i.e. the chronology. The chronology represents an expression of common forcing remaining in a group of series after the chosen standardization method has been applied and the series averaged. Thus, judgements of standardization cover the post-standardization operations of normalization and averaging as well. Judging the success of the chronology in representing the signal that it was originally intended to highlight is limited by our knowledge of the nature of the signal and the noise. Here, it is important to distinguish between signal that we are searching for, i.e. the expected signal, and the assumed expression of this signal in the chronology, i.e. the observed signal. The commonly used parameter, chronology signal-to-noise ratio,

$$SNR = N\bar{r}/(1-\bar{r}) \tag{7}$$

where $\bar{r}$ is the observed signal (i.e. the chronology common variance or mean inter-core correlation), is not necessarily relevant unless one assumes that the observed signal is a faithful representation of the expected signal. It is clearly invalid to base a standardization success criterion on the assumption that the standardization has been successful!

One method of assessing successful standardization might be to correlate the standardized data (or the chronology) with the known expected signal. Unfortunately, the expected signal is rarely well known. In dendroclimatology this might be done by measuring the strength of the chronology/climate link statistically (c.f. Guiot et al., 1982; Blasing et al., 1983). The general validity of this approach is limited in two ways, by the fact that the chosen climate variables may only crudely represent the true climate signal in the chronology and by the usual uncertainty associated with statistical relationships. In spite of these limitations, this method may, in many situations, be the only means of evaluating the success of standardization or the relative success of different standardization methods.

Another approach to assessing standardization would be to compare some characteristic of the standardized data (actually the chronology) with the same a priori determined characteristic (usually spectral) of the expected

signal. For example, if it were known that the expected signal only had variance in a specific band (as, for example, the ENSO reconstructions of Lough and Fritts, 1985) then the standardization could be judged by how well this frequency band had been isolated in the standardized data.

One might expect that this could be done by comparing the spectrum of the chronology and the forcing. The closer these match, the more appropriate is the standardization. This argument, however, is based on the false assumption that the link between forcing and ring width changes is direct. Unfortunately, as we have already seen, even white noise forcing may produce a red noise ring-width time series. In other words, because of physiological carryover and feedback processes, the spectral character of the chronology is unlikely to be the same as that for the forcing. Recall that this very fact was the main justification for the time series approach to standardization.

The proper approach is to make direct spectral comparisons between the expected growth signal and the chronology. This is, of course, exceedingly difficult because the expected growth signal is not generally known. Nevertheless, we often make a tacit assumption about the frequency band of the expected signal. In climate reconstruction for instance, we may decide a priori that climate data cannot be reconstructed outside a certain frequency band, which is dictated by the age of the trees, by the perceived complexity (and frequency characteristics) of non-climatic forcing factors and, primarily, by statistical considerations. Given this, it is clear that a good standardization method should be one which ensures that the spectral character of the chronology doesn't vary too much in time. Digital filtering methods do this automatically.

We have noted above that chronology signal-to-noise ratio (SNR) is not necessarily a measure of the success of standardization. SNR is, nevertheless, important, since it does tell us (through more appropriate, but related measures) how well the chronology approaches the hypothetical population chronology. Although this is not a measure of the success of standardization in isolating the expected signal, it is a measure of success in a different sense. Indeed, in applications such as archaeological dating where common high frequency variance arising from any source must be isolated, it is the primary measure of success. Independent of whether or not the expected signal has been successfully isolated, it is still important to assess the statistical confidence of the observed signal.

5.   ASSESSING CONFIDENCE IN CHRONOLOGIES

5.1. High frequency chronology confidence

In a high frequency chronology the mean inter-series correlation coefficient ($\bar{r}$) can be used to quantify the statistical confidence of different parts of the chronology. In conjunction with the number of series averaged at any point (n), $\bar{r}$ can be used to calculate the Expressed Population Signal (EPS), i.e. the fraction of the hypothetical population chronology variance that is explained by (or expressed in) the size-n sample chronology. This is given by

$$EPS(n) = n\bar{r}/(1+(n-1)\bar{r}) \qquad (8)$$

(Briffa, 1984; Wigley et al., 1984).

Wigley et al. also define the Subsample Signal Strength (SSS) which quantifies how well a part of a chronology made up of n series reflects the signal expressed by that part of the chronology made up of all of the data

(i.e. N series where N>n),

$$SSS = \frac{n(1 + (N-1)\bar{r})}{N(1 + (n-1)\bar{r})} \qquad (9)$$

SSS quantifies the relative uncertainty in early parts of chronologies where series replication is reduced and is equivalent to the variance of the N-sample chronology that is explained by the n-sample chronology. In both equs. (8) and (9), and in equ. (7), $\bar{r}$ is based on all standardised series pairs i,j where i ≠ j and is best calculated over the whole length of each particular i-j overlap.

Mean inter-series correlations between high-frequency standardised series can vary significantly from the overall $\bar{r}$ value. This is illustrated in Figure 3, where $\bar{r}$ is plotted for 30-year running periods along with the overall $\bar{r}$ value. If chronology confidence in a particular frequency range (e.g. greater than 1/T yr^{-1}) is of interest, then values taken from a plot of running T-year $\bar{r}$ values might be useful for assessing chronology confidence as a function of time. Running $\bar{r}$ values provide new and potentially important insight into the characteristics of tree-to-tree variability in a stand. The causes of changes in $\bar{r}$ warrant further investigation.
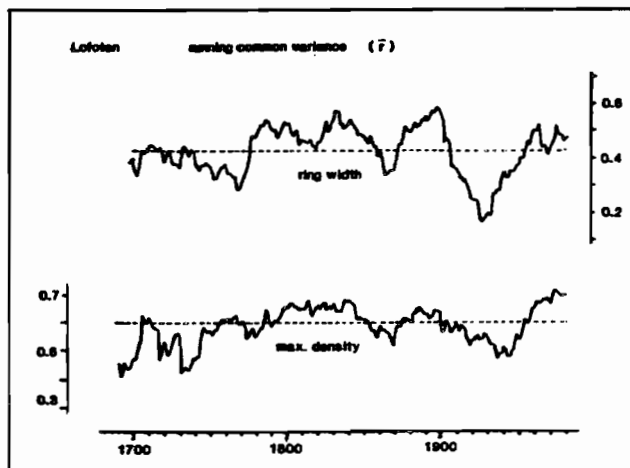
FIGURE 3   30-year running values of $\bar{r}$, the mean inter-series correlation (values plotted at the end of each 30-year period): (upper) Pinus Sylvestris (ring widths), Lofoten, Norway (68°29'N, 16°07'E), standardised with a 60-year low-pass filter; (lower) Pinus Sylvestris (maximum late wood density), Lofoten, Norway (68°29'N, 16°07'E), standardised with a 60-year low-pass filter. Overall period $\bar{r}$ values are: ring widths, 0.42; maximum late wood densities, 0.60. Data kindly supplied by F.H. Schweingruber.

5.2. Low frequency chronology confidence

For a relatively high-frequency chronology, the calculated value of $\bar{r}$ is an unbiased estimator that can be estimated using relatively few series (see Figure 4). In contrast, the $\bar{r}$ value for a low-frequency chronology may be much more difficult to estimate accurately (see Figure 5). This is
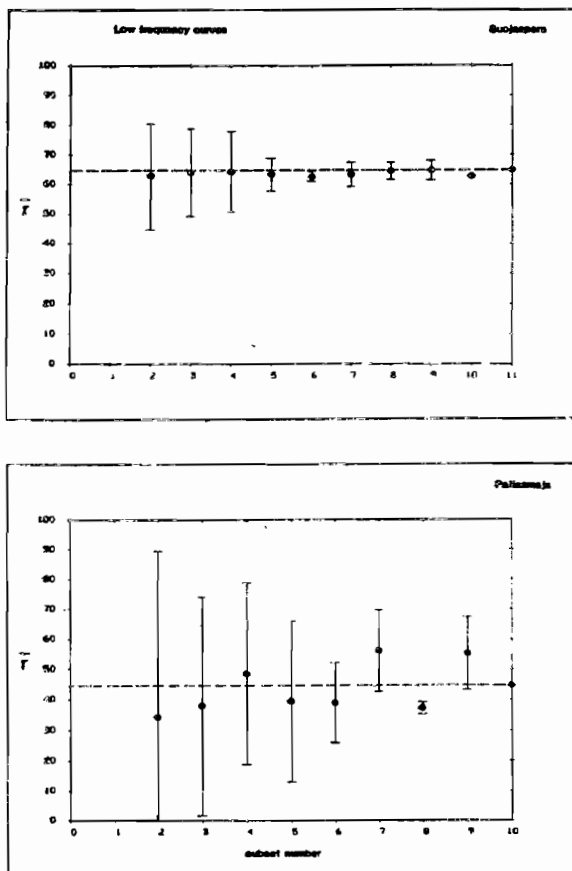
FIGURE 4 Estimates of <u>high-frequency</u> chronology mean inter-series correlation ($\bar{r}$) or common variance using randomly selected subsets of series. The error bars about each central point are two standard deviation limits calculated from many individual samples of size 2,3....N. (Upper) <u>Pinus Sylvestris</u>: Suojanperä, Finland (69°19'N, 28°08'E), standardized with a 60-year low-pass filter. (Lower) <u>Pinus Sylvestris</u>: Pallasmaja, Finland (68°0'N, 24°12'E), standardized with a 60-year low-pass filter.

because the variance of the individual r_{ij} values tends to be greater for low-frequency time series than for high-frequency series. $Var(r_{ij})$ (an important, but neglected parameter in crossdating) is dependent on the extent of autocorrelation in the time series being compared.

It is not immediately clear how many cores are required in order to estimate $\bar{r}$ accurately in general (i.e. in both the high and low frequency
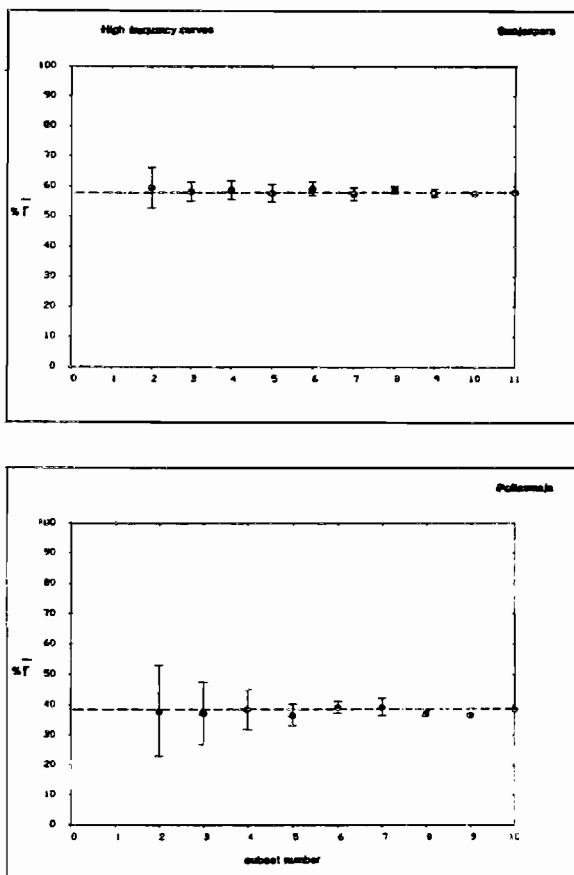
FIGURE 5 Estimates of <u>low-frequency</u> chronology mean inter-series correlation ($\bar{r}$) or common variance using randomly selected subsets of series. The error bars about each central point are two standard deviation limits calculated from many individual samples of size 2,3...N. (Upper) <u>Pinus Sylvestris</u>: Suojanperä, Finland (69°19′N, 28°08′E), standardized with a 60-year low-pass filter. (Lower) <u>Pinus Sylvestris</u>: Pallasmaja, Finland (68°0′N, 24°12′E), standardized with a 60-year low-pass filter.

cases). Our own empirical analyses suggest the following: high-frequency $\bar{r}$ values (i.e. those applicable to "standard" chronologies) can be accurately estimated with ≥ 5 cores, and the estimates are unbiased; $\bar{r}$ values for low frequency chronologies are not necessarily the same as those for high frequency chronologies (the differences are usually much greater than in the cases shown in Figures 4 and 5); $\bar{r}$ values for low frequency chronologies tend to have wider confidence limits than those for high frequency chronologies (i.e. larger N is required to establish their values accurately).

6. SUMMARY AND CONCLUSIONS

Before deciding on what standardization approach should be adopted it is important to carefully consider the nature of the tree growth forcing signal that one is seeking to isolate. How successfully this can be achieved will vary from case to case. Though we have drawn many of our illustrations from dendroclimatology, standardization has far greater applicability and needs to be defined in a general way. The variety of relevant signals and the range and complexity of the noise associated with them demands this and requires that standardization should be a versatile and controllable tool. No one method of standardization is ideal for all situations. For any particular technique, the user should be aware of its strengths and potential limitations. The following factors should be considered.

1. Good standardization must be based on an a priori definition of the expected signal. In other words, characteristics of the signal to be highlighted from the initial data must be clearly identified prior to standardization.

2. One should be careful to ensure that no spurious variability or short term trends are inadvertently introduced into the standardized series merely as an artefact of the standardization.

3. The chosen technique should be homogeneous in time. In other words, its performance should, as far as possible, be consistent throughout the length of the standardized time series.

4. The method of standardization should be chosen to remove the noise efficiently while retaining a high proportion of the expected signal. Unfortunately, it is virtually impossible to determine how much of the expected signal has been retained.

5. Analysis of the observed signal (i.e. the chronology common variance) is, nevertheless, an important diagnostic tool. Chronology confidence should always be assessed using some measure such as EPS, but EPS results should not be interpreted as providing information about the success of standardization in isolating the expected signal.

In conclusion we recommend that standardization be considered, in general, as a frequency-dependent, spectrally-specific noise reduction method. We also suggest that, for many applications, digital filtering techniques have a number of advantages over other methods. Digital filtering is a simple, controllable method that maintains spectral integrity.

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**4.2   SOME NEW APPROACHES IN THE CONSTRUCTION OF MORE RELIABLE
DENDROCHRONOLOGICAL SERIES AND IN THE ANALYSIS OF
CYCLE COMPONENTS**

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1.   INTRODUCTION

Several methods have been developed in the Institute of
Plant and Animal Ecology (Ural Science Center, Academy of
Sciences of the USSR, Sverdlovsk) to obtain more reliable
dendroclimatological series. Much attention is being given to
the analysis cyclic components in them. The most important
approaches are presented.

2.   TREE-RING STANDARDIZATION USING THE "CORRIDOR" METHOD

Estimating the percentage of ring width deviations from
the biological growth function is the most popular method for
tree-ring standardization. A variety of standardization pro-
cedures are determined by the difference in the construction
of growth curves. These can be obtained either by graphically
or by mathematically (estimation of exponential, polynomial
and other function parameters, smoothing by moving averages).
As a rule, this method involves elimination of prolonged fluc-
tuations, series shortage, unadequate estimation of the growth
curve, thus reducing the accuracy of paleoecological recon-
structions.

Numerous plots of annual ring widths of trees growing at
the climatic range limit (upper and polar forest boundaries)
show that age-specific increment trend may be more accurately
evaluated if judged from maximal and minimal possible incre-
ment curves rather than from the average increment dynamics
standard. To obtain such curves, one should join extreme
increment values, as Fig. 1 shows. The absolute increment mi-
nimum, i.e., the missing ring, is distinctly displayed in the
minimal curve. In case the widths of the narrowest rings do
not exceed 0.2-0.3 mm and the probability of the missing ring
is large, the minimal curve practically merges with the X-axis.
Curves of maximal and minimal possible increment have been
plotted subject to the following condition: they must not be
wavy and must run in the same direction.

Curves of maximal and minimal possible increment generate
a corridor of points illustrating annual increment fluctuations.
The width of the corridor varies regularly with the age of the
tree, reaching its maximum during the period of the most inten-
sive growth. The corridor thus displays a range of increments
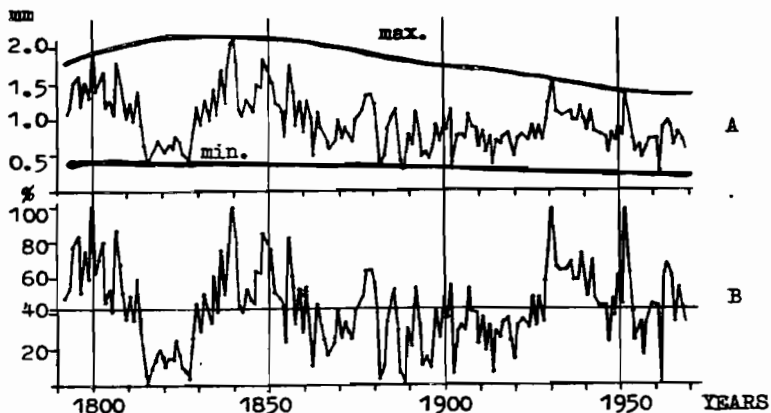
FIGURE 1 Curves of maximal and minimal increment, plotted for computing indices by the "corridor" method. A – tree-ring widths, B – tree-ring indices.

in response to environmental fluctuations in different spans of life of the tree.

In calculations of increment indices for each particular year, the width of the corridor is taken as 100% (200%), the values of the indices are computed from the formula:

$$I_t = (x_t - a_t)/(b_t - a_t) \cdot 100(200) , \qquad t = \overline{1, n} \qquad (1)$$

where I_t is the increment index for the year t, x_t is the tree-ring width, a_t, b_t are the minimal and maximal possible increments accordingly for the year t (Shiyatov, 1972; 1986).

An advantage of the corridor method is its simplicity. It permits revealing long-term fluctuations, the series length remaining the same. However, a more careful technique of rings of tension and compression wood is required. Besides, a subjective factor appears. The effect of the latter can be minimized if a sufficient number of trees is used in the analysis.

In what follows we propose formulation of the problem of tree-ring standardization.

Definition. Suppose we have a time series x_t, $t = \overline{1, n}$ of absolute increment values. Suppose a_t and b_t are discrete values of continuous functions of the set of "biological growth curves" defined in the same line segment. Consider also that the values of a_t do not exceed those of x_t and the values of b_t are not less than corresponding values of x_t.

We term the discrete values of $a(t)$ and $b(t)$ functions the minimal and maximal possible increments, respectively, provided the area between the curves of these functions is minimal and the function humps are reached at the same t value.

The following function of the set of biological growth curves is chosen:

$$G(t) = c_1 \cdot (t + c_2)^{c_3} \cdot \exp(c_4 \cdot (t + c_2)) + c_5 \qquad (2)$$

Problem statement: find the minimum value of

$$\sum_{t=1}^{n}(b(t) - a(t))$$

constrained by $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (3)

$$b_t - x_t \geqslant 0, \quad x_t - a_t \geqslant 0 \quad \text{for all t values.}$$

3. METHOD OF COMPUTING TREE-RING INDICES FOR SEPARATE CALENDAR YEARS IN OBTAINING MEAN AND GENERALIZED SERIES

It has been established methodically that the indices of a generalized tree-ring series should be estimated by the arithmetic mean indices of the growth of individual crossdated trees for each calendar year. To this end one has to be sure that the index distribution in each year is normal or, at least, unimodal and symmetric. Analysis of histograms has shown that this condition is not always fulfilled. Consequently, the selection of the mean as a measure characterizing the growing conditions in each year should be based on index distribution at the relevant dates.

By convention, two types of distributions were distinguished from analysis of over 300 histograms: unimodal (single peak) and polymodal (multiple peaks). In our view, the differences in distribution patterns of the same model trees in different calendar years result from the sensitivity of limiting factors. As a rule, during unfavorable years (cold summer, water shortage) the indices on the histogram were closely grouped about a small value and were almost normally distributed, while, in contrast, the range of indices was rather large during years favorable for growth. In the latter case, their distribution may be both unimodal and polymodal. In practice, a strong emphasis is being placed on bimodal ones, because the estimation of parameters with more components in the mixture of distributions on amount of sampling 30-50 model trees would not be strict enough.

The existence of bimodal distributions in a particular year may be attributed to the fact that part of the model trees were influenced by specific limiting factors which enhanced the decrease in their annual increment compared to other models. The increment in the latter is limited mostly
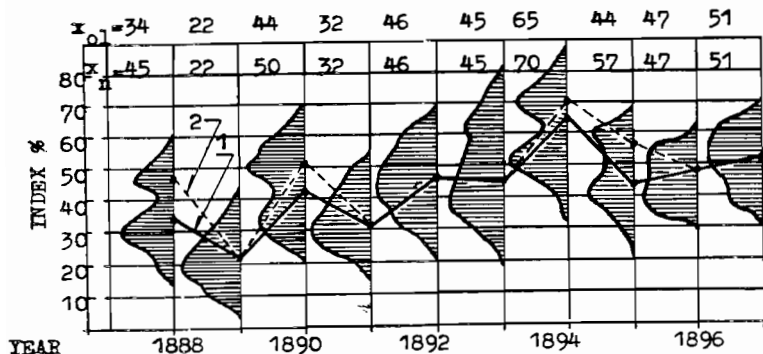
FIGURE 2 Illustration of the proposed method for computing values of generalized tree-ring series (x_{ol} is the old value, x_n is the new value). 1) series segment (1888–1897) computed using typical method; 2) series segment computed using proposed method.

by climatic factors. Partial factors such as fruit bearing, pest outbreaks, fungal colonization, etc., will act selectively.

Based on these theses, a new procedure of computing values of a generalized series was developed (Mazepa 1982). A histogram of increment indices of individual model trees is constructed for each year, and the statistical hypothesis is verified as to its membership in the class of normal distributions. If the hypothesis is not rejected, the mean is a measure of relative wood growth. An alternative hypothesis should be that indices of individual models for a given year form a mixture of two or more normal distributions. Then it is necessary to compute the mean value of the maximal grouping and to use it as an estimate of the index of the generalized dendroclimatological series. Thus, the effect of specific constraints is disregarded and the role of general climatic factors is revealed.

As a formal model of the increment index distribution for each year the following model of a mixture of fixed number normal distributions was adopted:

$$F(x) = \sum_{j=1}^{k} \alpha_j \cdot F_j(x) \ , \quad 0 \leqslant \alpha_j \leqslant 1 \ , \quad \sum_{j=1}^{k} \alpha_j = 1, \quad (4)$$

where $F_j(x) \sim N(\mu_j, \sigma_j)$, k is known, $\mu_j, \sigma_j, \alpha_j$ are unknown. The task is to estimate the parameters $\mu_j, \sigma_j, \alpha_j$ from the sample $\{x_i\}$, $i = \overline{1, n}$. There is a good review on the methods for estimating the parameters (Holgersson, Jorner 1978).

Figure 2 illustrates the proposed method for computing the values of a generalized series of <u>Larix sibirica</u> that
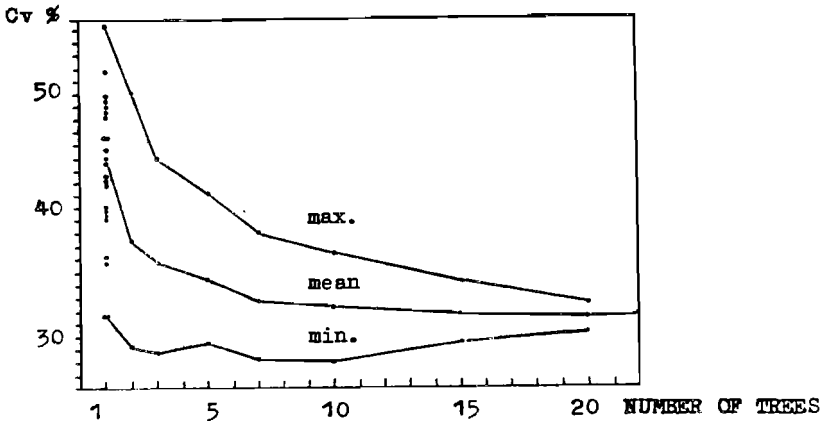
FIGURE 3   The variation coefficients of tree-ring chronologies
obtained from different number of trees.

grows within the West-Siberian forest-tundra. The correlation
coefficient between generalized series whose indices are com-
puted by the method proposed, and a series of July temperatures
(for 89 years) proved to be considerably higher than in the
case of using the typical method. The coefficients changed
from 0.49-0.59 to 0.65-0.75. We consider, therefore, that im-
proved series reflect temperature fluctuations better.
     Analysis of increment index histograms for each year may
be used to reconstruct partial limiting factors such as fruit
bearing, tree defoliation by insects and fires, etc.
     We are aware that further development of the proposed me-
thod is necessary. In particular, one should take into account
the effects of increments for preceeding years on the increment
of a current year.

4.   ELIMINATION OF DISPERSION HETEROGENEITY IN THE SEGMENTS OF DENDROCHRONOLOGICAL SERIES SUPPLIED WITH INSUFFICIENT AND UNEQUAL NUMBER OF MODEL TREES

     To obtain the mean chronology, model trees of different
age are commonly used. Therefore, different time segments are
often supplied with an unequal number of model trees. Averaging
gives dispersion heterogeneity in the series, which so far has
practically been neglected. Almost all dendrochronological
series obtained to date have this disadvantage.
     Analysis of the mean chronology shows that when the number
of sampling decreases, the increment indices become more vari-
able in the corresponding time segment. Figure 3 shows changes
in the variation coefficient of the increment indices against
the number of the models used. The 22 model trees of Larix
sibirica from 170 to 290 years old were used to construct the
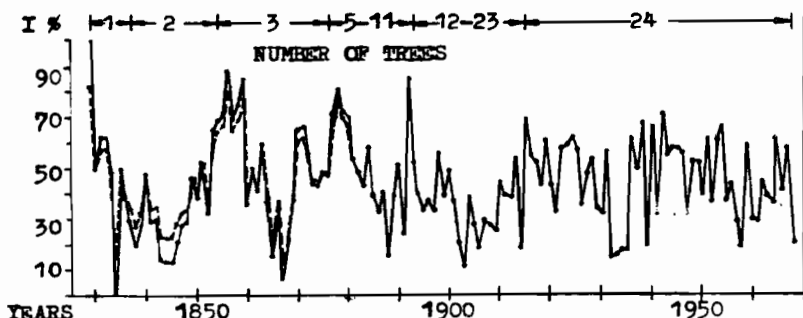
FIGURE 4   **Mean chronology with series segments** obtained from
a different number of trees (from 1 to 24). Solid
line stands for the indices averaged for each year
to obtain chronology, dotted line for improved ones.

plot. The figure gives the mean, maximal and minimal variation
coefficient values, obtained by exhaustive search of these
models. These variation changes are most significant on the
left hand side of the plot, when the number of models was not
great (1-10 sp.). As the amount of sampling increases, the
variation coefficient diminishes and reaches a certain stable
level.

Further calculations of the index variation as a function
of the number of models used were carried out on constructing
more than 100 mean chronologies of Larix sibirica, Picea
obovata, Pinus sibirica that grow at the upper and polar forest
boundaries. In most of the series, significant changes in the
variation coefficients are observed only when less than 7-10
models used. Poorly supplied series segments have an index
variation of 20-35% over the standard. Heterogeneity is a sig-
nificant limitation of many dendrochronology series published.
A wrong conclusion may be drawn if one disregards this espe-
cially if one reconstructs climatic conditions and finds simi-
larity measures between the series. Heterogeneity may be over-
come by excluding those series segments for which the number
of models is inadequate. As a rule, the most ancient and va-
luable series segments, which contain less accurate but very
important information about the ecological changes in the past,
are sacrificed. Therefore, this method is not always accept-
able. A new method, aimed at avoiding heterogeneity in tree-
ring series through corrections in increment indices, has been
proposed (Shiyatov 1980).

The method consists in reducing those series segments
which are insufficiently supplied with model trees to a level
of variability that is typical of well-supplied segments (over
10 sp., as a rule). To introduce corrections, the following
procedures are carried out. The dependence of the increment
index variation coefficient on the number of model trees used
is determined for each series. The mean value of the variation
coefficient, obtained for the series segment supplied with

over 10-12 model trees, is taken as a standard. Thereupon the
increment indices for the time segments, provided with few mo-
dels, are multiplied by the coefficient of contraction which is
equal to the ratio of the standard variation coefficient to the
variation coefficient, typical of the above-mentioned time seg-
ments. The computational formula is:

$$I_t^{cor} = (I_t^{ol} - I) \cdot k + I , \qquad t = \overline{t_i, t_j} \qquad (5)$$

where I_t^{cor} is the corrected value of the increment index, I_t^{ol}
is the old value of the increment index, I is the average value
of the increment indices for the series, k is the coefficient
of contraction.

Figure 4 shows actual (solid line) and corrected (dashed
line) increment indices for Picea obovata from the lower
Pechora river. The increment indices for this series are cal-
culated graphically by the corridor method.

5. SPECTRAL APPROACH TO INVESTIGATE THE CYCLIC DYNAMICS

Dendrochronologists are aware of the fundamental possibi-
lity to split tree-ring series into cyclic components. Thus,
these series are often represented as a trend plus cycles plus
random error. However, the terms used are not well-defined.
Widely spread methods of smoothing do not permit statistically
admissible terms to be worked out.

Our approach to the analysis of the cyclic components in
increment dynamics is based on a spectral presentation of ran-
dom stationary process. One of the main practical results of
the spectral theory is the following: any jump of the spectral
function is interpreted as an increased contribution of the
corresponding frequency band to the total variation of the
series. Most practical problems are solved when neither the
type of spectral function, nor the class of parametric model
is known a priori. Therefore, estimates of the spectral func-
tion are used. Estimates may be good or bad in the sense of
their proximity to the estimated function of the process, sta-
tistical properties of this estimate, ease of calculation, etc.
But that falls into the line of practical spectral analysis
(Kay, Marple 1981). Two methods of spectral density estimation
were used in computer experiments: the Blackman-Tukey method
and the maximum entropy method. The results were as follows:

the spectra of ring-width indices for individual trees
growing in homogeneous ecological and extreme abiotic condi-
tions of the same climatic region are similar. The spectra cal-
culated from time series segments of 200-1010 years do not
change significantly within the period of 300 to 500 years
(Fig. 5);

spectral analysis shows the existence of important narrow
frequency bands with fluctuation amplitudes much higher than
those of the neighbouring ones. Their widths are about
0.02-0.05 cycles a year.
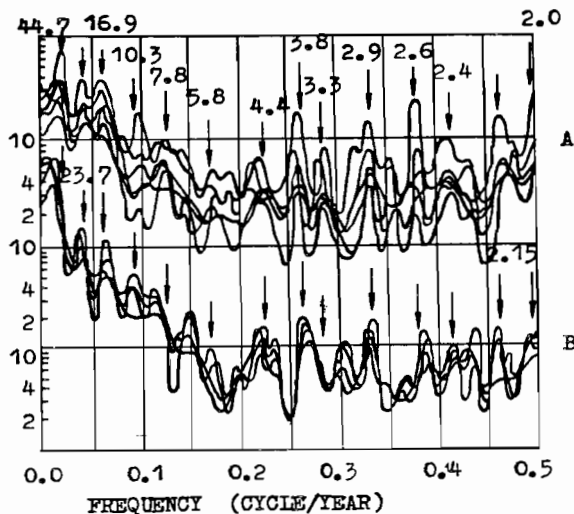
FIGURE 5   The maximum entropy power spectrum of the single
tree-ring series coming into use for generalized
series. A - spectra for the series within the period
XVII-XX cc; B - spectra for the series within the
period XII-XVII cc.

When important for the majority of the tree-ring chrono-
logies in the area investigated, these frequency bands may be
used as characteristics in studies of wood increment dynamics.
Thus, by a cycle we mean a tree-ring series component which
corresponds to a certain important narrow frequency band.
      This concept is methodically convenient. Purposeful narrow
band-pass filtration with a prescribed transfer function be-
comes possible. When extracted, the important frequency bands
can be analysed by choosing a corresponding filter. In our
work we used a filter with coefficients that are truncated
Fourier series coefficients of the ⊓-shaped function. Good
results are obtained with optimum (in the minimax sense) finit
impulse response linear phase digital filters: in designing
such filters, the Chebyshev approximation problem is used
(McClellan, Parks 1973). Using this filter, an explorer may
control the magnitude and position of unwanted fluctuations in
the transfer function. This enables one to extract a certain
frequency band by means of a filter of a given length with
minimal risk of contaminating the outgoing series by spectral
components that belong to some other frequency bands.

WEST-SIBERIAN FOREST-TUNDRA

$N = 14$; $r = 0.56$; $K_s = 68\%$; $S = 29\%$

YEARS
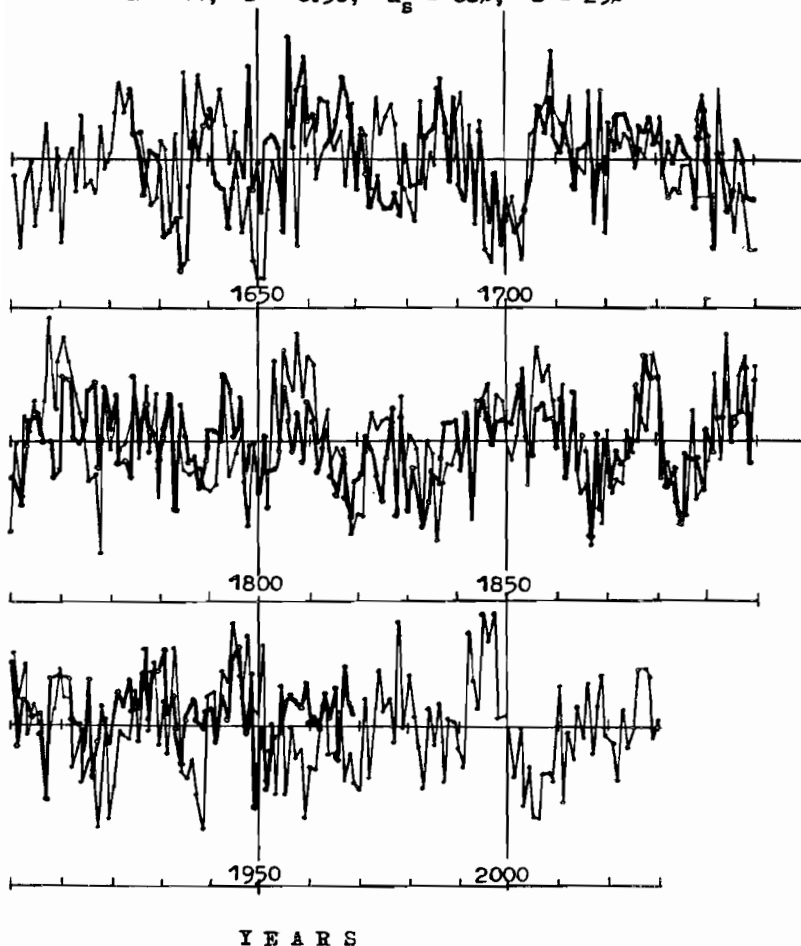
FIGURE 6   Tree-ring chronology (thick line), its approxima-
tion and extrapolation by sinusoids (thin line).
N is the number of sinusoids in the approximation,
r the correlation coefficient, K_s synchronization
coefficient, S the mean-root-square error.

6. APPROXIMATION AND EXTRAPOLATION OF A TREE-RING CHRONOLOGY BY A SUM OF SINUSOIDS WITH UNDIVISIBLE FREQUENCIES

One of the practical purposes of analysing the cyclic components in tree-ring series is the forecast the woody plants increment dynamics due to climate.

Our experience of computer experiments has shown that, if one employs a reasonably narrow band-pass filtration of tree-ring series, the outgoing series may be quite accurately approximated by a sinusoid with a frequency belonging to a spectral band over many periods. It stands to reason that outgoing series will not be strictly periodic even if the band is very narrow. Sinusoids approximating such components are to have different amplitudes and phases in various time segments. However, the changes in them, in particular phases ones, are quite slow to succesfully approximate the filtered component by a sinusoid.

Based on this, we used narrow band-pass filtration aiming at extraction of only those frequency bands which give increased spectral density estimates. The extracted components were then approximated by a sinusoid and the forecasting series of increment due to climate was represented as a sum of sinusoids.

Amplitudes and phases were estimated by the least squares method. Frequencies were evaluated by exhaustive-search in the extracted bands.

The approximation is specified by several quantities: correlation coefficient, synchronization coefficient and mean-root-square error of approximation. Correlation coefficient between the original and approximated series was 0.5-0.8, synchronization was 65-75%, the mean-root-square error was not more than 20-30%.

Figure 7 gives an example of approximating and extrapolating the mean tree-ring chronology, obtained for _Larix sibirica_ growing in West-Siberia forest-tundra.

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4.3 STANDARDIZATION AND SELECTION OF THE CHRONOLOGIES BY THE ARMA ANALYSIS

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1. INTRODUCTION

The greatest problem encountered by dendroclimatologists when preparing tree-ring master chronologies is "whether age-related trends can be removed without distorting the climate" (Hughes et al, 1982, p.29) and then if these trends and the low-frequency climate responses can be separated. When this trend is the standard negative exponential curve, there is no difficulty, but when the trend is more twisted, the dendroclimatologist has to use polynomials, splines, filters (Graybill, in Hughes et al., 1982; Guiot et al., 1982b). Other papers do exist on this topic, but it not the aim here to review them.

An objective approach is possible through the time-series analysis and more particularly through the autoregressive-moving average analysis. Guiot et al. (1982a) have introduced it as a method for building an integrated model of the growth including this trend, the persistence, and the effect of the climate. The purpose now is to present a specific and original approach of the standardization based on the same techniques (section 2). The problem of the coherency of the individual cores that are to be introduced in the master chronology will also be studied in section 3.

2. THE STANDARDIZATION METHOD

The usual standardization method is illustrated by the mean of the individual series sampled in Bush Lake, Northern Québec (Payette et al., 1985). This chronology (Figure 1:1) shows three periods in the growth (these periods are intentionally overlapping, because the limits are rarely clear):

(1) a youth phase (1400-1499), characterized by a relatively high variability;
(2) a maturity phase (1480-1879), characterized by a relatively low variability;
(3) an awakening phase (1860-1982), characterized by an explosive growth; in fact the mean growth and its variability are multiplied by two, probably because of a climatic improvement.

In these sub-arctic regions, it is necessary to divide the chronology into 3 parts in order to obtain stationary sub-series. Usually the process is less complex. The young trees have a high and very variable growth; this phase is followed by a maturity phase with a stationary growth: then it is sufficient to split the series into two sub-series.

Each of these sub-series, being stationary and autocorrelated (like most of the tree-ring series), may be considered as AutoRegressive-Moving-Average (ARMA) processes. As shown by Tessier (1984), this kind of process represents the structure of the growth by an equation where the ring-width $T(t)$ at year t is related to the ring of previous years and to a white noise process $W(t)$. This random process is

itself influenced by the climate. As this climate may influence the tree-growth during several years, the equation becomes

$$T(t) = \varphi_1 \; T(t-1) + \ldots + \varphi_p \; T(t-p) + W(t) - \theta_1 \; W(t-1) - \ldots - \theta_q \; W(t-q) \qquad (1)$$

This process, called ARMA(p,q), is defined by p coefficients φ_i and q coefficients θ_i. It implies that the climate can be represented by a random function. Indeed
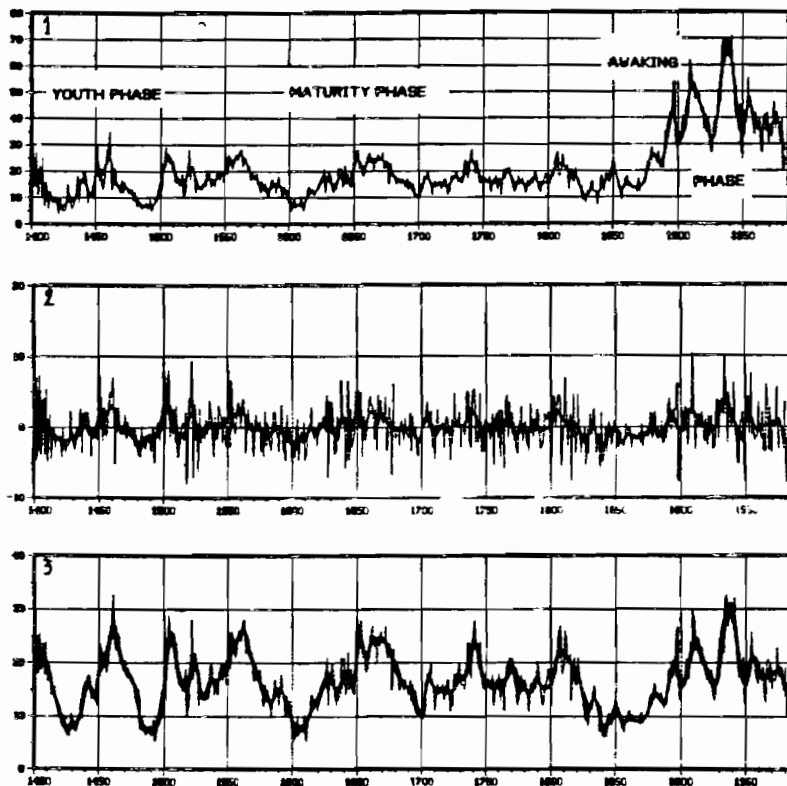
FIGURE 1. The various mean chronologies of Bush Lake: (1) the mean ring widths of all the individual cores; (2) the white noise series obtained by applying the ARMA models of Table 1 to the three sub-series; (3) the reddened series obtained by applying the model of 1480-1879 sub-series to the full white noise series (2).

the high frequency variance most frequently is largely dominant in the climatic series so that they may be considered as white noises. Moreover the random function does not represent only climate but it is not possible to remove the non-climatic factors from these high frequencies variations.

The first step is to identify the model, which must be the result of compromise between a low order (p,q) and a good fit (i.e. a low variance of a_t). Akaike (1974) proposed the use of the Akaike Information Criterion (AIC) which must be minimized so as to obtain the optimal model:

$$AIC(p,q) = n \log S_W^2 + 2 (p+q) \tag{2}$$

where n is the size of the series and S_W^2 is the white noise variance.

2.1. The processes identification

The identification of the ARMA model, the more speculative phase of the method, is based on the profile of simple autocorrelation coefficients r(k) of the series:

$$r(k) = (\sum_{t=k+1}^{n} (T(t)-mT) \ (T(t-k)-mT) \ /ST^2 \tag{3}$$

where k is the lag of the autocorrelation, mT is the mean and ST^2 the variance of the series. The autocorrelation coefficient at lag k is dependent on the autocorrelation at lags less than k. It is the reason why the curve SA (Figure 2)
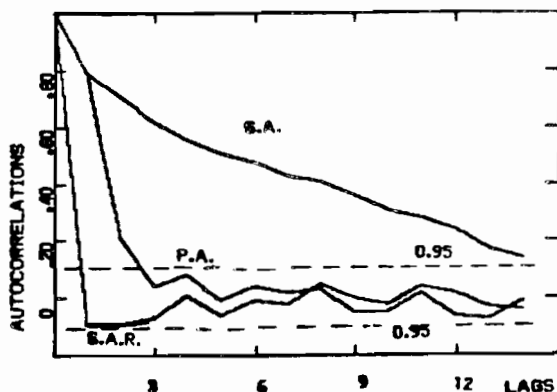
FIGURE 2. Simple and partial autocorrelation functions of the 1480-1879 sub-series of Bush Lake; (S.A.) simple autocorrelation function of the raw data; (P.A.) corresponding partial autocorrelations; (S.A.R.) simple autocorrelation function of the residual series obtained by applying to the raw series the partial autocorrelations as autoregressive coefficients.

decreases steadily from lags 1 to 14. The identification must then be based on an other function: the partial autocorrelation function which removes the effect of the intermediate autocorrelations. The curve PA (Figure 2) shows that only the first two lags are significant in the example.

First, the identification method used here is somewhat simplified as compared with that of Box and Jenkins (1970) because it is applied in a well-defined biological context.

First, the autocorrelation coefficients significant at lags greater than 3 years should not be taken into account unless they are caused by parasites inducing a more or less marked cycle in growth. Second, the coefficient ϕ_j symbolizing persistence will usually be positive. When the period of analysis starts during the youth of the trees, the series are generally non stationary in mean and in variance: first differencing and logarithm are then used. When the period of analysis is short as compared with the total length of the series, the series must be considered to be stationary, although the possibility that climate can induce an apparent non stationarity effect should not be excluded.

The technique for identifying the ARMA processes of a dendroclimatic chronology can be summarized as follows:

a) computation of the variance of the raw series T_t and of that of the first differences T_t-T_{t-1}. In the next steps, differentiated series will be used when the variance of the latter is smaller than that of the raw series;

b) computation of the simple (SA) and partial (PA) autocorrelation functions of the selected series. If the SA's decrease exponentially and the PA's fall after p lags, an ARMA(p,0) or AR(p) model is identified (Figure 2). If the PA's decrease and the simple autos fall after q lags, it is a ARMA(0,q) or MA(q) model. Mixed ARMA(p,q) models are more difficult to identify.

c) In practice, an AR(p) model is at first fitted to the series with coefficients given by the significant PA's. So the model

$$T(t) = 0.79\ T(t-1) + 0.21\ T(t-2) + W(t) \tag{4}$$

has been applied to the series of which the autocorrelation functions are presented in Figure 2.

d) Then the residual series and the corresponding AIC(p,0) are computed. Then q is the number of significative simple autocorrelations (SAR) found for these residuals, starting with lag 1. In the case of Figure 2, q=0. If the corresponding AIC(p,q) is not lower than AIC(p,0), q is decreased until the AIC(p,q) becomes minimum. In all the cases, close models (i.e. ARMA(p-1,q) or ARMA(p,q-1)) may be tried to check that AIC(p,q) is actually minimum.

2.2. The raw series prewhitening

Coefficients ϕ_j and θ_j are calculated using here the generalized adaptative filtering technique (Makridakis and Wheelwright, 1978). Other more sophisticated methods do exist (Priestley, 1981) but in dendroclimatology, this method is largely sufficient. Table 1 shows how to identify the ARMA models and gives the results of the selected models for the 3 sub-series presented before.

Using the identification method, an ARMA(p,0) model is applied to the sub-series. These models are good, since the AIC(p,0) are lower than the corresponding AIC(0,0) but the final models are better, as the AIC(p,q) are still lower. For each case, close models are tried: slightly higher AIC(p,q) prove that the selected models give a minimum AIC.

The residual sub-series a(t) are calculated. Portmanteau tests — or chi-squared statistic equal to the sum of squared autocorrelations multiplied by the sub-series size — (Table 1) show that they are really white noises. These residuals sub-series [1400-1489, 1490-1869, 1870-1982] are joined (Figure 1;2).

TABLE 1. Identification and estimation results of the ARMA models for the 3 sub-series of the Bush Lake mean chronology (see text); res.var. = residual white noise variance; chi2 = $n \sum r(k)^2$ where n is the size of the series, $r(k)$ is the autocorrelation coefficient at lag k, the sum is done on 14 lags.

model	statistics	1400-1499	1480-1879	1860-1982
ARMA(0,0)	variance	48.0	24.7	195.8
	AIC	386.1	1281.1	648.1
	chi2	127.4 *	1245.5 *	507.1 *
ARMA(p,0)	p	3	2	11
(first	res.var.	34.4	9.4	79.9
estimation)	AIC	356.9	900.3	560.8
	chi2	10.0	15.3	94.4 *
final	(p,q)	(3,0)	(2,2)	(2,2)
ARMA(p,q)	res.var.	23.8	8.7	40.4
	AIC	323.0	874.0	463.0
	chi2	12.3	21.8	17.5
	$\varphi(j)$	0.29 0.19 0.21	0.39 0.33	0.40 0.37
	$\theta(j)$	-	-0.20 0.07	-0.20 -0.11
close	AIC(1,2)	338.2	874.2	464.5
models	AIC(2,1)	333.9	874.5	463.6

2.3. The white noise series reddening

The final master chronology may not be a white noise series because the climate has usually a low frequencies pattern. Then it is necessary to redden this white noise series. But one must be careful not to restore the part of the tree-growth trend which is not climatic. The reddening process is based on the estimation of R(t) from W(t) by using the corresponding ARMA model. Nevertheless, if the exact model is applied to each sub-series, the raw series is restored (R(t)=T(t)). If a model calculated on a stationary sub-period is applied to the whole series, a stationary reddened series will be restored. The maturity phase (1480-1879) has this property.

In fact, after its youth phase, the tree-growth is often a stationary process unless an external factor modifies it. Here the climatic improvement has induced an internal physiological mechanism. It is then interesting to know how the growth would be under a favourable climate influence but without this amplifying physiological factor. This is done by the application of the maturity phase model to the whole series a(t):

$$R(t) = 0.39 R(t-1) + 0.33 R(t-2) + W(t) + 0.20 W(t-1) - 0.07 W(t-2) \quad (5)$$

Figure 1 shows that I(t) reproduces very well the short-term variations of R(t). It also shows that the climate improving from 1870 is clear but that the maximum of

1940 is hardly higher than the preceding maxima, as was shown by Fritts and Lough (1985) for North America and more particularly by Guiot (1985a) for northern Canada.

3. THE CORES SELECTION

A master chronology is usually based on the maximum of cores available in the site analysed (Fritts, 1976). The misinterpretation of the statistical law of large numbers leads to include in the chronology noisy cores, i.e. cores sampled from trees in a particular environment.

The site of Vallée des Merveilles, French Alps, (Serre, 1978) is of particular interest to show the efficiency of a standardization method including a core selection. In this site, trees are old and sparse (some are 1000 years old), so the coherency of some of them is not always good. Twenty cores were chosen because they yielded the longest chronologies. An ARMA model was fitted to each of these 20 series and 20 white noise series were thus obtained (Guiot, 1984; 1985b).
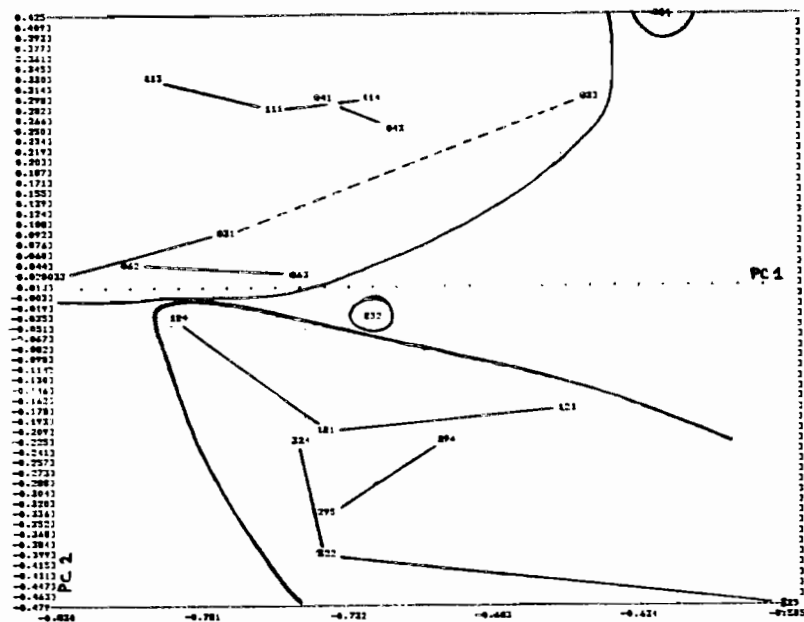
FIGURE 3. The first two principal component of the correlation matrix between the 20 cores of the Vallée des Merveilles, French Alps, on the 1200-1974 period, and the clusters obtained by a hierarchical cluster analysis: the continuous lines link the closest cores; the last four groups clustered are also figured; a broken line show an intermediate link.

In Guiot (1984; 1985b), 7 cores have been selected on the basis of their correlation with the June-July temperature. But this may lead to do a selection over a too short period, i.e. the period when climatic data are available. Therefore. it is better to work on the full series as proposed by Guiot (1982b). The coherency between cores may be checked through either the low or the high frequencies of the series. Here, only the high frequencies variations of the growth are analysed so that the ability to reconstruct the short-term variations of the climate is optimized. Moreover accidental factors, such as fires, clearing, are removed and thus do not disturb the intercores relations.

Figure 3 shows the first two principal components (PC) of the correlation matrix between the 20 cores calculated on 1200-1974. These two PC explain 60% of the total variance. The cumulative eigenvalue product (PVP or CEP) becomes less than 1 after the 9th eigenvalue (Guiot, 1985c). Finally the 20 cores can be considered as equivalent to 9 independent variables. A hierarchical cluster analysis (Lebart et al., 1979) is made on these 9 PC, which explain together 85% of the total variance.

In Figure 3, the first clustered cores are linked with a line. The first two digits of the labels indicate the tree and the last digit the core in the tree. It is clear that cores coming from the same tree are clustered first. Cores 044 and 232 are clustered last: they are rejected. Finally two groups are distinguished. The corresponding cores are averaged, so as to obtain two white noise mean chronologies: W1(t) and W2(t).

The raw series of the two groups are also averaged into two mean chronologies, called T1(t) and T2(t) (Figure 4). Now, as in section 1, an ARMA process is applied to T1(t) and T2(t), on the 1500-1974 sub-period, during which all the series are stationary. The models obtained for T1(t) and T2(t) are finally applied to W1(t) and 2(t), giving the reddened series R1(t) and R2(t):

$$R1(t)= 0.18 \ R1(t-1) +0.08 \ R1(t-2) +0.04 \ R1(t-3) +0.12 \ R1(t-4) +0.13 \ R1(t-5) +W1(t)$$

$$R2(t)= 0.29 \ R2(t-1) +0.16 \ R2(t-2) +0.13 \ R2(t-3) +0.11 \ R2(t-4) + W2(t) \qquad (6)$$

T1(t) is clearly non stationary (Figure 4): tree-growth is larger than mean before 1500 A.D. and weaker after. It is not a climatic effect: it is removed by the standardization in R1(t). The stationnarity is not so well marked for T2(t).

The de visu comparison of series shows (i) that the ARMA modelling is an efficient standardization technique, (ii) that the two chronologies have a different pattern which is low-frequency dominant in R2(t) and high-frequency dominant in R1(t) and (iii) that the indices chronology I(t) computed by polynomial standardization is more similar to R1(t) than to R2(t). This justifies the core selection and the eventual computation of two master chronologies in order to obtain additional information.

An other point of comparison may be obtained by the computation of the correlation between each of these mean series and the June temperature which is the climatic parameter influencing at best the tree-growth in this site. Table 2 shows that the signal-to-noise ratio is improved by the standardization: the correlation with June temperature is the lowest with the raw series. The comparison of corresponding · correlations for the various mean series R1(t), R2(t) and I(t) (this latter is obtained by polynomial standardization) shows that R1(t) is more related to the June temperature than R2(t) and I(t): the ARMA technique optimizes better the signal to noise ratio than the usual technique. If it is considered that the cluster analysis has enabled to remove some outlier series and to build two series with a clearly different low frequencies behaviour, it is objectively evident that a supplement of information is so obtained.

TABLE 2. The correlation between the mean chronologies (see text)
and the June temperature at Marseille, France, and Grand-St-Bernard,
Switzerland. The calibration period is indicated in brackets;
* (**) indicates a 0.05 (0.01) significance level.

station	T1	W1	R1	T2	W2	R2	I
Marseille (1851-1974)	0.31 **	0.36 **	0.34 **	0.17	0.31 **	0.22 *	0.29 **
Gd-St-Bernard (1818-1960)	0.21 *	0.36 **	0.32 **	0.15	0.33 **	0.27 **	0.26 **
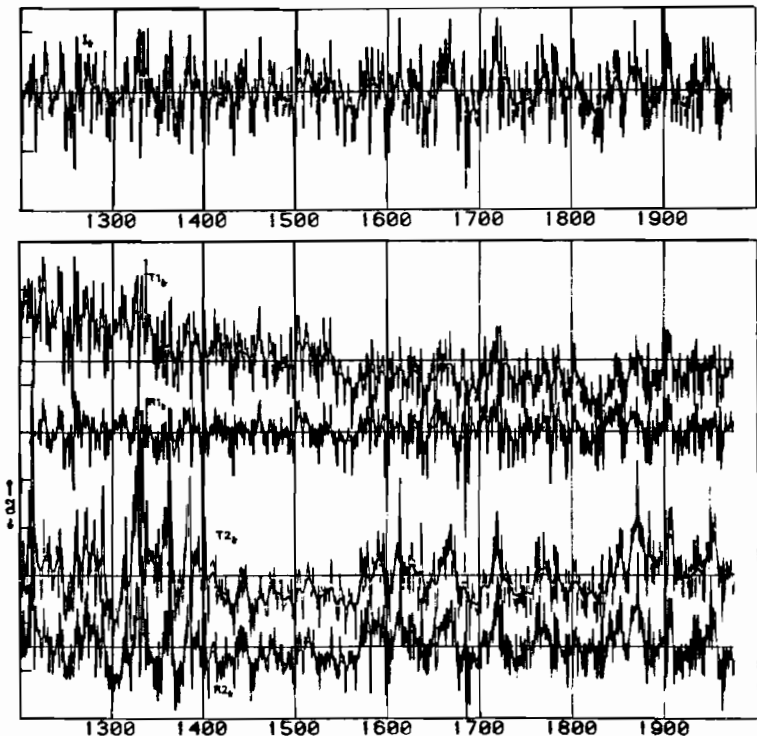
FIGURE 4. The two raw series T1(t) and T2(t) (see text) obtained by averaging the cores found in the two main groups of Figure 3; the two corresponding reddened series R1(t) and R2(t); the indices chronology I(t) computed on all the cores by using polynomials curves. The smoothed values are the result of a digital filter (the loadings are 0.16, 0.14 0.12, 0.09, 0.05, 0.02).

4. IN CONCLUSION

The example of two sites with completely different climatic conditions shows the efficiency of the ARMA modelling used for a standardization purpose. Moreover, this method is objective, as it only requires the determination of a maturity phase in the tree-growth. Now numerous methods are existing to facilitate the identification of the ARMA process, so that this method may be easily used and considered as a real progress in dendroclimatology. Thus the traditional difficulty, met in separating the non-climatic trend from the climatic one, is now solved. It is also shown that the analysing of the core coherency makes it possible to avoid the introduction of noisy series in the master chronology and thereby improves the climate reconstructions, especially in sites with a weak forest density.

I am grateful to F. Serre-Bachet, for providing the series of Vallée des Merveilles and reviewing the manuscript; I also thank S. Payette and L. Fillion, who provided the series of Bush Lake, and finally M. Pellet, who has corrected my english.

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5. REQUIREMENTS FOR SPATIAL AND TEMPORAL COVERAGE

5.1 REQUIREMENTS FOR SPATIAL AND TEMPORAL COVERAGE: INTRODUCTION

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1. INTRODUCTION

In September 1983 a group of fifteen scientists from six nations met at the Lamont-Doherty Geological Observatory of Columbia University, New York. Convened as the 'Global Dendroclimatology Working Group', they had come together with two aims in mind. The first was to discuss the available global coverage of tree-ring data and to assess its potential for use in the reconstruction of past climate. The second was to explore the feasibility of collaborative dendroclimatological research on very large spatial scales, that is from sub-continental to hemispheric.

These objectives arose from the recommendations of the 2nd International Workshop on Global Dendroclimatology, held in Norwich, U.K. in 1980 (Hughes et al, 1980). A systematic review of the prospects for progress in dendroclimatology indicated that very large spatial scale palaeoclimate reconstructions might become feasible during the 1980's (Fritts, 1982). Pioneering work by Fritts et al (1979) had demonstrated the potential and the growth of the tree-ring database outside western North America promised comparable spatial and temporal coverage in other regions of the Northern Hemisphere.

The main outcome of the 1983 meeting was the establishment of the International Project in Dendroclimatology (IPID) with clearly defined scientific goals and an agreed set of protocols for the exchange of data and the publication of results. The Working Group met at the University of Arizona in March 1985 and will meet again in late summer 1986. I propose to examine the experience of IPID up to spring 1986 as a potential source of insights of wider applicability in considering requirements for spatial and temporal coverage of tree-ring datasets.

2. WHAT IS IPID?

The International Project in Dendroclimatology (IPID) was conceived as a pilot project designed to assess the feasibility of reconstructing Northern Hemisphere mean surface temperature back to 1700 A.D. Large-scale temperature provides a convenient measure of the state of the climate system. The reasons for recent fluctuations in this variable are a matter of current concern (Bolin et al, In press). In particular, there is a need to place the large-scale warming of the present century (Jones et al, 1986) in its proper long term context in order to assess the possibility that the warming may be anthropogenic.

The study of changes thought to take place over decades and centuries is limited in scope by the temporal and spatial limitations of the

instrumental record (Figure 1). The hemispheric database of high-quality
temperature records has only recently been extended back to 1851 and it is
unlikely that much further extension will be possible. This is well after
the great industrial expansion in Europe and eastern North America commenced
and hence this record cannot be used to determine the 'natural' pre-
industrial conditions against which anthropogenic effects must be judged.
Further, significant reservations have been expressed as to the reliability
of the detail of the Northern Hemisphere temperature record in the decades
immediately following 1850, although the broad trend of the series is thought
to be reliable (Jones et al, 1985). These reservations arise in large part
from the limited geographical distribution of instrumental stations in those
decades (Figure 1) (Bradley et al, 1985).

It was in the light of these limitations of the temporal and spatial
coverage afforded by the instrumental temperature record and of the consider-
able scientific interest in Northern Hemisphere temperature variation that
IPID was set up. It was clear from the review of the apparently available
tree-ring data that suitable chronologies have a spatial distribution in
major parts of the Northern Hemisphere landmass that is complementary to
that of instrumental records. Over much of the hemisphere, considerable
numbers of suitable chronologies with an appropriate degree of internal
replication were apparently available from 1700 A.D. Hence this period was
chosen for study in the pilot project. Two main approaches were adopted.
In one a group of chronologies believed to be temperature sensitive and
drawn from throughout the Northern Hemisphere was to be collated and its
potential as a source of information on past hemispheric temperatures
investigated. In the second approach, regional networks were to be estab-
lished. These were to consist of all suitable chronologies, not only those
thought to be temperature sensitive. In this case the intention was to study
the feasibility of reconstructing regional mean temperatures and then to
determine whether either the regional tree-ring databases or the regional
reconstructions might be combined in some way to give an alternative recon-
struction of hemispheric temperature.

3. THE APPARENTLY AVAILABLE DATA

A major review of the existing tree-ring database suitable for use in
dendroclimatology was carried out for the 2nd International Workshop on
Global Dendroclimatology (Hughes et al, 1982). Using this as a basis,
Working Group members at the 1983 meeting identified several hundred
chronologies from the Northern Hemisphere likely to be of the necessary
quality in terms of adequate within-site replication and full cross-dating.
This was done by reference to the dendrochronological literature, members'
and their co-workers' unpublished collections and the list of holdings of the
International Tree-ring Data Bank (ITRDB)   This latter source (the ITRDB)
was considered to be of particular value as it contains only data from
identified sites where the trees or timbers have been fully cross-dated and
where there is at least a modicum of within-site replication. Even more
important was the requirement that raw tree-ring measurements, usually ring
widths, must be lodged for each core, tree or timber contributing to any
chronology stored in the ITRDB.

The spatial and temporal distribution of the chronologies identified
at the 1983 meeting is shown for three major regions in Figures 2 and 3.
The most diverse and dense network is to be found in Western North America
(Figure 2). This has been extensively documented in the published literature
but accounts by Brubaker (1982), Cropper (1984) and Fritts and Shatz (1975)
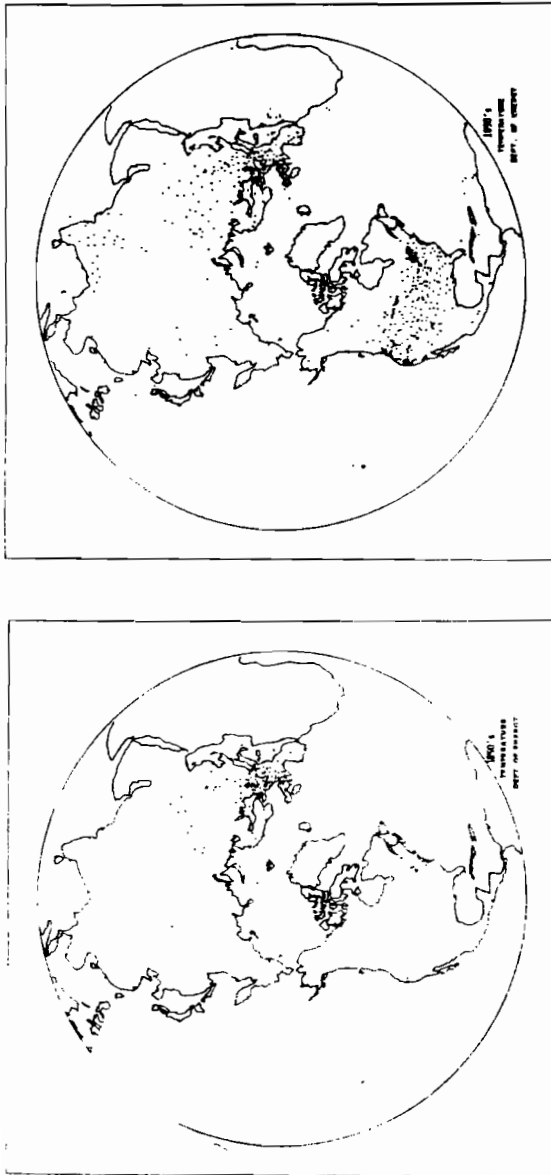are of particular relevance to our present concerns. The only extensive

FIGURE 1 Distribution of temperature recording stations in the U.S. Department of Energy Data Bank. Stations shown operated for at least six years in the decade indicated and continued at least as far as 1960. Left : the 1850's; Right: the 1880's. (Reproduced from Bradley et al, 1985).
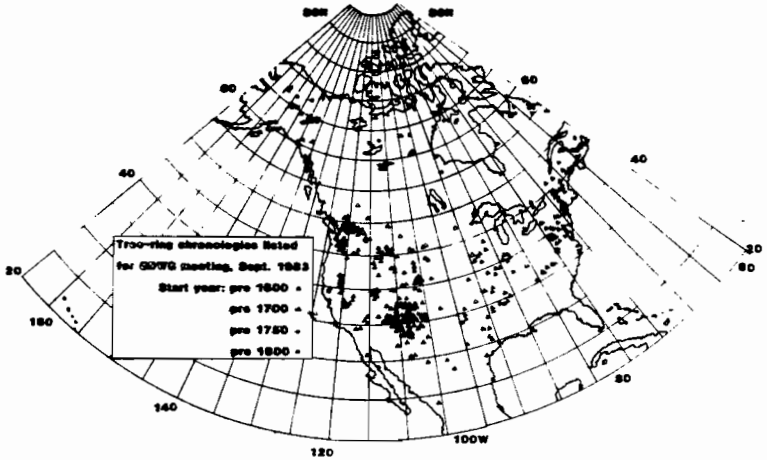
FIGURE 2 North American tree-ring chronologies listed for the Global
Dendroclimatology Working Group meeting, 1983. The division between 'West-
ern' and 'Eastern' North America referred to in the text is at 100 degrees
West.

region poor in chronologies in 1983 was western Canada. There are many
chronologies commencing before 1600 A.D. in Western North America, and a very
high proportion predate 1700 A.D. There is a relative shortage of pre-1750
A.D. chronologies in the far north. An enormous range of ecological condit-
ions is represented, from the northern and high altitude tree-lines to semi-
arid sites in the American South-west and Mexico. Even so, the overwhelming
majority of these chronologies meet all the ITRDB criteria mentioned above
and have been produced by a common system of standardisation and averaging
(Fritts, 1976).

The network of chronologies for Eastern North America (Figure 2) has
been developed more recently than its western counterpart (Cook, 1982;
Conkey, 1982; DeWitt and Ames, 1978), but was already extensive and diverse
by 1983. Almost all chronologies start before 1700 A.D., and many before
1600 A.D. The raw data for this dataset are generally stored in machine-
readable form, as are those for western North America, and so are susceptible
of treatment by newly emerging techniques for standardisation and chronology
preparation. There has been a development of such new methods in association
with the growth of this dataset (e.g. Cook, 1984). The perceived need for
this arises from the very different growth conditions in mesic, closed
eastern forest stands as compared with the more open stands often sampled in
the American West. A wide range of ecological conditions is represented,
from riverine oaks in the relatively dry mid-West to conifers in mesic sites
in the north-eastern U.S.A. The 1983 survey indicated that the North
American continent was remarkably well provided with a large number of long
diverse and well replicated chronologies that meet the ITRDB criteria and
are suitable for use in dendroclimatology. Most of the North American
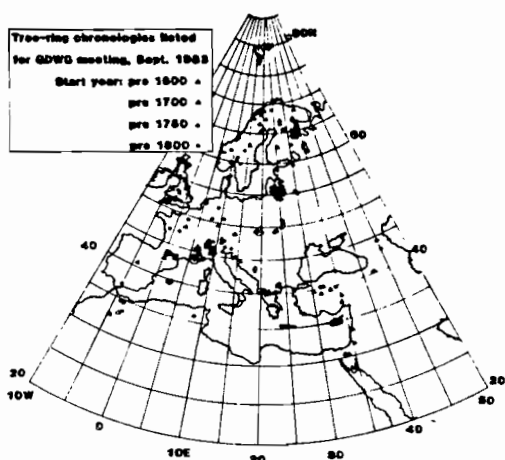
FIGURE 3 European tree-ring chronologies listed for the Global Dendroclimat-
ology Working Group meeting, 1983.

chronologies shown in Figure 2 were either sampled or have been resampled
since 1960.

The situation in Europe was found to be rather more complex. Eckstein
(1982) indicated the most significant reasons for this, namely the small
forest area, taxonomic paucity and intense human influence evident over most
of Europe. Although a considerable number of chronologies were identified
as being potentially suitable for use in dendroclimatology, many commence
only in the eighteenth century (Figure 3). Even in the case of chronologies
markedly longer than this, many of the individual trees included are relat-
ively young. This not only results in poor replication in the early part
of many European chronologies, but may limit severely their value in the
study of low-frequency environmental change. The effects of human activity
extend beyond limiting the availability of old trees to a wide range of
influences associated with forest utilisation over thousands of years in
Europe and the Mediterranean area (Munaut, 1982). This necessitates consid-
erable care in the preparation of chronologies for use in dendroclimatology,
and has been a stimulus for developments in techniques for standardising
tree-ring series analogous to those taking place in Eastern North America
(Braeker, 1981; Briffa, 1984; Guiot et al, 1982).

The apparently available chronologies cover a very wide range of site
conditions, from subalpine to boreal forest and from mediterranean to mari-
time. In contrast to the situation in North America, dendrochronology and
dendroclimatology in Europe have developed in numerous laboratories in
several countries. One important disadvantage of this has been that chron-
ologies have been prepared in a variety of ways and may be recorded in
mutually incompatible forms. In particular, the primary goal of much work
in Europe has been the construction of dating chronologies, usually presented

as mean ring-width series and hence unsuitable for use in dendroclimatology. A further disadvantage of the polycentric development of dendrochronology in Europe has been that if a small laboratory based around an individual scientist closes or changes direction, only minimal information on sites sampled and some form of mean chronology may be all that remains in the literature. This has the effect of making proper resampling and updating of some chronologies built in earlier decades very difficult and limits their usefulness in studies of environmental change. Fortunately, a number of European scientists have lodged considerable volumes of the primary data on which their chronologies were based with the ITRDB, along with precise site information, so that these problems will be much diminished in the future.

The likely availability of chronologies suitable for use in dendro-climatology was reviewed for all of the Northern Hemisphere at the 1983 meeting. The data available to the Working Group members were very much more limited outside the three regions described here, although considerable attention was paid to the prospects for establishing collaboration with scientists in the other areas and for the development of new networks of chronologies.

4. GENERAL CONSIDERATIONS

In any use of tree-rings as records of past environment or of tree performance, it is necessary to construct an appropriate dataset. In the case of IPID the simple collation of a number of chronologies from the literature, for example, would have been quite inappropriate. It is necessary to build site chronologies by methods that maximise the common external signal at the expense of within- and between-tree differences. This in turn means that there must be adequate within-site replication to preserve this common signal at the beginning of the period of interest as well as in recent decades. Briffa et al (1983) demonstrate one method for assessing this. Once such a grid of chronologies demonstrated to be good site records throughout the period of interest is established it becomes possible to explore the properties of the dataset as a whole. It is at this stage that the consequences of producing regional mean chronologies or other condensations of the dataset may be assessed objectively. It is also at this point that the effects of including composite chronologies containing, for example, archaeological timbers, may be considered. The precise provenance of such timbers is rarely known. Hence such composite chronologies are, in effect, small region mean chronologies. These considerations are likely to be of particular importance in regions such as much of Europe where trees older than 300 years are relatively rare.

Whether the primary interest is in tree-rings as records of past climate, other features of the atmospheric environment or of tree performance itself, it is essential that there be a good understanding of the behaviour of the dataset used in both time and frequency domains. This is particularly the case where trend over decades or centuries is of interest. Such an understanding would make it possible to assess what part, if any, of the dataset is likely to yield a reliable record of the components of past environment under investigation. Ideally, the original, unmodified, dated tree-ring measurements should be available for such analysis. The ITRDB is the best means for making data available in this way. If, however, it is necessary to use site chronologies, it is extremely desirable that full details of the methods of chronology preparation, chronology statistics and internal replication throughout the length of the chronology be available.

The consequence of all this is that the effective spatial and temporal coverage given by a tree-ring dataset may be considerably less than a

compilation of apparently available chronologies might indicate.

5. ACTUALLY AVAILABLE DATA

In the period up to spring 1986 the major activity of IPID has been the collation of the hemispheric and regional or sub-continental tree-ring datasets. This is now largely complete for both the hemispheric ("temperature sensitive"), western North American and eastern North American datasets. Extensive further collections have been made in North America in recent years.

Very considerable progress has been made with the European dataset, so that analyses of the properties of the continent-wide tree-ring dataset are now in progress. In fact, the actually available data for Europe constitute an improvement on the apparently available data as assessed in 1983 in both temporal and spatial coverage. This has arisen to a great extent as a result of extensive new and up-dating collections in six countries carried out as part of a project conducted by the Belfast, Liverpool and Norwich laboratories and funded by the Commission of the European Communities. In contrast to the North American case where almost all the available data come from active participants in IPID, significant contributions have been made to the European dataset by other workers. In addition, a number of chronologies have been drawn from the literature.

Whereas good coverage is available for much of North America back to 1600 A.D., there are severe limitations to the coverage in Europe before 1700 A.D. The number of chronologies meeting the ITRDB standards falls from around 70 in the early eighteenth century to around 30, with a limited spatial spread, in the early seventeenth century. If the IPID Europe data set displays strongly coherent patterns of behaviour, then it may be possible to use a smaller, but longer subset to almost equal effect in the study of environmental change. Schweingruber's (In press) analysis of cross-dating throughout Europe suggests that this may be the case.

The major weakness of the existing IPID datasets for the Old World is in their coverage of the U.S.S.R. and Asia. Bitvinskas (1982) has given scientists in Western Europe and North America an introduction to the extensive work of Soviet dendrochronologists and Zheng et al (1982) have discussed potential developments in China. The present meeting constitutes an important opportunity to progress towards the degree of mutual understanding of scientific techniques and objectives needed to facilitate free and informed exchange of primary data.

6. ACKNOWLEDGEMENTS

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5.2 LONG COMPOSITE CHRONOLOGIES AS INDICATORS OF BACKGROUND VARIATIONS IN TREE GROWTH

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1. INTRODUCTION

There is much international interest in the effect of human activities on global climate and the likely long term implications this might have. One of the most powerful tools for studying recent changes in climate is dendrochronology. However, over most of the globe the trees available for this research are seldom more than a few centuries old. For example in a current research programme to study Northern Hemisphere temperature this limitation has restricted the temperature reconstructions to the range AD 1700 to the present (Hughes 1986). While this range is enough to reveal some changes that may be ascribed to the activities of man, it is not a long enough time-span to show the natural range of tree growth variations. An understanding of these variations on a scale of millennia would make the interpretation of recent changes more reliable.

2. LONG COMPOSITE CHRONOLOGIES

Long composite chronologies include non-living trees from a variety of sources. Normally the place where the trees grew is not known even if it can be assumed that they grew close to the site of preservation. Archaeological chronologies are already being used for climate reconstruction studies in the American South West (Rose et al. 1981). This paper explores the few very long chronologies that extend for five or more millennia.

The first very long chronology was the bristlecone pine (<u>Pinus aristata</u>) chronology from the White Mountains in California (Ferguson 1969). This chronology is ideal for a study of natural variations in tree growth as the trees are very long lived and were growing in a restricted area. A further advantage is that there are trees of the same species on the same site today, allowing the use of a modern analogue in the interpretation of the responses of the trees to climate. The only published millennia-scale climate reconstruction based on tree-rings is derived from the bristlecone pine (LaMarche 1974).

In the cool moist climate of western Europe there are no very long-lived trees, but conditions are suitable for the preservation of wood in waterlogged conditions. Laboratories in Ireland and Germany have constructed long chronologies using preserved wood of oak (<u>Quercus petraea</u> and <u>Quercus robur</u>). The longest published European chronology is 7272 years long from Northern Ireland (Pilcher et al. 1984).

2.1. The Belfast Long Chronology

The construction of the Belfast chronology started in 1969 and was completed in 1984. The main impetus for the project was the need for a continuous sequence of samples for radiocarbon calibration. At the time the project started major road construction work was in progress in Northern Ireland. The new motorway linking Belfast with the west of the province passed through the fenland to the south of Lough Neagh. In cutting the trench for the road foundations many hundreds of bog oaks were brought to the surface. These were sampled from the unstratified heaps left by the road builders. There was no indication of the depth from which the trees derived and no indication of age. Similar unstratified heaps of sub-fossil oak were collected from drainage work at numerous other locations in Northern Ireland. It was not possible to start to build a systematic chronology starting from the present and working backwards.

Each sub-fossil site was treated as a unit and studied independently. From each site one or more chronologies was constructed from those trees that cross-dated strongly. In the early years of the project many of these site chronology units, typically of about 500 years length, were radiocarbon dated (Smith et al. 1972). The radiocarbon dates seemed to suggest that the bog oaks were distributed over the whole of the last 7000 years. By 1972 a number of these site chronology units had been linked. In the the mid-1970's land reclamation started on the largest bog in Northern Ireland, Garry Bog, from which many hundreds of bog oaks were recovered. These were found to span most periods from 5000 BC down to 200 BC. By 1977 a floating section of chronology just under 3000 years in length was completed (Pilcher et al. 1977) and used for radiocarbon calibration (Pearson et al. 1977). This chronology spanned approximately 4000 BC to 1000 BC but was still "floating" i.e. not joined to present day chronologies. In addition there were three short chronologies earlier than 4000 BC and a chronology spanning approximately 1000 BC to 200 BC.

While this work was in progress a chronology of living trees and archaeological timbers was being constructed back from the present day (Baillie 1982). The final linking of the sub-fossil and archaeological chronologies is a complex story, well documented elsewhere (Pilcher et al. 1984; Baillie and Pilcher 1986). It was not possible to link the Northern Irish chronology using local timbers. The final links at 1000 BC and 200 BC were made using timbers from England and involved extensive collaboration with workers in Germany.

Long chronologies have also been prepared in Northern Germany (Schmidt and Schwabedissen 1982) and Western Germany (Leuschner and Delorme 1984). Oak wood preserved in river gravels in Southern Germany has allowed the construction of sections of chronology that should soon enable a chronology of over 8000 years to be completed (Becker 1981; Becker and Schmidt 1982; Becker personal communication).

2.2. The sources of sub-fossil oaks

The oak chronologies described above are all formed from trees of relatively short age span, typically 200 to 400 years. In the case of the oaks from bogs it is possible to get some indication of the conditions under which the trees were growing. These conditions have few modern analogues as the peat bogs of the present day do not normally carry oak woodland. From pollen analysis and study of the peat it is possible to envisage a very wet woodland of oak, alder (Alnus) and willow (Salix). On the other hand, the river gravel oaks were trees of dry land that were carried by the river, perhaps some distance before being buried.

In addition to these variations in conditions of growth and preservation of the sub-fossil trees, most of the very long chronologies depend on archaeological samples to bridge the gap between living trees and the sub-fossil trees. In the case of the Belfast chronology the time span between 200 BC and 1650 AD was built mostly from archaeological samples. A similar situation pertains in the German chronologies. For this reason only the section of chronology before 200 BC will be used in the analysis that follows.

3. LONGER PERIOD VARIATIONS IN A 7000-YEAR OAK CHRONOLOGY

One may be able to reconstruct climatic fluctuations from a long chronology without even considering the ring-widths of the trees themselves. The sub-fossil timbers collected from many different sites in Ireland are not uniformly distributed in time - it is difficult to find trees from some periods. Baillie (1982, p.231) has suggested that changes in rainfall were responsible for this effect, since trees growing on bogs could be killed by fluctuations in the water table; this might not be a simple matter of trees being drowned by high rainfall, since they will also have been limited by the supply of nutrients. Figure 1 gives the number of trees included in the first section of the Belfast chronology for each year, and clearly shows these periods of scarcity and abundance.
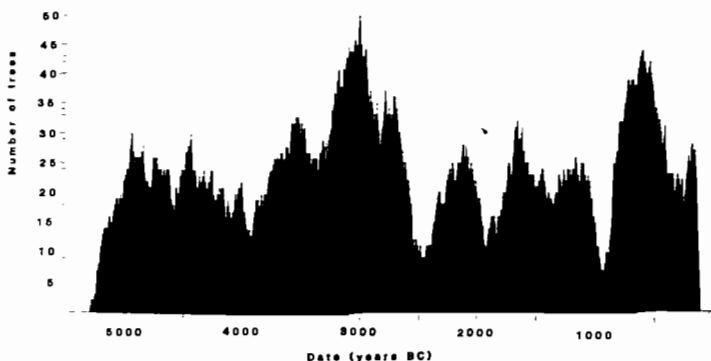
FIGURE 1   The number of trees included in the first section of the Belfast long chronology.

3.1. Long-period ring-width variations

If climatic changes caused these fluctuations they should also have affected the ring-widths, and should appear as long-period variations in a chronology, provided that these are not removed when it is being built. Unfortunately if each tree is standardized before inclusion (e.g. by converting it to a percentage deviation from some function fitted to the ring-width series) it will be difficult to detect some variations, such as a period of several centuries when all trees had narrow rings.

Accordingly we built the full 7272 year Belfast chronology as the arithmetic mean of the unstandardized ring-widths. Figure 2 shows two sections of this chronology that have been smoothed using a filter that halves frequencies with a period of 30 years and has a narrow transition band (almost completely eliminating frequencies with periods less than 20 years). Surprisingly, the long-period variations in the chronology do not seem to coincide with the maxima and minima of Figure 1. For example the lower part of Figure 2 covers the rise to (and fall from) the highest peak of Figure 1, but shows no corresponding trend.
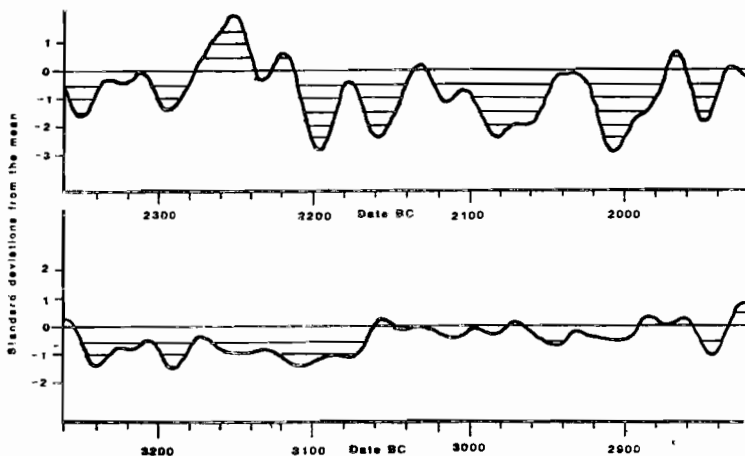
FIGURE 2 The mean version of the Belfast long chronology filtered with a 30yr low-pass filter - two periods.

3.2. Medium-period ring-width variations

There are remarkable medium-period variations in this chronology, noteably those shown in the upper part of Figure 2 where the deviations from the mean of the whole chronology reach levels that can only be paralleled in the last 250 years (when the chronology includes living trees from the unusual environment of carefully managed parkland). Could this reflect some climatic influence? There are two objections to this: the growth trend of the individual trees included in the chronology might cause such variations (particularly if several trees entered or left the chronology at the same date), and if there was a period when most of the trees came from a single site one might expect that strictly local changes could be responsible (the effects of erosion or silting on the hydrology of a single bog, for example).

The first objection could be disposed of by changing from mean to index chronologies, losing the lowest frequencies but also eliminating the effect of trees entering or leaving the chronology, and showing that the variations occured on several unconnected sites would meet the second
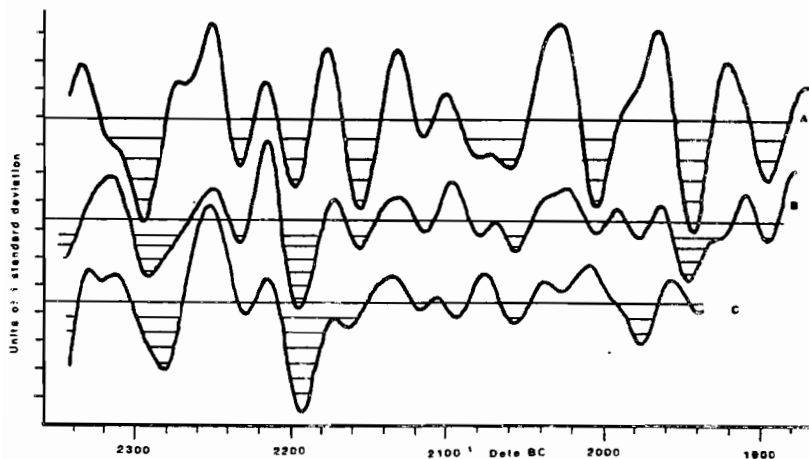
FIGURE 3 Site index chronologies filtered with a 30yr low-pass filter.
A - Ballymacombs More; B - Garry·Bog; C - Randalstown.
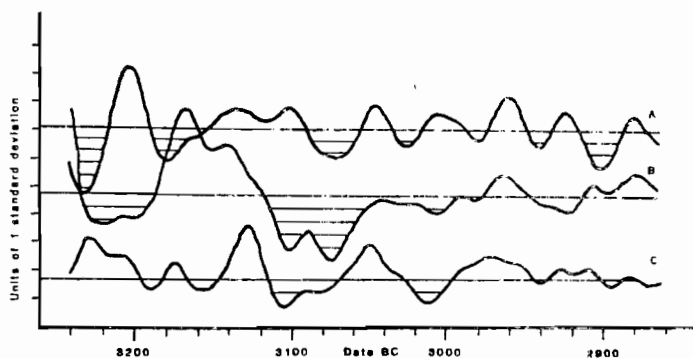
FIGURE 4 Site index chronologies filtered with a 30yr low-pass filter.
A - Lisnisk; B - Balloo; C - Garry Bog.

objection. Figure 3 is an attempt to do this by decomposing the mean
chronology into three index chronologies from unconnected bogs in
different parts of Northern Ireland. The INDEX program from the
Laboratory of Tree-Ring Research in Tucson (Graybill 1984) produced tne
indices (percentage deviations from a fitted polynomial), and the same
filter used on the mean chronology removed the high frequencies. The
three chronologies show clear synchronous variations corresponding to
those in the mean chronology, strongly suggesting an external cause.

However not all periods contain these clear patterns: Figure 4 shows three index chronologies from sites that helped to make up the section of mean chronology at the bottom of Figure 2, and in this case very few of the variations are synchronous. Either the events that produced large variations in ring-width only occured once, during a interval of four centuries at the end of the third millennium BC, or there were only a few chronologies that responded to climatic changes by medium-period changes in ring width, so that these were masked by the random variations of the other chronologies except during this interval. In any case there are certainly no stationary low or medium frequency cycles in the full Belfast chronology, since the power spectra of pairs of contiguous 512 year blocks taken from it are seldom similar at the lower frequencies, and neither are those of individual site chronologies.

4. CONCLUSION

Spatially coherent medium frequency growth rate variations can be demonstrated in oak tree-ring chronologies for at least some periods of the post-glacial. These variations are on a time-scale comparable with the effects of acid rain and those of CO_2 mediated global warming.

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5.3 SOME REGULARITIES IN THE DYNAMICS OF THE RADIAL INCREMENT OF THE SCOTCH PINE WITH RESPECT TO SPATIAL-ECOLOGICAL FACTORS OF THE WESTERN REGIONS OF THE SOVIET UNION

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1.   INTRODUCTION

In the Institute of Botany of the Academy of Sciences of the Lithuanian SSR and in the Lithuanian Scientific Research Institute of Forestry, extensive and diverse dendrochronological investigations of the Scotch pine, Norway spruce, English oak and some other local and introduced species have been carried out. The Scotch pine (*Pinus sylvestris L.*) is considered as one of the most widely used species for dendrochronological investigations. Its wood is suitable for such investigations, because it has a distinctly marked structure of the early and late wood. As far as the ecology of habitats is concerned, the Scotch pine is a plastic species — it grows in sands, peat bogs, highlands. This is a widely geographically spread boreotemperate Eurasian species. Thus a diversity can be expected both in the quantitative value of the radial increment of trees and in its cyclic dynamics.

2.   DENDROCHRONOLOGY OF THE SCOTCH PINE IN LITHUANIAN SSR

If possible, during an investigation of the population of a species, a definite area of investigation, not separate trees, is regarded. The investigation has the aim to involve both exogenous and endogenous factors which influence the growth the plant community.

Using the Scotch pine data, the analysis is made of such exogeneous factors as dependence of the increment on temperature and precipitation (Bitvinskas, 1978a; Karpavicius, 1978), the relation between increment cycles and cycles of the solar activity (Stupneva and Bitvinskas, 1978), and cycles of moist periods (Pakalnis, 1978) and others. Among the exogeneous factors of pine populations we distinguish biogeocenosis factors, and firstly, those of soil and phytocenosis. This is clear from a comparative analysis of the Scotch pine date from moors and from normal conditions (Karpavicius, 1981; Bitvinskas, 1984).

The influence of endogenous factors which cause differences in the growth and in the dynamics of increment among the trees of different phytocenosic significance in the population was studied. The increment of dynamics was analyzed according to the tree classes by Kraft, or to selective classification of trees in the populations or in the forest stands. Finally, both exogeneous and endogeneous factors have a complex influence and manifest themselves through the general indices of the growth of trees.

3.

PROFILE METHOD IN DENDROCHRONOLOGY

To reveal the regularities of the Scotch pine, radial increment dynamics investigations were carried out in various points of the vast natural habitat along the lines North—South and West—East. The Scotch pine radial increment investigations along the Murmansk — Carpathians line (see Figure 1) were carried out in the Dendroclimatochronological Laboratory at the Institute of Botany, Academy of Sciences of the Lithuanian SSR in Kaunas. Investigations were carried out in 41 sites, and annual rings of 2692 trees were studied.

The profile includes the entire Scotch Pine habitat along the geographical latitude. In more southern parts the Scotch pine can be met only in highland as well as in the Carpathians. This is a whole forest belt, from the tundra to the steppe. The whole profile is in the suboceanic region (Meusel et al., 1978). Along the profile, considerable changes in growth conditions are apparent both in climate and soil. According to the botanical-geographical classification of the European part of the USSR, the habitat of the Scotch pine covers the whole latitude of the northern taiga province (see Figure 1)(Isachenko and Lavrenko, 1980).

One of the tasks of the investigation along the whole profile was to check the correlation between its cyclic and 22-year cycle of the Solar activity. The results witnessed the expectation that the width of yearly tree-rings noticeably decrease from the South to the North. The age dynamics characteristics of the increment change noticeably (see Figures 2 and 3).

4.   THE ACCELERATION EFFECT IN THE LOWER LATITUDES

In the northern part increment value changes little on the whole life-time of the trees (see Figure 2; the investigation sites 1 and 2). It is characteristic to the whole northern group of the profile (sites 9, 10, 12 and 13). In the middle part of the profile (sites 20—31) a noticeable decrease of the increment value takes place at the end of the period of investigation, i.e., when the trees mature (Figures 2 and 3). There are sudden changes in the character of curves in the investigation sites of Southern Lithuania, between 30, 31 and 32, 33 investigation sites. This is explained by a qualitative change of site conditions, which is confirmed by forming the boundaries of the phytogeographical provinces and subprovinces at that latitude (Figure 1).

Further to the South (sites 38—41) increment curves show very sharp recession of the yearly increment value (Figure 3). This is linked with the acceleration of biological processes under the most favorable growth conditions. In the South the growth is intensive, but natural maturity of forests comes earlier. In the North, the growth is slower but ageing is less noticeable and longer.

It is quite natural that the longest series involving 273 and 357 years were successfully made in the northern part of the profile (investigation sites 1 and 2) in the Kola Peninsula and 271—354 years in northern Karelia (sites 3—9). In the southern part of Byelorussia and the Ukraine, the longest series involved 150—198 years (sites 32—37).
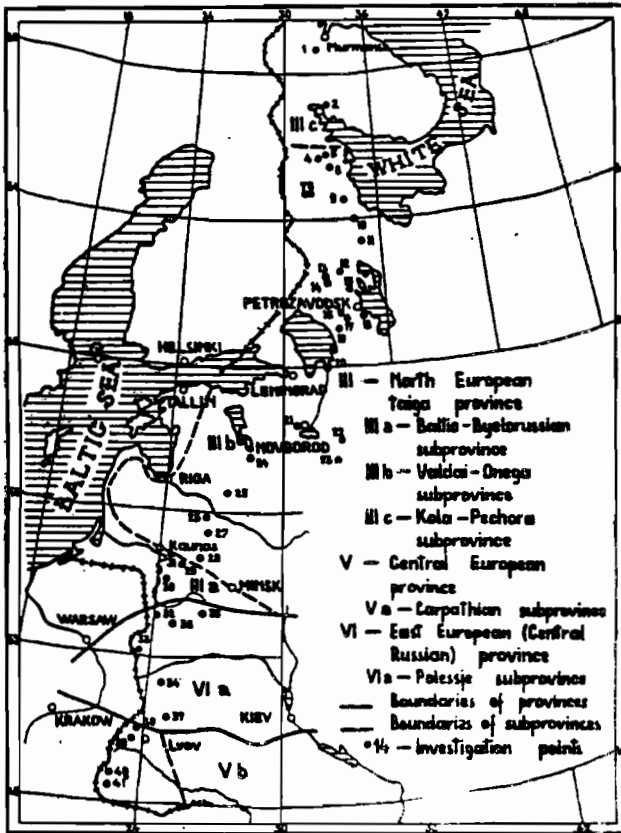
Figure 1. Location of the investigation sites along the Murmansk - Carpathi
ans profile.

In the lower latitudes both physical and biological phenomena manifest
acceleration and distinctness, for example alternation of day and night,
maturing, ageing, etc. With regard to vegetation, the main criterion is the
intensity of the main vital processes, i.e., assimilation and metabolism. The
faster those processes proceed, the faster the plants go through the life cycle
and more abruptly complete it.

Figure 2.   Series of the annual tree-rings width in the northern part of the
Murmansk – Carpathians profile: Kola Peninsula, Karelia, Novgorod
region. The figures in the right-hand column indicate the numbers
of investigation sites.

Along the Murmansk–Carpathians profile, 20–22 cycles prevail in the
northern part. However, 30–33 year cycles take place in the peat bogs of
northern Karelia (Stupneva and Bitvinskas, 1978). In the Lithuanian SSR part of
the profile, 20–22 year cycles are distinct on peat bogs only, and an
approximately 11-year cycle is distinguished under normal site conditions (see
Figure 4) (Bitvinskas, 1984). In the southern part of the profile, an appoximately
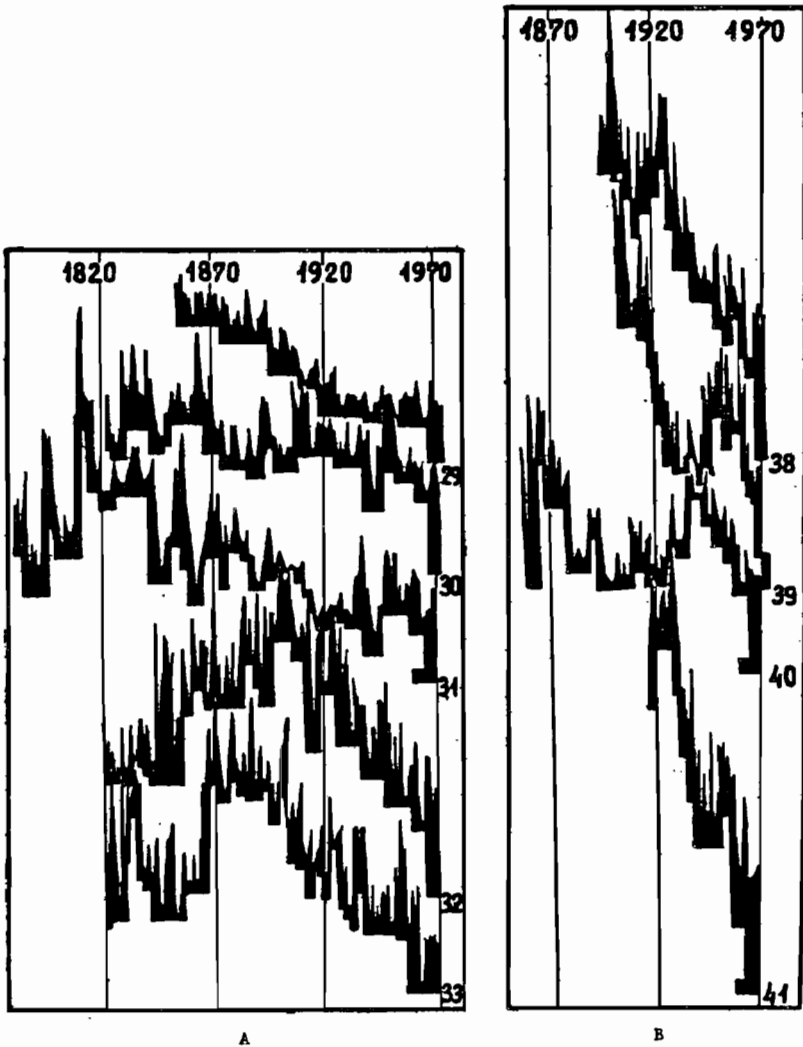
Figure 3.   Series of the southern part of the Murmansk — Carpathians profile:
A — Lithuania, Byelorussia; B — the Ukraine.

The figures in the right-hand column indicate the numbers of inves-
tigation sites

11-year cycle remains as well, and a 6-7 year cycle shows up slightly (Stupneva and Bitvinskas, 1978).
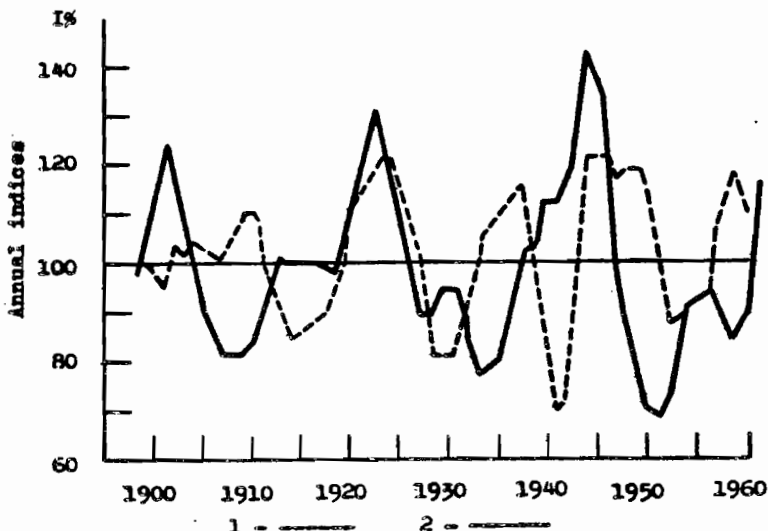
Figure 4.   Radial increment dynamics in various sites of the Lithuanian SSR:
1 — in normal sites; 2 — in upland moor.

It is well-known that geographical zones and mountain belts exert a similar influence on the vegetation types. Extremely adverse site conditions, which are far from normal, can also be met at the same latitude and altitude above sea level. For the Scotch pine it is an upland moor.

An azonic phytocenosis growing in the upland moors of a temperate zone has representatives of northern vegetation. For example, in Lithuanian, in the middle part of the profile in upland moors one can meet such boreal species as *Betula nana* L., *Rubus chamaemorus* L., *Carex chordorhiza* L., *C. limosa* L., *C. loliacea* L., *C. pauciflora* Lightf., *C. paupercula* Michz., *Trichophorum caespitosum* (L.) Hartm. and others.

It should be noted that according to the dynamics of the radial increment, the Scotch pine growing in the upland moors of Lithuania behaves similarly to that growing in northern Karelia. According to the characteristics of the growth dynamics, the increment of the Scotch pine in the upland moors seems to be more to the North by one phytogeographical category.

5.   CONCLUDING REMARKS

Cyclic regularities of the radial increment differ among plant populations of the same species growing in remote regions according to the geographical latitudes. We can observe the same effect in nearby habitats even if they have extremely different environmental conditions.

In the taiga forests of the western part of the European SSR, the Scotch pine growing in optimal conditions of the central part of the natural habitat has a distinctive 22-year cycle, i.e., the cycle of the Solar activity. The regularities of the radial increment dynamics for other species of the forest zone in the whole natural habitat and in sites beyond the borders of the entire habitat should be studied.

Using a wider material, conclusions could be made about general regularities of the radial increment dynamics, and better data comparisons of investigations carried out in the remote and qualitatively different habitats could be made as well. To describe the biological productivity, radial increment cycles should be studied in typical sites of the region. Samples taken from non-typical sites may show regularities peculiar to other regions, but not to those under investigation.

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5.4 THE EUROPEAN DATA BASE AT THE EAFV[*]

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1.1 Aim of data base:

A network of tree sites of subalpine and boreal vegetation type has been established at the EAFV. At each site tree-ring data based on a uniform plant association have been compiled to form a chronology for the relevant conifer species. The aim of the data base is primarily to allow a climatic interpretation, although the data can be used in ecology, forest economics, or environmental research. Today the network consists of 130 European chronologies, concentrated in the Pyrenees, the Appennines, the Dinaric Alps, the Pindus Mtns. and Balkan Mtns., the Alps, the Carpathians and the Tatra Mtns., Scandinavia and Scotland. The commonest genus /species are: Pinus /silvestris (PISY), Abies /alba (ABAL), Picea /abies (PCAB).

1.2 Sample selection:

A Swedish increment borer (5 mm diam.) was used to take two cores from each of the 10 to 15 dominant or co-dominant trees at each site.

1.3 Data acquisition:

The preparation of the cores for measurements and the X-ray densitometric measuring procedure as well as the dating of the time series were all done by the same person (see LENZ ET.AL., 1976).

1.4 Data transformations:

To build up site chronologies, the raw values, including long-term variations due to aging, are transformed to indices. As the main function for the aging process, the "Hugershoff" function ($Y = a0 * t^{**}a1 * e^{**-t*a2}$; $t=$ time; $a0,a1,a2 =$ coefficients; see BRAEKER, 1981) is smoothed to each of the core data with a least aqusre procedure . The indices are calculated for widths as quotients of raw value and smoothed value, for densities as residuals of the above two values. The chronology is constructed from all indexed core series from each site which crossdate significantly ($=95\%$). Crossdating is checked by correlation coefficients and the Gleichläufigkeits-test (sign test of intervals, percentage of agreement).

1.5 Chronology data:

The network of chronology data is being published in series (with microfiches; magnetic tapes available on request).
Vol.1: Iberische Halbinsel, is available now (BRAEKER,SCHWEINGRUBER, 1984),
Vol.2: Appenninen-Halbinsel, Vol.3: Balkan-Halbinsel, Vol.4: Grossbritannien are in preparation.

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[*]EAFV = Eidgenössische Anstalt für das Forstliche Versuchswesen

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Region					
Location	Country	Lat./Long./Elev. deg.+min.	m/s.l.	Species code	Chronol. IDENT
Pyrenees:					
Bosque de Rabassa	AND	4232N00130E	2100	PIMU	RABAS
Alcala de Selva	E	4023N00040W	1960	PIMU	ALCA
Calvero,S.d.Gredos	E	4016N00536W	1400	PISY	CALVE
Las Blancas, Jaca	E	4241N00034W	1760	PIMU	JACA
Puerto da Navacerrada	E	4048N00402W	2050	PISY	NAVA
Torrecilla, Ronda	E	3640N00505W	1650	ABPI	RON TA
Turbon, Ordessa	E	4240N00007W	1870	PIMU	ORDES
Arette, Col St. Martin	F	4259N00045W	1500	ABAL	ARET
Formigueres	F	4236N00204E	1700	ABAL	FORMI
Llipodere	F	4227N00223E	1950	PIMU	LLIPO
Miraules Refuge, Prades	F	4228N00224E	1720	ABAL	MIRAU
Pic Aubas	F	4246N00037E	1800	PINI	AUBAS
Pic d'Anie, Biarritz	F	4258N00044W	1750	PIMU	ANIE
Roc de Perches Blancas	F	4236N00203E	2100	PIMU	PERCH
Appennines:					
Col de Sorba, Korsika	F	4204N00912E	1400	PINI	SORBA
Vizzavona,Korsika	F	4205N00912E	1500	ABAL	VIZZA
Abetone	I	4407N01042E	1400	ABAL	ABET
Aetna,Linguaglossa	I	3747N01503E	1800	PINI	AETNA
Ceppo,Bosque di Martense	I	4241N01326E	1700	ABAL	CEPPO
Gambarie, Aspromonte	I	3810N01555E	1850	ABAL	ASPRO
Monte Mattone, Abruzzo	I	4147N01402E	1550	PINI	MATT
Mt.Falterona, Firenze	I	4352N01140E	1450	ABAL	FALT
Mt.Pollino, Kalabrien	I	3954N01612E	1720	ABAL	POLL
Sierra da Crispo,Mt.Poll.	I	3954N01614E	2000	PILE	CRISPO
Balkans:					
Sipenski prohod,Kazanlak	BG	4244N02520E	1300	PCAB	KAZAN
Vihren Nat.Park	BG	4146N02323E	1920	PILE	VIHREN
Katara Pass, Metsovon	GR	3948N02113E	1750	PILE	KATARA
Langada (Sparta)	GR	3705N02220E	1450	PINI	LANGAD
Menalon Oros	GR	3738N02217E	1620	ABCE	MENALO
Olympos Oros	GR	4005N02225E	2250	PILE	OLYMP
Panetolikon-Oro	GR	3843N02140E	1350	ABBO	PANET
Capra,Munt Agarasului	R	4533N02440E	1600	PCAB	CAPRA
Novaci	R	4518N02340E	1650	PCAB	NOVACI
Roncan, Gium Vau	R	4727N02528E	1480	PCAB	RONCAN
Cakor Pass, Pec	YU	4238N01956E	1750	PCOM	CAKOR
Jahorina, Sarajevo	YU	4345N01838E	1700	PCAB	JAHOR
Pelister Nat.Park	YU	4101N02111E	1900	PIPE	PELIST
Rajinac, Senj	YU	4450N01500E	1550	PCAB	SENJ
Vlasic, Travnik	YU	4418N01735E	1600	PCAB	VLASIC
Vrsic,Krajanska Gora	YU	4628N01345E	1600	PCAB	VRSIC

Region Location	Country	Lat./Long./Elev. deg.+min.	m/s.l.	Species code	Chronol. IDENT
Great Britain:					
Ballochbuite	GB	5659N00319W	381	PISY	BALLO
Coulin	GB	5732N00521W	250	PISY	COUL
Dimmie, Blargowie	GB	5607N00320W	200	PISY	DIMM
Franchise Wood, Cadnam	GB	5057N00141W	100	PISY	FRAN
Glen Affric, Inverness	GB	5717N00455W	300	PISY	AFFRI
Glen Derry	GB	5701N00334W	457	PISY	DERRY
Inverey, Braemar	GB	5700N00335W	500	PISY	INVER
Loch Maree	GB	5738N00520W	100	PISY	MAREE
Mallaig,Loch Morar	GB	5658N00545W	20	PISY	MALLA
Mar Lodge, Braemar	GB	5659N00330W	400	PISY	MARLO
Mar Lodge, Braemar	GB	5659N00330W	400	LADE	MARLOL
Plockton	GB	5720N00540W	100	PISY	PLOCK
Shieldaig	GB	5730N00537W	12	PISY	SHIEL
Scandinavia:					
Lofoten,Loedingen	N	6829N01602E	200	PISY	LOFOTN
Narvik	N	6829N01744E	50	PISY	NARVIK
Skibotn	N	6915N02035E	80	PISY	SKIBOT
Skjerstad, Bodö	N	6704N01527E	40	PISY	SKJER
Tua,Steinkier	N	6357N01053E	300	PISY	TUA
Veolia	N	6125N00859E	880	PISY	VEOLIA
Arjeplog	S	6604N01759E	600	PCAB	ARJEPL
Duvberg, Sveg	S	6204N01420E	550	PCAB	DUVBER
Fjäll,Glaskogen Naturres.	S	5928N01224E	250	PISY	FJAELL
Gallejonr,Glommerstärk	S	6510N01928E	480	PCAB	GLOMME
Middagsberg.Myckelgensj.	S	6321N01859E	280	PCAB	MYCKEL
Nyteboda	S	5609N01404E		PCAB	NYTE
Tothumeln	S	6325N01311E	700	PCAB	TOTHUM
Vemdalskalet	S	6230N01359E	800	PCAB	VEMDAL
Haaparava,Nat.Park	SF	6235N03110E	145	PISY	HAAPAR
Iso Syete	SF	6537N02736E	300	PCAB	ISOSYE
Koliberg	SF	6306N02529E	300	PCAB	KOLIBG
Kovero	SF	6150N02329E	180	PCAB	KOVERO
Kyynärä, Liesjärven	SF	6040N02353E	115	PCAB	KYYNRA
Laagennus,Pyhänturin	SF	6700N02707E	320	PISY	LAAFOE
Laagennus,Pyhänturin	SF	6700N02707E	270	PCAB	LAAJEN
Oulnangan	SF	6622N02926E	260	PCAB	OULUAN
Palasjärvi	SF	6802N02406E	270	PCAB	PALASJ
Pyhan Hakin, Jyvaskyla	SF	6251N02529E	185	PISY	PYHHAK
Rokuan, Ouken Lääni	SF	6433N02631E	150	PISY	ROKUAN
Alps:					
Katscherpass	A	4702N01338E	1800	PCAB	KAT.PA
Mariazell	A	4747N01518E	1380	PCAB	MARIAZ
Stubaital	A	4708N01117E	1850	PICE	STU.AR
Stubaital	A	4708N01117E	1850	PCAB	STUBAI
Arosa GR	CH	4648N00941E	2000	PCAB	AROS.S
Arosa GR Rot Tritt	CH	4648N00941E	1940	PCAB	AROS.N
Grindelwald BE	CH	4636N00804E	1370	PCAB	GRWALD
Lauenen BE Brüchli	CH	4625N00719E	1500	PCAB	BRUECH

Region Location	Country	Lat./Long./Elev. deg.+min. m/s.l.	Species code	Chronol. IDENT

Alps: (continued)

Monte Generoso TI	CH	4556N00901E 1600	PCAB	M.GEN.
Riederalp VS Aletschwald	CH	4624N00801E 2000	PICE	ALE.AR
Riederalp VS Aletschwald	CH	4624N00801E 2000	PCAB	ALE.FI
Riederalp VS Aletschwald	CH	4624N00801E 2000	LADE	ALE.LA
Riederalp VS Binna	CH	4622N00802E 1800	PCAB	BINNA1
Riederalp VS Binna	CH	4622N00802E 1800	LADE	BINNA2
Rigi Klösterli SZ	CH	4702N00829E 1400	PCAB	RIGI K
Rigi Staffel SZ	CH	4703N00829E 1600	PCAB	RIGI S
Col d'Allos	F	4416N00634E 1900	PCAB	C.ALFI
Col d'Allos	F	4416N00634E 1900	ABAL	C.ALTA
Le Tournairet, Meeralpen	F	4352N00720E 2050	PCAB	TOURN
Mt.Cenis, Ht.Maurienne	F	4516N00655E 1950	PCAB	M.CEN.
Nizza,Foret d'Aillon	F	4353N00720E 1700	PCAB	NIZ.FI
Nizza,Foret d'Aillon	F	4353N00720E 1700	ABAL	NIZ.TA
Blumone,Malga, Trentino	I	4553N01025E 1650	PCAB	BLUM
Cortina d'Ampezzo	I	4632N01204E 1820	PCAB	CORT.N
Cortina d'Ampezzo	I	4632N01204E 1900	PCAB	CORT.S

Jura Mts.:

Chasseral NE Jura	CH	4708N00705E 1500	PCAB	CHAS.N
Chasseral NE Jura	CH	4707N00705E 1400	PCAB	CHAS.S
Lac de Bourget Jura	F	4553N00544E 1340	PCAB	L.BOUR

additional:

Andreasberg,Harz	D	5143N01034E 900	PCAB	ANDRB.
Gasienicowy, Hohe Tatra	PL	4915N01955E 1500	PCAB	GASI.
Swistowko, Hohe Tatra	PL	4915N01955E 1500	PCAB	SWIST
Baikalsee, Irkutsk	SU	5336N10500E 700	PISY	IRKUT
Troodos,Zypern	CY		PINI	TRODOS

Alps: W.Lingg

Bürchen VS Bielwald	CH	4617N00750E 1740	PCAB	BBW FI
Bürchen VS Bielwald	CH	4617N00750E 1740	ABAL	BBW TA
Bürchen VS Mittl.Hellela	CH	4619N00750E 1510	PCAB	MHW FI
Bürchen VS Mittl.Hellela	CH	4619N00750E 1510	ABAL	MHW TA
Leuk VS Bannwald Nord	CH	4620N00738E 1240	PCAB	BWN FI
Leuk VS Bannwald Nord	CH	4620N00738E 1240	ABAL	BWN TA
Leuk VS Bannwald Süd	CH	4620N00738E 1230	PCAB	BWS FI
Leuk VS Bannwald Süd	CH	4620N00738E 1230	ABAL	BWS TG
Leuk VS Bannwald Süd abst	CH	4620N00738E 1230	ABAL	BWS TK
Leuk VS Susten Zänd	CH	4618N00737E 840	PCAB	ZND FI
Leuk VS Susten Zänd	CH	4618N00737E 840	ABAL	ZND TG
Leuk VS Susten Zänd abst.	CH	4618N00737E 840	ABAL	ZND TK
Niedergesteln VS Stockw.	CH	4620N00747E 1850	PCAB	STW FI
Niedergesteln VS Stockw.	CH	4620N00747E 1850	ABAL	STW TA

29.5.1986/oub

6. PREDICTING FUTURE GROWTH TRENDS FROM TREE-RING SERIES

6.1 A DENDROCHRONOLOGICAL APPROACH TO FORECASTING

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Description, explanation and prediction are the basic functions of each field of the science. To make solution of many problems more efficient, preventive information is necessary. Ecological forecasting by which is meant forecasting of ecological systems on varios organization levels is growing in importance for
rational use and conservation of natural resorces.

If dendrochronology is a science of an ecological profile
(section of bioindication), then it has every right to prediction,
especially as tree-ring chronologies contain unique retrospective
information. Dendrochronological forecast is a group of ecological
forecast based on tree-ring data. The principal object of dendrochronological prediction is forecasting changes in tree increment estimates. Knowledge of functional relations and correlations between
growth indices, environmental factors and natural processes allows
also a qualitative or quantitative prediction of the latter. The
commonly used reconstraction of natural conditions of the past
from tree-ring data may be termed "retroprognosis".

Common methods of ecological predictions and approaches used
in predictions of dynamic systems may be applied. It is necessary
to take into account the peculiarities of dendrochronological series, which are discrete time series and reflect the influence of
envirinmental and common factors, mainly climatic ones. Specific
characteristics of these series are also the relations caused by
the effect of the increment value and previous growth conditions
on the growth of the current year, and possibility of statistical
estimation for particular years.

Although the problem of dendrochronological forecasting was
stated by F.N.Shvedov (1892) and A.E.Douglass (1928,1936) as early
as the end of the past and the beginning of the current centuries,
advances in this field are not considerable. Up to now the attention is mostly drawn to the reconstruction of natural processes, that
is to retroprognosis.

Methodological approaches used in dendrochronological predictions may be divided into intersystemic and intrasystemic (or parametric) ones. The essence of the intersystemic approach is to use

the dynamics of one system (predictor) for forecasting another system dynamics (predictant). The parametric approach is based on the use of intraseries relations in the dendrochronological series.

The intersystemic approach shows more promise and often used in the dendrochronological forecasting. It is necessary to note, that both systems should interact, the predictor system should be ahead of the predictant one in time or parameters, and they should originate from the same source. Prediction systems are dynamical series of the sun activity, lunar and solar atmospheric tides, growth limiting factors and dendrochronological series themselves.

Possible correlations between different estimates of the sun activity and the tree growth are of the great interest up to now. It is not occasional. Their existence would support the hypothesis that the sun activity affects geophysical and biological processes. Moreover, the sun activity series are rather long and cyclic fluctuations are clearly seen in the estimates. There is much experience in long-term predicting of the sun activity.

The review of literature shows that relations between the sun activity and the tree growth are distinct in some regions, in others they are less pronounced, and in some regions they are absent at all. The pattern and narrowness of relations greatly depend on phases of the sun activity. The correlation sign may unexpectedly change. Various phase shifts have been observed. This presents dificulties in using the sun activity estimates as predictors. To obtain more reliable correlations many authors transform them. I suggest that in those regions, where correlations are sufficiently stable in time, they may be used for dendrochronological forecasting. However, it is dificult to expect much success from this method untill the sun activity mechanism influencing on natural processes on the Earth is known.

The promising method which allows to predict the most anomalous hydrometeorological and tree growth estimates is to use maximal lunar and solar atmospheric tides as a predictor (Javorski,1975,1977). The tides produce blocking anticyclones and sharp changes in atmospheric circulation. The zone of the anticyclone attack becomes droughty with increased precipitation around its periphery. The range of the maximal atmospheric tides is 300-500 km in the longitude. If atmospheric tides arise over the precipitation forming regions (over North Atlantics, for example) vast territories may become arid. Sharp changes in the redistribution of precipitation and temperature course affect the tree growth. Therefore, growth indices and atmospheric tidal intensity correlate rather well. Dendrochronological series are usually long-term and

therefore are used to reveal such correlations (Javorski,1977). Calculations of lunar and solar atmospheric tides can be made many years in advance. Thus, by applying this method it was managed to successfully predict the droughts of 1972 and 1975 in the USSR. Many cyclic fluctuations in tree growth estimates from two to some hundred years are supposed to result from the effect of the atmospheric tides.

If we had reliable prediction of environmental factors, which determine tree growth, then tree growth forecasting would be easier and more reliable, especially for the regions with one or two limiting factors. Since long-term predictions of hydroclimatic factors are lacking or not reliable, their use as predictors is impossible so far. At present dendroclimatological series serve in the main to reconstruct the most important climatic factors (retroprognosis) and evaluate the adequation of the prediction models. Of great help in revealing correlation between growth indices and hydroclimatic factors may be the procedures employing some self-training systems (Rozenberg,Feklistov,1982).

During reconstruction of natural conditions of the past a dendrochronological series serves as a predictor. It may be a predictor to any other time series, if there is a stable and reliable relation between them, but which is shifted in time.

If we use the parametric method, one should know the extent to which the determined, regular random and purely random components are displayed in the series. There is disagreement about a determined component in dendrochronological series. Some authors claim that cyclic components may be regarded as determined only. Others do not entertain this idea and apply the methods of the theory of random stationary sequences in the analysis of cyclic components. Theoretically. the parameters of the regular random components should be predicted from the probabilistic model. But such models have not yet been developed in dendrochronology and predictions are made based on determined models, which approximate and extrapolate the observed fluctuations by sinusoids.

Intraseries development regularities are impossible to study and use for prediction purposes if sufficiently long-term series are not available. In this respect dendrochronological series have advantage over hydroclimatic ones. Accounting of prolonged cyclic fluctuatuons of growth indices is very important, so proper techniques of tree-ring standardization should be used. It should be noted, that parametric methods are less appropriate if significant qualitative changes in the predicted system are expected in future.

The cyclic procedure is most generally employed in dendrochrono-
logical forecast. It is based on revealing, approximation and extrapo-
lation of the most important cyclic components. Each series usually
contains several such cycles. Rather powerful applied mathematics and
computers we have at our disposal permit apprizing the necessary pa-
rameters of the cycles. Concurrent with the maximal entropy method
this procedure looks promising for evaluations of spectral densities
and bandpass filters. But reality of the revealed cycles, their sta-
bility in time, mechanism of formation – all these problems, stated
by A.E.Douglass, remain actual at present. Untill mechanisms of the
cycles formation are known, the only procedure to evaluate their rea-
lity is to analyse their distinction in sufficient number of long
chronologies. If the series contain distinct cyclic components, the
latter may be used for background predictions. If small cycles are
taken for extrapolation purposes, then annual forecast may be given,
though it may not very reliable.

Predictions based on autoregressive function were not practicable
in dendrochronology. They may be efficient in many cases, since dend-
rochronological series have better intrarelations than climatological
ones.

Thus, I may say, there is a theoretical and methodological base
: dendrochronological prediction. It is primarily the knowledge of
the main regulariries of woody plants growth, systematic approach and
the theory of random stationary processes. However, progress in the
development of concrete ways and means in prediction is not great. It
is very important to estimate prediction limits, that is to evaluate
how well and how far increment changes are possible to forecast. This
problem has not yet been raised or solved. We suggest that prediction
would be more accurate if it is based on the series, obtained from ex-
tremal growth conditions. Better predictions are also expected for ge-
neralised series compared to mean ones.

Applied mathematics used for prediction at present is based on
the assumption of stationarity of the processes. In nature there are
no purely stationary processes. How this contradiction would be overco-
me? Possibly, the theory of non-stationary random processes will be
developed to the level of practical use. In any case, the probability
approach holds greater promise for prediction than the determinate one,
though predictions should be as concrete as possible. Uncertainty is
not to be overcome completly in predictions. Different forecasting
procedures are advisable to use. The main thing necessary for success-
ful forecasting is the availability of reliable and long-term dendroch-
ronological series.

Increased anthropogenic impacts on forest ecosystems and new li-
miting factors having appeared (air pollution, for example) make the
problem of dendrochronological forecasting more complex. One can not
rely on autonomy of the process and intraseries relations. Other appro-
aches and improved models involving anthropogenic factors are necessary.

I think that dendrochronological forecasting is not only possible,
but it is necessary. It also permits better understanding mechanisms
of tree growth variability.

In conclusion I would like to give several quotations from N.N.
Engver (1976) to summarize almost everything that was said:
1. A poor forecast is better than none.
2. Predictions based on a standard procedure are better, than those
   based on intuition, because the first can be always improved.
3. One may predict only what can be predicted.
4. A probability prediction is better than a determined one.
5. It is not science but a scientist, who is responsible for a poor
   forecast.

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8.2 MODELING FLUCTUATIONS OF DENDROCHRONOLOGICAL INDICES TO PREDICT ECO-CLIMATIC BACKGROUND VARIABILITY

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The authors report on the investigation of a model and the prediction of environmental (eco-climatic) background fluctuations by using Dendrochronological Scales (DS) of 100–150 years and long-term (200–1250 years) from the Lithuanian SSR as well as from northern regions of the USSR and North America. Using the DS from different sites of the Lithuanian SSR, an eco-climatic background prognosis was obtained with the aid of a cyclic model; the authors used 76 series of dendroscales for the model construction. Subsequently, these data were used to predict the yield of grain crops for the period 1983–1995. Fluctuation cycles of 35 or more years in duration have been singled out by the method of harmonic analysis in both groups of DS from the northern parts of the USSR and North America. For this purpose, the authors investigated 17 dendroscales from the northern parts of the USSR and 34 from the USA and Canada. The authors thus found it possible to establish the values of the variables in the eco-climatic background on the trans-regional and hemispheric level.

1. INTRODUCTION

During the process of growth, tree rings accumulate information on environmental (eco-climatic background) phenomena and store it for a long, unlimited time. This creates the basis for a large spectrum of dendroindications. Dendrochronology as a science and the method of dating events and variations in the environment by a comparative study of tree rings have been highly developed during the last decades. Samplings (core) used for study are usually taken from growing trees (modern chronology), from archaeological relics or from fossil trees (long duration chronologies).

Although not all trees have rings which are suitable for dendrochronological purposes, there are meaningful records in the rings (when one measures the ring width or density) of both gymnosperm and angiosperm species in the northern and southern Hemispheres. The

International Tree-Ring Data Bank, housed at the University of Arizona, in Tucson, USA, has been established to preserve newly collected data.[*]

In addition to the national tree-ring data banks, the Dendrochronological Data Bank of the USSR in Kaunas (at the Institute of Botany of the Academy of Sciences of the Lithuanian SSR, and the Lithuanian Forestry Research Institute) was also established. A well-replicated tree-ring chronology network is being established for North America, Europe, Asia, Australia (including some states on other continents), Argentina, Chile, Morocco, New Zealand, etc.

Dendroscales (DS) which have already been created in the USSR (over 400) as well as several hundred in the USA and other countries reflect past climatic changes (Fritts, 1981, 1985; Bitvinskas and Kairaitis, 1981; Kolishuk, 1979; Shiyatov, 1972, 1977, 1979, Kairiukstis, 1981). The DS can also be used as a reliable basis for prediction of the main trends of eco-climatic fluctuations which are responsible for forest growth and the sustainability of ecological systems altogether.

2. OBJECTIVES AND METHODOLOGY

Already a visual examination of DS shows that there are fluctuations in tree-ring indices, which are repeated more or less regularly over time. These fluctuations differ in amplitude and duration; they reflect the eco-climatic variations of a given region over time.

The aim of our research has been the following:

- to investigate fluctuations in the DS of short and long duration;

- to find out if there exist cyclic regularities in replicate of fluctuations; and

- to try to use the cyclic fluctuations to predict the trends of eco-climatic background fluctuations on the regional and transregional level.

Related studies using statistical models are to be noted. For the elucidation of a 22-year cycle in dendroclimatological time series, several scientists (Fritts and Shatz, 1975; Fritts, 1976; La Marche and Fritts, 1972; Mitchell et al., 1979; Pilcher and Baillie, 1980; Stocton and Fritts, 1971; Stocton et al., 1979) used the method of spectral analysis. A. Stupneva and T. Bitvinskas (1978) also applied spectral analysis to study tree-ring cycles over different areas from Murmansk to the Carpathians. B. Berrie, A. Lieberman and S. Shiyatov (1979) investigated cyclic fluctuations of tree-ring increments for larch (Larix sibirica) by the method of harmonic analysis. These authors suggested the following model:

$$x(t) = a + bt + \sum_{j=1}^{n} A_j \cos (2\pi t / T_j - Y_j) \ .$$

[*]See Chronology Series I to V (1972-1980), Laboratory of Tree-Ring Research, University of Arizona, Tucson and recent issues of the Tree-Ring Bulletin.

where

$x(t)$ = tree-ring width indices,

$a + bt$ = refers to a linear part of the equation,

A_j, T_j, Y_j = amplitude, period and phase of j fluctuations, and

t = integer numbers.

As another example, D. Sipenyte and A. Zilevicius (1983) constructed the following model:

$$x(t) = M_t + F_t + Z_t \ .$$

where

M_t = a slowly changing function,

F_t = final sum of harmonic components, and

Z_t = process of autoregression.

To achieve the objects above, the subject of our investigations was mainly the dendroscales of the USSR covering the following length of record and for the following species respectively

- 90-200 years for Pinus silvestris from the Lithuanian SSR - Stravinskiene (1979, 1981) Bitvinskas (1974, 1981);

- 270-358 years for P.silvestris from Karelia - Bitvinskas, Kairaitis (1979);

- 413-505 years for P. silvestris from the Urals - Shiyatov (1979),

- 130-315 years for Quercus robur from the Lithuanian SSR - Kairaitis (1978, 1979);

- 103-120 years for Picea abies from the Lithuanian SSR Stravinskiene (1979, 1981);

- 287 years for P. abies from the Carpathians of the Ukraine - Kolishuk (1979);

- 723 years for P. abies from Western Siberia - Shiyatov (1972);

- 279-876 years for Larix sibirica from the Urals and Western Siberia Shiyatov (1975, 1979);

- 240-385 years for Pinus sibirica from the Carpathians of the Ukraine - Kolishuk (1981);

- 697 years for P. sibirica from Western Siberia - Shiyatov (1975,

- 90-110 years for Alnus glutinose from the Lithuanian SSR Stravinskiene (1979, 1981)

Additional dendroscales for conifer species from the upper limits for forest growth in the northern taiga have been used (Lovelius, 1979; We also included the dendroscales covering the year 906-1251 for Douglas fir ponderosa pine, limber pine and white spruce from the USA (Washington, Oregon) and from Canada. The latter were constructed by D. Crolier, C Ferguson, H. Fritts, T. Knowles, M. Parker, and C Stocton, (Cropper and Fritts, 1981 "Tree-ring Chronologies of Western America", 1973; Vols. 1,5,6

and "Tree-ring Chronologies for Dendroclimatic Analysis", 1976).

3. ANALYSIS OF CYCLIC FLUCTUATIONS OF DS OF SHORT DURATION

Initially, we investigated 76 dendroscale series covering 80–160 year records for Picea abies, Quercus robur, Pinus silvestris and Alnus glutinosa from the Lithuanian SSR. Approximately 13% of these are master chronologies for these species and sites. A visual evaluation of the series leads to the inference that most of them may be considered as stationary time series. On average, in 85% of these series, fluctuations similar to the sum of periodic components can be detected visually. In dendroscales incorporating a large amount of material (Bitvinskas, 1974; Stravinskiene, 1981) from damp sites, the maxima and minima are repeated every 9–12 years. Significant peaks (95% significance) corresponding to the periods 10–13, 3, 20–24 years are noted in density spectra of almost all series. In 70% of the dendroscales, the order of significant coefficients of the correlation function exceeds 15. The correlation function of dendrochronological series from damp sites (Bitvinskas, 1974; Stravinskiene, 1981) on the whole does not decrease.

For description of a stationary time series (y_t), the following model is usually applied:

$$y_t = f(t) + Z_t + E_t$$

where

y_t = row of indices each calculated from many trees using the KRIEG* program,

$f(t)$ = deterministic function,

Z_t = process of autoregression, and

E_t = independent random values.

The results of the correlation and spectral analysis of dendrochronological series indicate strong cycles or a large order of autoregression. At the outset, we used the model $y_t = Z_t + E_t$. Calculations showed that the order to autoregression is more than 3 in 70% of the dendroscales, while in 60% it is more than 4. In 70% of the series, dispersion of $\{E_t\}$ exceeds the dispersion of a series by 65%. Further, in DS and in the series of indices obtained logarithmically, a cyclic component was singled out as follows:

$$f(t) = A_o + \sum_{j=1}^{n} A_j \cos(2\pi t / T_j - Y_j) ,$$

where the index T_j refers to the integer. We applied this method because the length of cycles determined according to the peaks of density spectrum or according to the significant coefficients of Fourier depends upon smoothing. The values of the length of cycles are expressed by fractional

*The KRIEG program has been constructed in FORTRAN and is at the Computer Center of the Lithuanian Forest Research Institute, Kaunas, Lithuanian SSR, USSR.

numbers (one assumption is that integer numbers conform more to reality). The correlation function of residuals $U_t = y_t - f(t)$ or $V_t = \ln y_t - f(t)$ (here the index y_t refers to a series of indices) decreases very slowly. The order of autoregression U_t and V_t ranges from 5 to 10. In 70% of the series, residual dispersion exceeds the dispersion of series U_t or V_t by 70%. These series are not approximated to the series of autoregression because we need models for prediction purposes for a period of 10 to 15 years.

The results discussed above enable one to assert that the dynamics of indices $x(t)$ of the series of dendroscales covering the 90-150 year records for the Lithuanian SSR are reflected best by the models:

$$x(t) = A_0 + \sum_{j=1}^{n} A_j \cos (2\pi t / T_j - Y_j) + E_t . \tag{1}$$

or

$$x(t) = \exp \{ A_0 + \sum_{j=1}^{n} A_j \cos (2\pi t / T_j - Y_j) + E_t \} . \tag{2}$$

where E_t is a random correlated series and n is selected in such a way that the actual and approximating series might show a higher level of agreement whilst the sum of squares of deviation might be as little as possible.[*] T_j, $j = 1$, and n are usually selected from the intervals 7-14 and 20-25 years (Figures 1 and 2).

With regard to the adequacy of models as shown in equations 1 and 2 above, almost all series (or average in 90%) the approximating function detects 85-90% of significant fluctuations while in master chronologies from damp sites of the Lithuanian SSR the range is 95-100%. It must be noted that considerable rises and falls in DS (8-22 years in duration) characterize the general favorable or unfavorable growth conditions. Therefore, the prediction of these rises and falls is of paramount importance. In the dendroscales for the construction of which a large amount of material (Bitvinskas, 1974) from dry sites of the Lithuanian SSR was used, the actual series have been smoothed with the sliding to three years. A comparison was made between the actual and approximating series of the dendroscales incorporating a large amount of material (Stravinskiene, 1981) from damp sites of the republic and between those of the dendroscales from dry sites. Their agreement ranges from 74-84%. The residual dispersion is less than half the dispersion of a series. In 66 of 76 dendroscales studied, the agreement between the approximating and actual series smoothes with the sliding to three years exceeds 65%. In 80% of the dendroscales covering the years 100-150 (or the last 100-150 years of the dendroscales of long periods) for other regions of the USSR between-series comparisons average over 65%.

Calculations revealed that the models shown in equations 1 and 2 are not applicable for DS with great dispersion (800 and more). Agreement values (coefficient of synchronization) and a sum of squares of deviation in

[*]A_j and Y_j are estimated by the method of least squares; T_j selected those trigonometrical amplitudes which are highest.
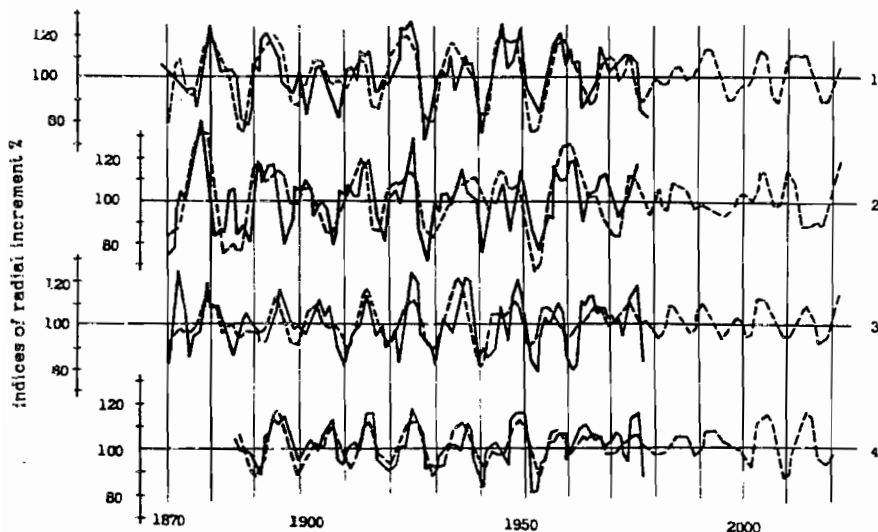
Figure 1: Actual trend of increment indices (____) and values for the approximating function (——)

1, 2 =   Picea abies stands of Carex-Calamagrostis forest type;
3, 4 =   Alnus glutinosa stands of Carex-Calamagrostis forest type in the Lithuanian SSR (according to the dendroscales) (Stravinskiene, 1981).

this case are not convenient characteristics for the adequacy of the models. It is not difficult to find some series which reflect the fluctuations very similarly. However, they have only 50% agreement.

Since DS $x(t)$ covering the years 100–150 are approximately stationary, it is feasible to predict $x(t)$ for 10–15 years by equations 1 and 2. In order to verify this statement, we calculated the predicted values of the indices, the parameters of approximating functions (1–2) of 23 series of dendroscales (3, 7, 8 and 15) without the last 10–15 and 20–30 years. The results were compared with the actual data. It appeared that in 19 series significant fluctuations (8–22 years) were reflected properly, although the agreement of the ends of some series of dendroscales was less than 50% (Figures 3 and 4).
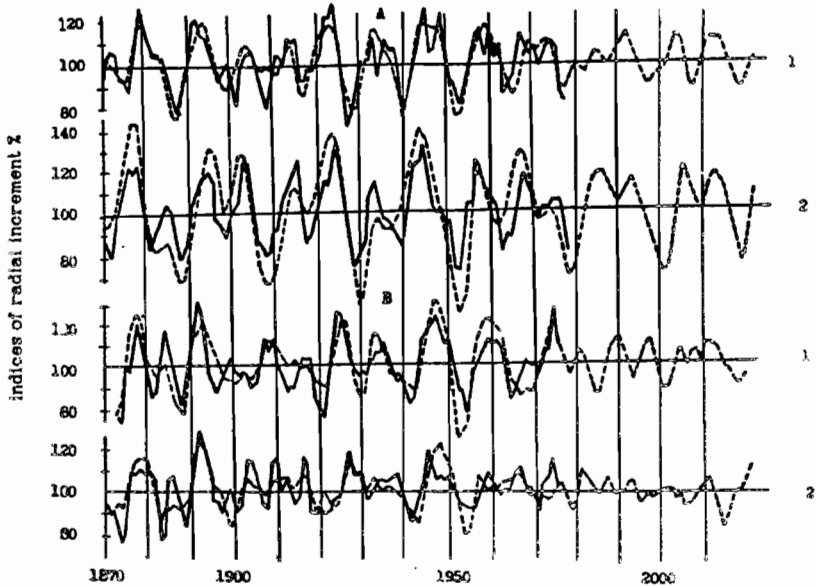
Figure 2: Actual trend of increment indices (_____) and values of the approximating function (----).

Pinus silvestris (1) and Picea abies (2) on very damp (A) and dry (B) sites of the Lithuanian SSR [according to dendroscales (Stravinskiene, 1981) (A) and (Bitvinskas, 1974, 1981)(B)].

4. ANALYSIS OF CYCLIC FLUCTUATIONS IN DS OF LONG DURATION.

A question arises as to whether it is possible to apply the models (equations 1 and 2 above) to approximate and predict fluctuations in dendroscales over long periods, for instance 200–450 years. Such scales, as a rule, are not stationary; for example, in some rows this may be noted visually (Figure 5). In these series, the spectral and harmonic analysis of non-crossing intervals of 100–150 years resulted in dynamics changeability of small cycles (8–13, 20–25 years in duration). Therefore, these cycles are revealed best in DS covering only the years 100–150. If T_j, A_j and Y_j are determined in the whole series of DS covering the years 200–450, these models are not appropriate for an approximation and prediction of series with such cycles.
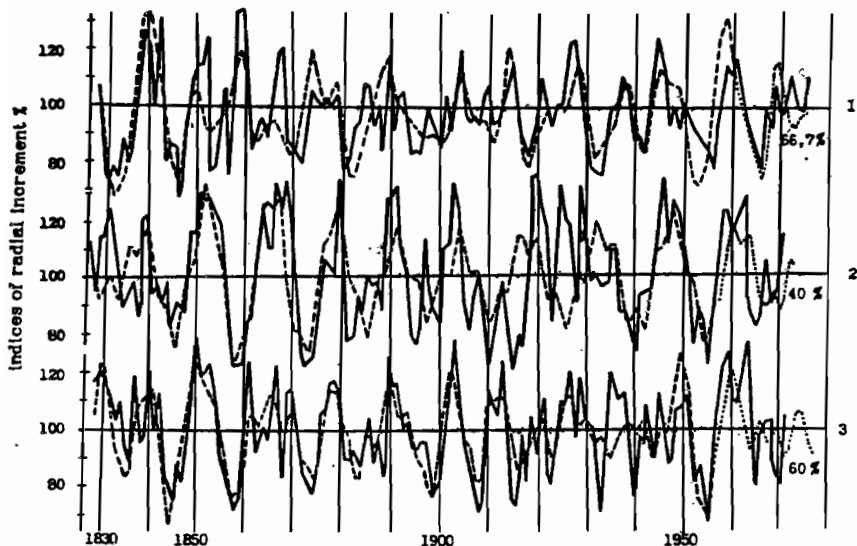
Figure 3: Actual trend of increment indices (——), values of the
approximating function (——) and predicting function (....).

    1 =   Pinus silvestris stand of Sphagnum forest type from the
            Kaunas region;

    2-3 = Quercus robur stands of Oxalis forest type from the Kaunas
            and Vi'nius regions of the Lithuanian SSR [according to
            dendroscales (Stravinskiene, 1979) (1) and (Kairaltis,
            1979)(2-3)]. The prognoses in 1 are calculated according
            to equation 2, and in 2-3 according to equation 1. The
            agreement values (%) between the actual and predicted data
            are indicated on the right hand side.

Let us consider long-term cycles. Suppose that long-term cycles can
reflect the general favorable or unfavorable climatic background of a
region. Then short-term (8-13, 20-25 years in duration) cycles of growth
processes will be revealed on the background of a favorable or unfavorable
impact of long-term cycles. In order to elucidate the general tendency for
eco-climatic background changeability of the northern parts of the USSR
and North America, we attempted to single out long-term cycles (35 and
more years in duration) in DS from these regions. For this purpose we have
investigated 17 dendroscales from the northern parts of the USSR (the
Urals, Karelia, West Siberia and Lithuania)(Bitvinskas, 1979; Komin, 1978;
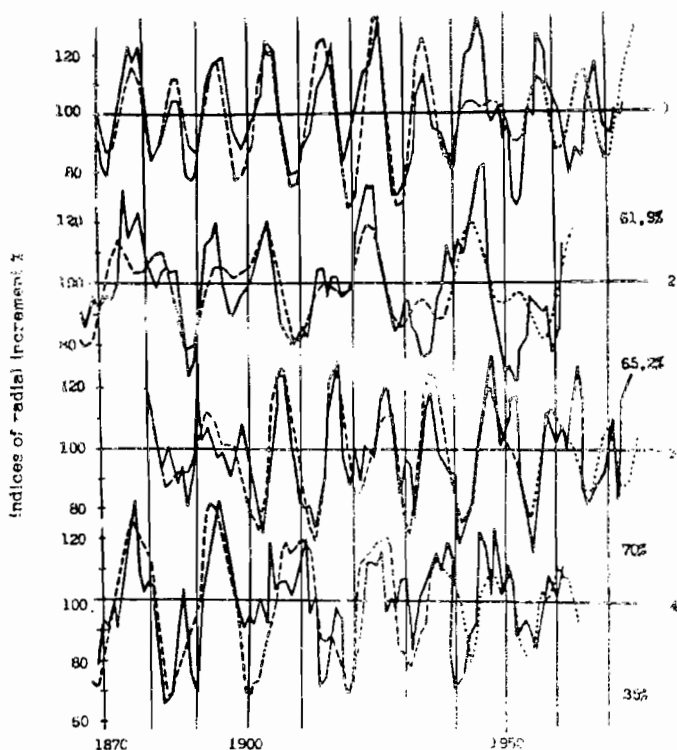
Figure 4: Actual trend of increment indices (———), values of approximating function (---) and predicting functions (   )

1   =   Pinus silvestris stand from very damp sites (master chronology for the whole Lithuanian SSR),
2   =   Pinus silvestris stand of Sphagnum forest type from the Svencioneliai region of the Lithuanian SSR;
3   =   Picea abies stand of Vaccinium myrtillus forest type from the Anyksciai region; and
4   =   Pinus silvestris stand of Vaccinium myrtillus – Oxalis forest type from the Kaunas region of the Lithuanian SSR [according to dendroscales (Caravinskiene, 1981) (1,3), (Bitvinskas 1974) (2–4)]. The agreement values (%) between the actual and predicted data are indicated on the right hand side
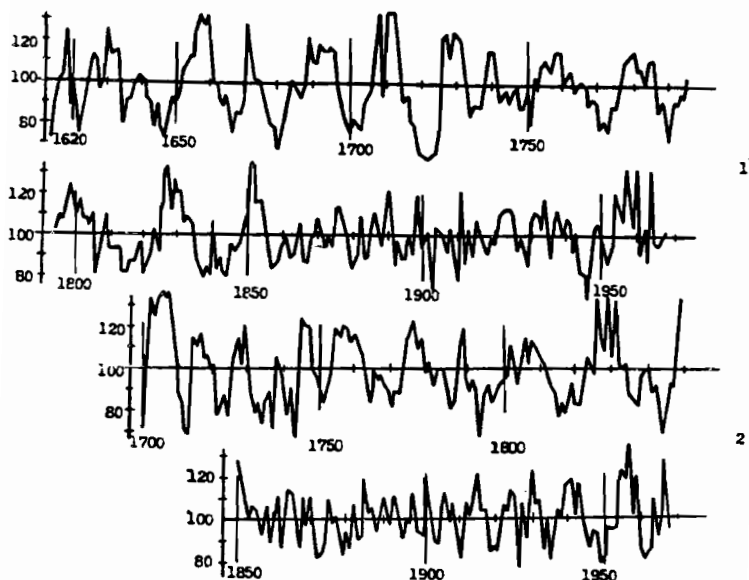
Figure 5:   Examples of distinctly non-stationary DS. Pinus silvestris stands
            from the Kola Peninsula (1) and the Karelia ASSR (2)
            (dendroscales (Bitvinskes and Kairaitis, 1979)). Absolutely
            different dynamics of indices' fluctuations are noted in the
            intervals 1650–1850 and 1850–1960 (1) and 1750–1850,
            1850–1940 (2).

Lovelius, 1979; Shiyatov, 1972, 1973, 1975, 1977, 1979) and 34 dendroscales
from Canada and the USA (states of Washington, Oregon) (Cropper and
Fritts, 1981; "Tree-ring Chronologies for Dendroclimatic Analysis", 1973:
Vols. 1,5,6 and 1976). Each of these has a span of more than 260 years.

        To single out long-term cycles, we calculated the trigonometrical
amplitudes in each series for the periods from two to half of the row.
Calculations also included density spectra with different duration of
smoothing. It turned out that the maxima of the trigonometrical amplitudes
and density spectra are revealed with a frequency corresponding to the
following cycles: 35–40, 50–54, 58–60, 76–84, 90–93, 110–117 and
171–176 years in duration in the dendroscales from the USSR (Figure 6). In
the DS from the USA and Canada the maxima of the trigonometrical
amplitudes and density spectra are also revealed with a frequency

corresponding to the very similar cycles: 37—39, 46—53, 58—62, 72—78, 96—105 and 178—192 years in duration.

A synchronization is observed in all groups of cycles. The peaks of the trigonometrical amplitudes appear at points of maxima and minima of almost all (90%) fluctuation cycles in the temporal interval 1880—1980. These points differ from the mean point of appearance of the corresponding extremum by no more than 20% of the length of the mean rhythm of the conformable fluctuation. It must be noted that almost half of the maxima of the trigonometrical amplitudes and density spectrum lie below the 95% confidence limit.

Being concerned as to whether the maxima might or not be a consequence of short-term cycles, we created several dendroscales covering the years 300—400, according to equation 1.

We assume that $E_t = 0$, a A_j T_j and Y_j are the length of the cycles, amplitudes and phases adequate to the predicted parameters of series of 100—150 years. For such series, we calculated trigonometrical amplitudes and density spectra. It turned out that with frequency corresponding to the long-term cycles, the peaks of these functions were not observed. Thus, the aforementioned results confirm the presence of long-term cycles and enable one to establish the mean duration of it T_j and phases of fluctuation Y_j where $j = 6.7$. Following the data of visual observations of DS discussed above and observations made by other authors (Berrie et al., 1979; Komin, 1978) the following general principle was accepted: with increase in T_j, A_j increases as well. On this basis we attributed an amplitude for each rhythm appropriate to its length. With the aid of the formula

$$\sum_{j=1}^{n} A_j \cos\left(2\pi t / T_j - Y_j\right) . \tag{3}$$

$$n = 6.7 , \quad t = 1,2,...., $$

where the index t refers to time (years) and we determined the average variables of conditional change in the ecological-climatic background.[*]

Formula (3) describes fluctuations with respect to some average value (100 in Figure 7). These values in both groups of dendroscales (from the northern parts of the USSR and North America) have a certain similarity. Hence the background impact of long-term climatic fluctuations on the rhythm of short-term fluctuations may be similar in the whole Northern hemisphere during the corresponding periods (for instance, 1920—1980).

5. APPLICATION OF CYCLIC FLUCTUATIONS IN DS FOR PREDICTION OF ECO-CLIMATIC TRENDS

Let us analyze the application of the results mentioned above for prediction purposes. If we put the data of prognosis of short-term cyclic fluctuations (determined by equations 1 and 2) for the Lithuanian SSR on the

[*]The year 1500 was considered to be the start of fluctuations in ascertaining Y_j, with $j = 1.7$.
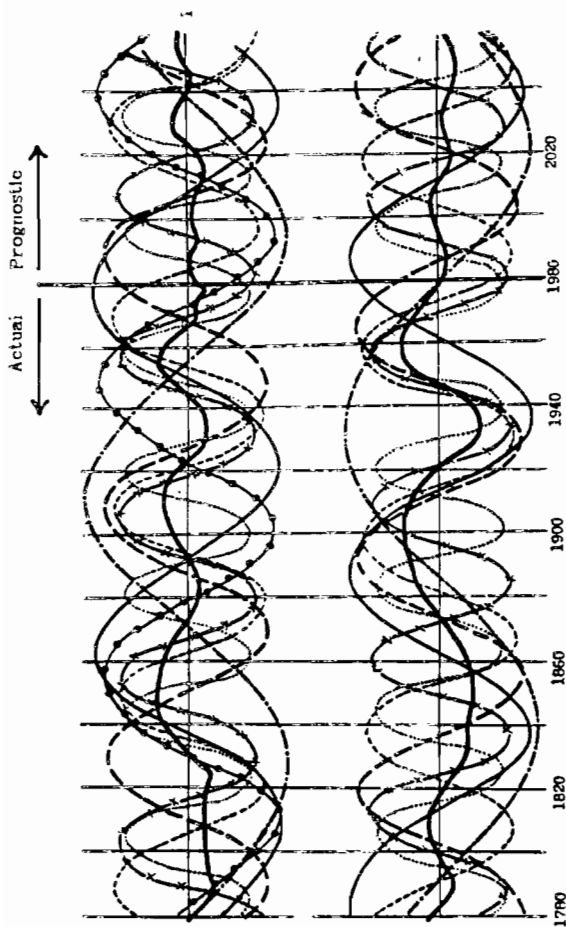
Figure 6: Rhythmical fluctuations in the dendroscales of the USSR (1) and the USA, Canada (2).

- `....` cycles of 30—40 (1) and 37—39 (2) years in duration;
- `-x-` cycles of 50—54 (1) and 46—53 (2) years in duration;
- `-:-` cycles of 58—60 (1) and 58—62 (2) years in duration;
- `-:-` cycles of 76—84 (1) and 72—78 (2) years in duration;
- `•:` cycles of 90—93 (1) years in duration;
- `——` cycles of 110—117 (1) and 96—105 (2) years in duration;
- `-:-` cycles of 170—173 (1) and 178—192 (2) years in duration;
- `——` average variables of cycles.

curve of the general climatic background determined by the model shown in equation 3, we can obtain the forecast of the general climatic background for the given territory (Figure 7). The variables of long-term cycles (equation 3) obviously may be used for the general characterization of forest growth base line and carrying capacity of ecosystems (biogeocenosis) in the northern Hemisphere. This is particularly the case when discussing forest dieback due to anthropogenic pollution. It is also applicable for creating a number of scenarios related with the perspective of forest use and with change in the CO_2 concentration in the atmosphere, etc. Let us consider these questions in more detail.
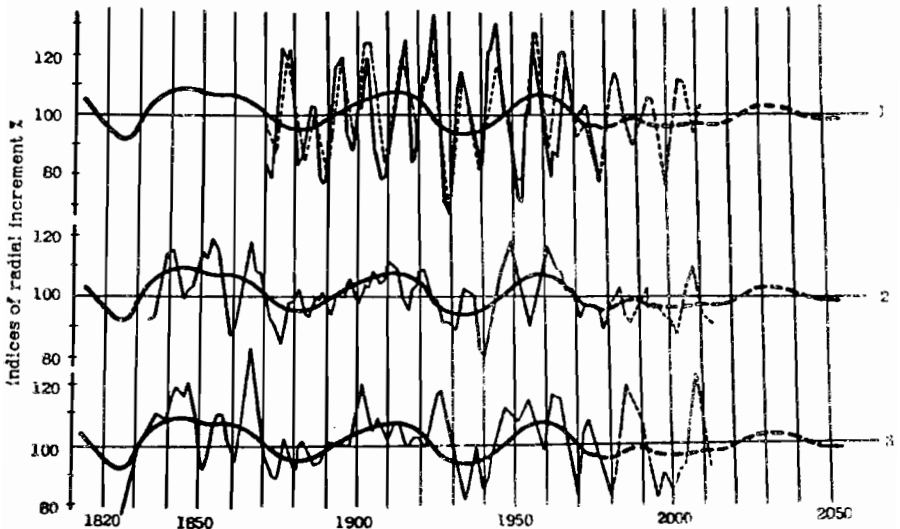
Figure 7: The average variables of actual increment (climatic background fluctuations) in long (> 35 years; ___) and short (___) cycles, approximation and forecast (—) in very damp sites (1) and dry sites (2-3) of the Lithuanian SSR

5.1 Application of Cyclic Fluctuations of Short Duration

The models shown in equations 1 and 2 approximate well to the generalized DS for different species over various sites. So it is feasible to use them for predicting the carrying capacity of ecological systems. Let us therefore discuss the application of predictions in different fields.

Prediction of the yield of agricultural crops on a given region. Such a prognosis has, for example, been calculated for the Lithuanian SSR. We investigated the dependency of the dynamics of grain crops in the Lithuanian SSR on the fluctuation of series DS $x_1(t)$ and $x_2(t)$, where $x_1(t)$ refers to a series of indices of increment of Pinus silvestris master chronology from dry sites of the Lithuanian SSR, whilst $x_2(t)$ to that from very damp areas of the republic.

The same climatic factors (temperature, precipitation, etc.) affect the tree increment on dry and damp sites differently. It is possible to assume that vector $(x_1(t), x_2(t))$ reflects the impact of the eco-climatic background of the Lithuanian SSR. At the beginning of the series of yield of agricultural crops $y(t)$ (centners/ha) we singled out the $D(t)$ trend conditioned by fertilizers, agricultural practices, etc. For this purpose we applied the method of the least squares. Further, in accordance with the formula

$$w(t) = (y(t)/D(t)) \cdot 100\%$$

we determined $w(t)$ yield indices free from the trend. These depend only upon the weather conditions. With the help of the standard method of regression analysis (by the method of step-wise regression) we obtained $w(t)$ approximation (stand error of regression coefficient 0,2-0,44 respectively) in the form of the following series:

$$w(t) = 146 + 1.07\tilde{x}_2 (t-1) - 1.54\tilde{x}_1 (t+2) , \qquad (4)$$

where

$$\tilde{x}_i (t) = A_o^i + \sum_{j=1}^{n} A_j^i \cos (2\pi t / T_j^i - Y_j^i) , \quad i = 1,2 ,$$

is the approximation of the eco-climatic background of the Lithuanian SSR $(x_1(t), x_2(t))$. The coefficients A_j^i, T_j^i and Y_j^i for $\tilde{x}_1(t)$ and $\tilde{x}_2(t)$ differ because these functions are approximations of indices from different soil site conditions. Comparison between approximating series (equation 4) and the actual $w(t)$ indices gave agreement of 72%. On the basis of the yield trend prediction, the forecast of the eco-climatic background $(x_1(t), x_2(t))$ and equation 4, we calculated the data of the an exemplary yield prognosis (centners/ha) (Figure 8)

Application of Predictions in Forest Practice. Prediction of eco-climatic fluctuations of short duration have already found applications in the practice of forestry. For example, in the Lithuanian SSR, according to suggestions of the Lithuanian Research Institute of Forestry, fertilizers in the forest are applied each time when two years are left before the forthcoming increment maximum predicted for an adequate forest by DS on the basis of the 11-year cyclicity. The same recommendations were made with respect to timing of forest thinning. The forest reclamation is also applied when 1-2 years after the forest increment maximum on the same soils predicted by DS. This made it possible to obtain an additional 15-30% wood increment, while using the measures discussed above.
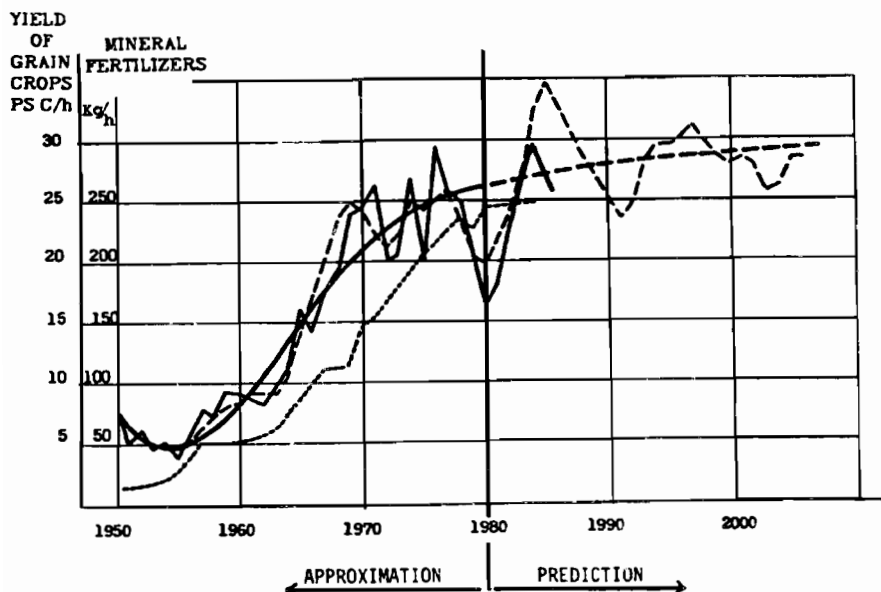
Figure 8: The actual yield of grain crops in the Lithuanian SSR (—), the quantity of mineral fertilizers kg/ha (...), the general trend of increasing crop yields (—) owing to fertilizers, agro-technique improvement and its prognosis (- -), approximation and prediction of crop yields on a dendrochronological basis.

5.2 Some Approaches to the Application of Eco-climatic Fluctuations of Long Duration in Regional Development

A series of price indices of wheat for the period 1500-1869 was formed in England by Lord Beverige. It is one of a more widespread economic series. Series $B(t)$ was obtained from the series of price indices of wheat after removing the trend by the 2-year sliding. We studied the correlation between $B(t)$ and $P(t)$ series of dendrochronological indices from Ireland (Pilcher and Baillie, 1980). It appeared that the agreement between series $B(t)$ and $P(t-1)$ averaged to three years is 41.4%. After the year of unfavorable growth conditions, prices for wheat increase. It lends support to the explanation of the regularity described. However, in Figure 9 we note that many of the peaks of these series are of a contrary character (see, for example, 1571-1574, 1576-1578, 1603-1606, 1622-1626, 1648-1652, etc.).
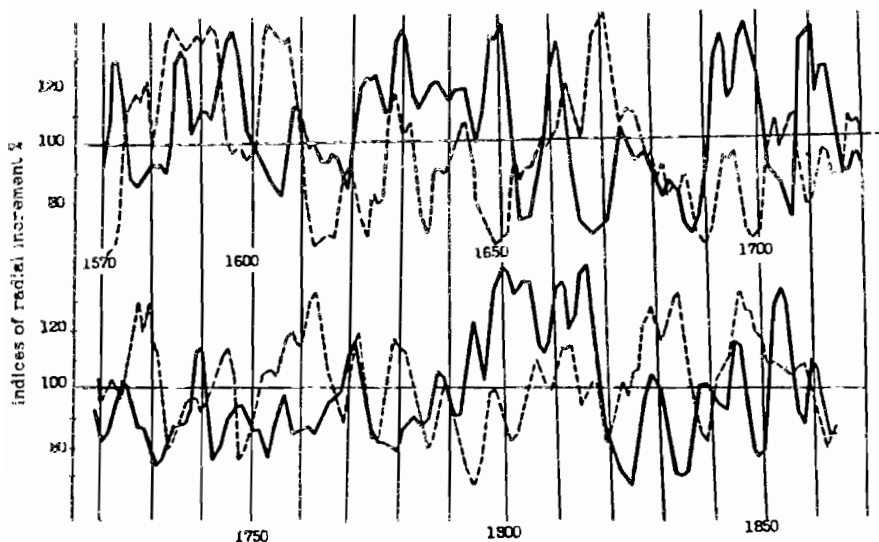
Figure 9: Price indices of Beverige after removing the trends with the 2-
year moving average (- -) and dendrochronological indices
(averaged to three years) (——) of Ireland by Pilcher and Baillie
(1980).

Exceptions to the rule may be explained in a way by social actions:
1586-1588: war with Spain, 1642-1648: Civil war; 1756-1763: Seven-Year
war; 1767-1769, 1780-1784, 1790-1792: Anglo-Mysore wars; 1799-1815:
Napoleon wars; 1829: an economic crisis.

The examples mentioned above might attract the attention to DS by
economists. Actually, in economic literature, there are publications about
cyclical development of the economy (Schumpeter, 1915; 1939). Attempts
have also been made to explain the cyclical development of the economy,
particularly Kondratieff cycles, by the increase and decrease of
entrepreneurial interests of people over time (Krelle, 1983). Taking into
consideration that Kondratieff cycles are quite synchronic with the above
mentioned (Figure 7) eco-climatic background averaged fluctuations and
that these fluctuations have a great impact on all living substances on
earth, such explanations can be supported by dendrochronologists.

A further example is that the ecological-climatic changes to a
considerable extent influence the sustainability and productivity of forest
ecosystems, sometimes strengthening, sometimes weakening them. The long

term changes of the forest systems productivity was estimated by dendro-
climatic methods for forests in the Lithuanian SSR. The results were used
to predict the overall cut for the twenty-first century. The following input
data were used: areas of tree species and age classes; volumes of the
stands to be cut; and, distribution of the dendroclimatic cycles. The indices
of the impact of climatic cycles on forest growth is calculated by the model.
These indices are used to estimate the cyclic changes of the volume of stand
in time. Felling areas and volume are determined by the module (Deltuvas,
1982). Two scenarios of the allowable out estimation were simulated: with
and without the impact of climatic cycles with a forecast period of
1985–2135 years.

According to simulation in the Lithuanian SSR forest sector, the
following situations are possible:

* a significant increase in shortage of wood by the middle of the 21st
  century due to the unfavorable climatic changes; this requires the
  augmentation in percentage of wood covered area;

* an increase in negative impact of climatic changes on agriculture
  increase in forest areas is excluded; tension in supplying the regional
  economy with raw materials will be even more evident;

○ calculation of data on climatic variations will essentially change the
  national model of optimizing the exploitation of natural resources and
  environment formation, territorial redistribution and investments in
  the economy sector are needed.

6. CONCLUSIONS

Fluctuations in dendroscale reflect eco-climatic changes. As far as
these fluctuations have a cyclical character, they can be used for practical
purposes to forecast the main trends in wood increment dynamics due to
eco-climatic changes.

Short cycles or cyclic fluctuations of 8–13 and 20–25 years in
duration are reflected best in DS covering the years 100–150. Therefore,
to predict changes in eco-climatic background of growth for 10–15 years
according to DS, it is better to apply the cyclic models in equations 1 and 2.
Approximating fluctuations in stationary DS detect 85% of significant
fluctuations (8–22 years in duration) of a series. In a 200-year (and over)
dendrochronological scales the dynamics of short-term cycles (8–13, 20–25
years in duration) are changeable. The models depicted by equations 1 and
2 are not appropriate for approximation and prediction of such scales in
the case when the parameters are determined in the whole series.

Long-term cycles (> 35 years in duration) are reflected best in DS
covering the years 260–1250 using equation 3. From the northern parts of
the USSR and northern America the following cycles have been singled out:
35–40, 50–54, 58–60, 76–84, 90–93, 110–117 and 171–176 as well as
37–39, 46–53, 58–62, 72–78, 98–105, and 178–192 years in duration,
respectively. Fluctuation phases are ascertained in all groups of cycles.
Variables of long-term changes in the ecological-climatic background
during the last 60 years have been found to be conditionally similar to the
northern regions of the eastern and western Hemisphere.

The variables of long-term cycles of DS may be used for the general characterization of tree growth base line and that of the activity of the production processes in the Northern hemisphere. Apparently it is also applicable for creating a number of scenarios associated with the perspective of forest growth, regeneration of natural resources, changes in the CO_2 concentration in the atmosphere, etc.

Prognoses of the generalized DS from dry and damp sites, calculated by means of equations 1 and 2, proved that they could be applied to predict the trend of yield of agricultural crops on a given region. Such prognoses are obtained for the yield of grain crops in the Lithuanian SSR up to 1995.

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7. REGIONAL NETWORKS AND CHRONOLOGIES

7.1 DENDROCLIMATOLOGY IN KASHMIR USING TREE RING WIDTHS AND DENSITIES IN SUBALPINE CONIFERS

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1. INTRODUCTION

The study of past climate suffers from the limited length of instrumental records. Even in countries such as England relatively few continuous instrumental records extend before the mid-nineteenth century, very few indeed before the mid-eighteenth century. This lack of long, dense datasets affects the study of the range of climatic variability that may occur in a region, the nature of that variability, whether it be systematic or not, and the mechanisms underlying such phenomena. In order to advance our knowledge and understanding of these important matters a number of additional sources of information on past conditions have been used. These are known as proxy records of past climate and range from historical documents through geological structures to biological records. In particular, workers in North America and Europe (Fritts, 1976; Hughes et al, 1982) have established the usefulness of the analysis of the annual rings of trees as a source of proxy climate data. Tree ring records are unique in their combination of high temporal resolution (annual or better) and wide spatial distribution.

Not only instrumental records of a century or more duration but also developed proxy records such as networks of tree-ring chronologies are concentrated in the industrialised countries of the temperate zone (Hughes, this volume). The Western Himalaya present an important opportunity to extend this coverage using tree-ring series. There are extensive temperate forests in this region, containing congeners of tree species known to be useful for dendroclimatology elsewhere. In particular, there are subalpine conifer forests with phytogeographical and ecological affinities with those of Europe (Aymonin & Gupta 1965; Meusel & Schubert, 1971). Schweingruber et al (1978) demonstrated that excellent reconstructions of past climate could be produced using series of ring width and wood density measurements from subalpine conifers. In the project described in this article we have sought to apply this approach to the reconstruction of past climate in the Western Himalaya. This was undertaken not simply because it appeared to be technically feasible, but because the region is one of great importance. In human terms, there is a very large population affected directly and indirectly by climate variability in the Western Himalaya, for example by its influence on the great rivers of the Indian sub-continent. The region has more general climatological significance, being at the western end of the greatest mountain barrier on Earth, where polar, tropical and mediterranean influences interact. An increase in knowledge of past climate in the Western Himalaya should cast light on these interactions and hence lead to improved understanding of climate variability in a much larger area.

2. THE APPROACH

Hughes et al (1984) used ring width and wood density measurements from pines (*Pinus sylvestris* L.) growing at cool moist sites in Scotland as proxy records of summer temperatures. They were able to use very long instrumental records available in the British Isles to examine rigourously the nature of such proxy records and their reliability. Further study confirmed that a relatively small grid of tree-ring chronologies was an effective recorder of regional summer temperature variation and that the major source of this information w₋ maximum latewood density (Hughes, In press). The Vale of Kashmir and the surrounding mountains make up a region of similar size, with a moderately long-established meteorological station (Srinagar, commenced 1893) at its centre. Although collections of tree-ring material were made in the Indian states of Himachal Pradesh and Uttar Pradesh during 1980 and 1982, greatest success in establishing a network of replicated crossdated chronologies was achieved in Kashmir. The properties of the material collected in Kashmir will be described in this article, and the potential for applying the methods used by Schweingruber et al (1978) and Hughes et al (1984) will be explored.

3. MATERIALS

The details of sites for which replicated crossdated chronologies have been established for ring width and wood density variables are given in Table 1. Only those chronologies of suitable quality for use in dendroclimatology are mentioned. The distribution of these sites in the mountains surrounding the Vale of Kashmir, where the Srinagar meteorological station is found, is shown in Figure 1. The principal tree species of subalpine conifer forests are *Abies pindrow* (Royle) Spach. at higher altitudes and on cool, north-facing slopes; *Picea smithiana* (Wallich.) Boiss. and *Pinus wallichiana* A.B. Jackson in less cool, medium altitude, south or southwest facing locations. Sampling was concentrated primarily on characteristic *A.pindrow* sites in order to explore the dendrochronological properties of this species, and to maximise the benefit gained from an analytical technique known to work well for conifers from cool moist subalpine sites.

Several of the chronologies extend back well into the seventeenth century, but the early eighteenth century marks the beginning of adequate replication in some cases. It was not found possible to identify particularly long-lived trees in the subalpine zone with any great degree of reliability. In part as a result of this, and in part to achieve sample diversity, the emphasis was on collecting from many locations rather than establishing a definitive sample at each. The length of chronologies was further limited by the prevalence of butt rot in *A.pindrow*. Many trees that were probably three centuries or more old suffered this defect. Chronology length and replication was also reduced by the difficulty of obtaining good density measurements from many cores or parts of cores that would be acceptable for ring width. Most of the remaining trees of moderate age (two hundred years or more) are found on steep slopes (Table 1) and so display distorted xylem structure. This increased the number of cores for which adequate density analysis was impossible. Ten *A.pindrow* and two *P.smithiana* chronologies were established.
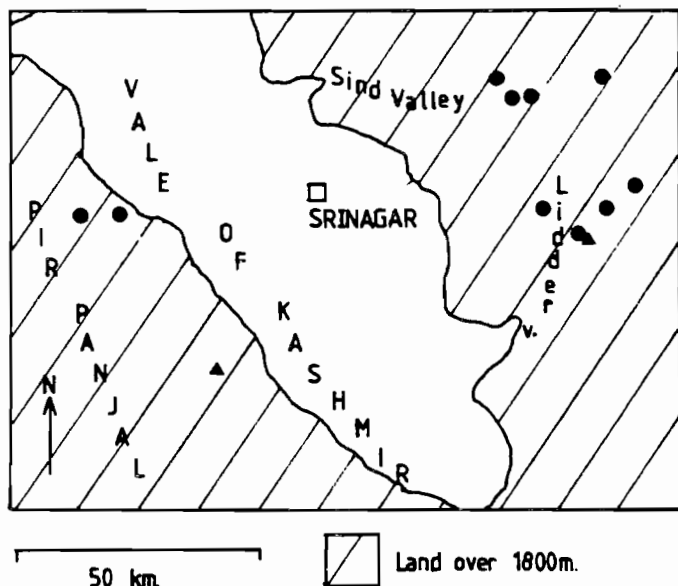
Chronologies: ● Abies pindrow: ▲ Picea smithiana

Figure 1. Sketch map of the location of replicated, crossdated chronologies in Kashmir.

TABLE 1 Site Details

Site	Abbrev- -iation	Latitude deg.min.N.	Longitude deg.min.E	Altitude metres a.s.l.	Aspect	Slope degrees	Species *	Time span +
1.Gulmarg	GUL	35 05	74 18	2740	S	0-40	ABPW	1620-1980
2.Khillanmarg	KHI	35 05	74 20	3125	ESE	55	ABPW	1660-1980
3.Tusmarg	TUS	33 45	74 36	2380	E	30	PISM	1780-1980
4.West of Sonmarg	WSO	34 39	75 28	3200	NE	40	ABPW	1687-1982
5.Sonmarg	SON	34 35	75 33	3125	S	60	ABPW	1764-1980
6.Thijwas	THI	34 35	75 32	3400	NWE	60	ABPW	1655-1982
7.Sarbal	SAR	34 30	75 45	3110	N	40	ABPW	1644-1982
8.Bhaisaran	BSA	34 02	75 42	2620	SW	40	PISM	1836-1982
9.Pahlgam	PAL	34 02	75 42	2620	ESE	40	ABPW	1656-1980
10.Chandarwani	CHA	34 15	75 55	3200	W	SC	ABPW	1777-1982
11.Arau Valley	ARA	34 06	75 12	2500	N	10	ABPW	1840-1982
12.Sesnag	SES	34 06	75 50	3650	N	21	ABPW	1636-1982

Site numbers refer to a series of collections, some of which have not yielded crossdated chronologies.

* ABPW Abies pindrow
  PISM Picea smithiana

+ This refers to the multivariable chronologies discussed in this paper.

4.   TREE-RING MEASUREMENTS

Most of the material was sampled as increment cores. Billets were
also obtained from one site (14.SES). For each site a subsample of
cores showing clear, undistorted ring patterns was chosen, surfaced to
reveal the details of xylem structure and ring width series measured on
a Bannister incremental measuring machine to one hundredth of a
millimetre. This machine was linked directly to a microcomputer using
data capture programs written by J.R. Pilcher. The microcomputer was
used to produce ring width plots for each core. Crossdating between
cores and trees was checked by visual comparison of these curves   ·
supported by statistical comparison using the program CROS (Baillie and
Pilcher, 1973). A mean ring width chronology for each site was produced
from these crossdated materials and used to check the internal dating of
materials subjected to densitometric analysis.

All other measurements were carried out in Liverpool Polytechnic's
wood microdensitometry laboratory. The technique of wood
microdensitometry using X-rays was first developed by Polge (1963). The
equipment and procedures at Liverpool are based on those developed at
the Swiss Forest Research Institute, Birmensdorf (Lenz et al, 1976).
All samples have resins, oils and heartwood substances extracted as
necessary. They are then cut to 1.25mm (+/- 1.5%) thickness at right
angles to wood fibre direction and conditioned to standard moisture
content. Radiographs of these samples and of a secondary calibration
wedge of plastic are prepared using a moving carriage system (Milsom and
Hughes, 1978). The optical density of the radiograph has a simple
curvilinear relationship to the physical density of the wood.
Calibration against standards of appropriate materials allows
measurements of radiograph optical density made using an optical
microdensitometer to be converted to wood specific gravity. This
primary calibration of wood density is achieved by a combination of
volumetric/gravimetric analysis and use of a program to integrate under
the density curve for a sample of the timber being analysed. At
Liverpool this is done using a Joyce-Loebl IIICS microdensitometer
modified in three main respects. A linearising optical wedge has been
fitted as described by Fletcher and Hughes (1970) and Hughes and
Sardinha (1975); a beam rotation device has been fitted so that the
image of the ring boundary is kept parallel to the measurement slit; and
the densitometer has been linked to an Apple microcomputer. This
controls a stepper motor used to move the optical stage carrying the
radiograph and receives an analogue input from a potentiometer linked to
the optical wedge drive. This input indicates the optical density of
the radiograph. Programs for the microcomputer are arranged so that a
secondary calibration wedge is analysed on each radiograph. The optical
stage carrying the radiograph is tracked in increments that may be
varied down to 2.5 micrometres by the program so as to ensure adequate
resolution of fine peaks in wood density, whilst taking larger steps
across regions of little density change. For most material increments
of 30 micrometres are used in the earlywood and 10 micrometres in the
latewood, which is where the ring boundary is detected by software. The
density trace for several rings is displayed on the microcomputer's
monitor as the measurements are being made so that the operator may
intervene if anomalies appear. Using an approach similar to that
described by Parker (this volume), the program records earlywood width
and latewood width in hundredths of millimetre and minimum and maximum
density in grams per millilitre for each ring. The ring-by-ring data
are stored on floppy disc by the microcomputer. These records are used

to produce time-series plots of all variables for each sample so that crossdating may be checked. The dated width and density measurements are then transferred from the microcomputer to a mainframe computer by direct hardwired link.

The series of measurements for maximum and minimum density, earlywood, latewood and total ring width for the crossdated trees at each site were then combined to form the five chronologies for that site. This was done by standardising the series of measurements for each core and variable to allow for the effects of age on tree growth and then averaging the individual core series to produce a site chronology. Standardisation was effected by fitting a curve (using a polynomial) to each core series and taking the quotient of the actual and calculated series as the index (Fritts, 1976). The analyses reported here concern a maximum of sixty site chronologies, twelve each for maximum latewood density (MXD), minimum earlywood density (MND), earlywood width (EWW), latewood width (LWW) and total ring width (TRW).

5. CHRONOLOGY STATISTICS

In order to compare the nature of the sixty series from Kashmir, a range of chronology statistics were calculated for a common period of sixty years. For each site and tree-ring variable three statistics are presented here (Table 2), namely the mean value of the variable, the serial correlation, and the proportion of the varance of the individual series attributable to the common between-year pattern (%Y). Apart from larger rings (mainly LWW) and higher MXD the two *P.smithiana* chronology sets resemble those for *A.pindrow*. Minimum earlywood density (MND) shows little common pattern (measured as %Y) for any combination of site and species and so will not be discussed further in this article. Of the remaining four variables LWW generally has the smallest %Y, but tends to have a low serial correlation, a positive attribute in terms of time series statistics which it shares with MXD. MXD has the lowest serial correlation in most cases. Ring width (TRW) usually has a much higher serial correlation. This persistence is manifest primarily in the earlywood width (EWW).

TABLE 2 Chronology Statistics 1921-1980

Site	Abies pindrow										Picea smithiana	
	1.GUL	2.KHI	4.NBO	5.GGB	7.THI	6.GNR	10.PBB	11.CHR	13.ARA	14.BNA	3.TOB	9.BNA
Number of trees(cores)	15(18)	9(13)	17(17)	6(6)	25(25)	16(16)	9(9)	9(9)	7(7)	6(6)	7(8)	7(11)
Maximum density												
mean (g/ml)	0.82	0.80	0.74	0.79	0.71	0.76	0.83	0.78	0.82	0.78	0.92	0.97
Serial r	0.25	0.32	0.27	0.16	0.45	0.45	0.49	0.35	0.09	0.53	0.32	0.15
%Y	31.0	26.3	17.9	23.0	14.3	16.0	26.9	37.2	34.7	20.7	21.1	19.7
Minimum density												
mean (g/ml)	0.36	0.34	0.30	0.31	0.32	0.31	0.33	0.30	0.29	0.29	0.33	0.34
Serial r	0.34	0.41	0.19	0.31	0.41	0.34	0.43	0.34	0.30	0.28	0.06	-0.06
%Y	3.5	3.3	7.1	1.7	8.3	4.8	8.4	8.2	2.6	4.6	2.0	4.9
Earlywood width												
mean (mm)	1.34	1.16	1.30	1.35	0.84	0.97	1.34	1.61	2.51	0.84	1.56	1.79
Serial r	0.64	0.80	0.80	0.63	0.43	0.63	0.90	0.51	0.53	0.62	0.52	0.56
%Y	24.3	11.2	26.4	20.0	14.6	27.3	19.6	30.7	21.6	19.7	18.3	27.1
Latewood width												
mean (mm)	0.22	0.34	0.18	0.17	0.21	0.20	0.20	0.36	0.27	0.17	0.59	0.52
Serial r	0.36	0.44	0.29	0.26	0.46	0.42	0.52	0.31	0.01	0.53	0.40	0.36
%Y	14.8	12.3	9.0	13.5	8.2	11.9	21.6	18.5	16.5	14.0	20.7	17.2
Total ring width												
mean (mm)	1.56	1.40	1.48	1.52	1.05	1.17	1.44	2.07	2.78	1.05	2.15	2.31
Serial r	0.66	0.67	0.64	0.64	0.46	0.65	0.42	0.50	0.82	0.48	0.60	0.40
%Y	24.3	14.3	34.2	31.5	17.5	27.4	25.1	30.0	25.5	20.6	16.8	25.4

%Y is the proportion of sample variance retained by the final chronology as determined from an analysis of variance over the 60 year period 1921 to 1980.

A full explanation of the calculation and interpretation of chronology statistics is given by Fritts (1976).

TABLE 3 Crossdating of Kashmir chronologies - 't' statistics

RING WIDTH

Site	Abies pindrow										Picea smithiana	
	1.GUL	2.KXI	4.NBO	5.GHB	9.MXI	6.ANR	10.MBS	11.CBR	13.ABR	14.MBS	3.TOS	9.DRR
1.GUL	-	13.3	16.7	15.0	13.9	22.3	6.1	9.5	7.4	-8.0	6.1	7.7
2.KXI	7.5	-	13.2	30.9	21.6	20.0	7.2	9.0	6.2	-4.6	6.7	7.3
4.NBO	7.8	6.3	-	37.3	14.9	16.8	6.7	9.3	9.0	7.3	6.2	6.4
5.GHB	4.5	4.9	8.3	-	15.1	15.5	9.4	10.1	7.3	9.7	4.1	6.5
7.MXI	6.6	5.1	8.6	6.9	-	15.2	7.2	7.9	7.9	6.3	4.3	7.5
8.ANR	6.0	3.9	9.7	7.3	7.1	-	7.7	6.9	8.1	8.4	4.5	7.3
10.MBS	1.7	2.2	3.5	3.5	2.2	3.3	-	6.6	4.5	-4.4	4.0	7.0
11.CBR	3.7	5.4	4.3	4.3	3.7	5.2	5.1	-	6.4	4.3	5.9	6.1
13.ABR	3.3	4.7	4.1	3.6	2.6	4.3	4.1	5.7	-	3.9	7.2	8.3
14.MBS	6.3	4.6	5.0	3.5	6.0	5.0	3.4	3.1	3.5	-	2.2	3.9
3.TOS	6.6	3.8	4.3	3.9	3.4	4.8	3.0	1.8	3.9	1.5	-	3.9
9.DRR	1.5	3.5	-4.8	3.6	2.6	4.3	0.5	3.8	4.1	1.0	2.1	-

* The upper triangle gives values for maximum latewood density (MXD), the lower for total ring width. All comparisons are for the maximum overlap between each pair of series. 't'-values were calculated by the method of Baillie and Pilcher (1973).

There is no evidence of any systematic variation in the three statistics for the *A.pindrow* chronologies on any geographical or habitat basis. The values of ty and serial correlation presented here are in general similar to those presented by Schweingruber et al (1978) for sites in the Alps (mainly *Picea abies*) and by Hughes (in press) for *Pinus sylvestris* in Scotland. The one major exception to this is that serial correlations are higher for MXD in several Kashmir *Abies* chronologies than for these other species and regions. Kienast (1985) reports a serial correlation of 0.31 for an *Abies alba* chronology in Switzerland. It may be that MXD in the genus *Abies* shows greater persistence than in other genera.

TABLE 4 Crossdating of Kashmir chronologies - 't' statistics

EARLYWOOD WIDTH

Site	Abies pindrow										Picea smithiana	
	1.GUL	2.KXI	4.NBO	5.GHB	7.MXI	8.ANR	10.PAS	11.CBR	13.ABR	14.MBS	3.TOS	9.DRR
1.GUL	-	7.8	7.7	4.3	5.2	8.0	1.5	1.0	3.0	4.6	4.8	3.0
2.KXI	8.1	-	4.8	4.9	4.0	3.6	1.6	5.0	5.1	4.8	8.4	4.3
4.NBO	9.3	7.2	-	8.2	7.2	8.9	3.0	4.3	4.0	4.3	2.3	3.6
5.GHB	7.8	7.4	9.7	-	8.4	7.8	3.1	4.1	3.8	3.3	1.4	2.9
7.MXI	4.8	5.4	8.4	6.6	-	6.6	2.6	4.1	2.1	3.9	2.5	2.5
8.ANR	8.9	8.1	11.0	9.9	6.7	-	3.1	8.0	4.5	4.8	3.8	3.9
10.PAS	3.2	4.4	5.1	6.9	1.2	3.7	-	5.0	4.1	2.5	3.0	7.8
11.CBR	7.0	4.6	5.8	6.1	4.6	7.7	4.5	-	6.6	3.8	4.2	4.9
13.ABR	5.2	4.6	7.5	5.8	4.7	6.9	3.4	6.3	-	1.4	4.6	5.9
14.MBS	5.8	3.5	4.2	2.8	1.5	6.5	5.2	2.3	1.4	-	1.3	3.8
3.TOS	7.9	6.2	4.4	6.0	5.6	7.4	4.7	5.2	2.6	4.0	-	2.2
9.DRR	3.3	2.4	4.7	4.4	2.9	4.5	6.4	4.4	2.7	1.9	3.0	-

LATEWOOD WIDTH

* The upper triangle gives values for earlywood width, the lower for latewood width. All comparisons are for the maximum overlap for each pair of series. 't'-values are calculated by the method of Baillie and Pilcher (1973).

6. THE CHRONOLOGY NETWORK

Pairwise comparisons were made between the twelve site chronologies for MXD, EWW, LWW and TRW according to the method of Baillie and Pilcher (1973). 't' values are given in Tables 3 and 4. In general, 't' values for pairs of *Abies* MXD series are markedly higher than for the other variables. There are particularly high values for MXD from the *Abies* sites from the Pir Panjal range (GUL and KHI), the Sind Valley (WSO, SON, THI, SAR) and one in the Lidder Valley (CHA). Figure 2 shows a section of four of these series and indicates the quality of matching associated with the 't' values cited. Similarly, Figure 3 shows the corresponding TRW series. The eight longest *Abies* chronologies for each variable were subject to an analysis of variance that showed strong regional coherence. The percentage of variance attributable to the common regional pattern varied thus for the ninety years 1891-1980: MXD 61%: EWW 29%: LWW 47%: TRW 45%.The two *P.smithiana* chronology sets (YUS and BHA) showed strong affinities with their *Abies* neighbours (GUL with KHI and PAH with CHA, ARA, Sind Valley respectively). This was especially marked for MXD (Tables 3 and 4).

7. DENDROCLIMATOLOGY

Both crossdating and analysis of variance results demonstrate the existence of strong regional pattern in the year-to-year variation of the four tree ring variables, especially in *A.pindrow*. This is particularly marked for MXD, there being great similarity in the series from sites as far apart as Gulmarg (GUL) in the Pir Panjal and Sonmarg (SON) in the Sind Valley (Table 3). The selection of sites for sampling, the species used and experience elsewhere all suggest that the large-scale environmental factors producing such remarkable common variation in MXD and ring width variables are likely to be related to growth season temperatures. There are similarities between the mean of the longest eight *Abies* series MXD chronologies (excluding SES with which there were measurement problems) and mean April to September air temperature at Srinagar (Figure 4). In fact the correlation coefficient between these two series for the period 1893-1980 is 0.53 (p < 0.0001) and between their first difference series 0.68 (p< 0.0001). It appears that the high-frequency components of the two series are more similar than are the lower frequencies. It is also evident (Fig. 4) that the mean MXD series does not record some particularly hot summers effectively (e.g. 1947). There is clearly potential for using the regional mean *Abies* MXD series as a proxy climate record, but its relationship with climate needs further investigation before this is done. The dendroclimatological potential of the Kashmir *Abies* material has been investigated in another way. Although LWW shows slightly stronger between-sits correlation than TRW, the latter is a more reliable measurement since it is relatively unaffected by the density level chosen to demarcate earlywood from latewood (see Parker, this volume). Bearing this in mind, a series of calibration tests were set up between the MXD and TRW chronologies for the eight longest *Abies* series (other than SES) as predictors and various combinations of monthly mean temperatures at Srinagar as predictands. The tree-ring data for years i-1 and i+1 were presented to the regression as well as those for year i so as to allow for autoregression in the tree-ring data and for lag effects. The combinations of monthly temperatures to be tested were chosen after examining the correlation structure of the temperature data for the fifty year period 1894 to 1943, and after
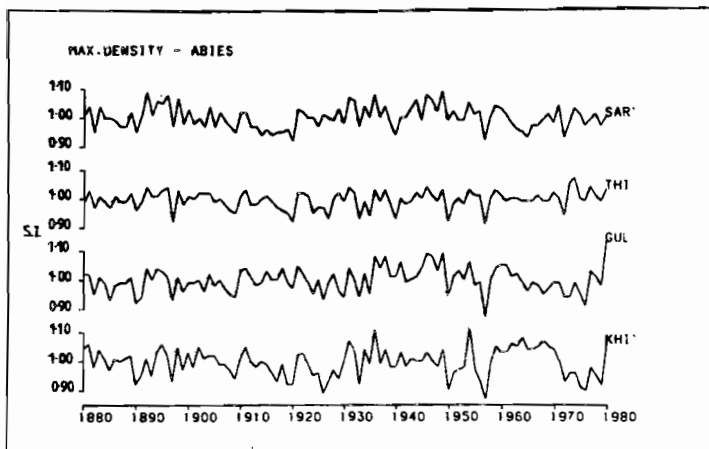
Figure 2 Indexed maximum latewood density (MXD) chronologies for *Abies pindrow* from four sites in Kashmir. The vertical axes are in the standardised indices (S.I.). A key to site name abbreviations is given in Table 1. GUL and KHI are from the Pir Panjal range, SAR and THI from the Sind Valley.
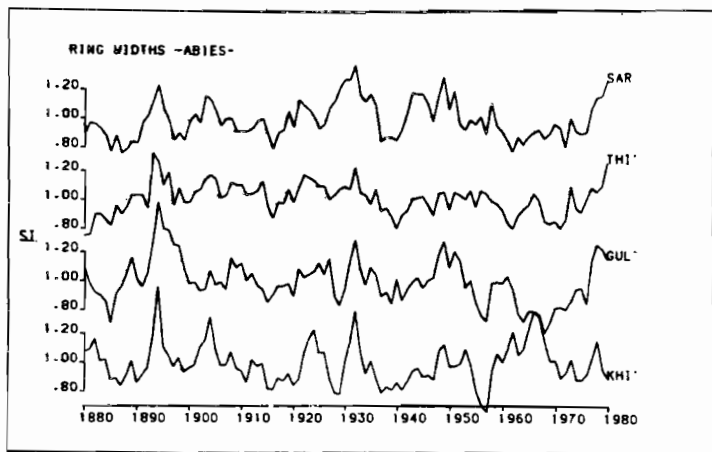
Figure 3 As in Figure 2 for total ring width (TRW)

considering the structure of the seasons in Kashmir (Raza et al 1978). The calibrations were derived using an orthogonalised stepwise multiple regression procedure described by Hughes et al (1984) and based on that developed by Guiot (1980). Temperature data were available for the Srinagar station from 1893. The period 1894 to 1942 was used for the calibration tests.

Two examples of promising calibrations will be presented here. As in several other cases (Parker and Henoch, 1971; Schweingruber et al 1978 Hughes et al, 1984) the predictor set including MXD yielded a significant calibration on late summer temperature, in this case the mean for August and September (Table 5). The predictor variable with the largest coefficient was current year MXD at CHA. The results for late spring and early summer (mean April - May temperature) correspond with those recently reported by Conkey (In press) for density series in New England. In the case of Kashmir the strongest calibration was for April-May temperature (Table 5), the largest regression coefficients being for current year (+ve) and prior year (-ve) MXD at GUL. Current year TRW at SON was also an important predictor. The contribution of current year MXD at GUL was much the greatest.

These calibrations were then verified against instrumental data not used in the calibration, namely those for the twenty-six years 1943 to 1968. The August-September calibration performed well in all tests (Table 5). Its sole significant failure in the verification period was in 1959 when August was extraordinarily hot (Figure 5). These positive results indicate that it should be possible to produce a reliable reconstruction of August-September mean temperature in Kashmir back to the late eighteenth century and quite possibly back to the late seventeenth century. The April-May calibration also performed well in the verification tests (Table 5), excepting that its performance in the sign test indicated a relative weakness at high frequencies (Figure 6).
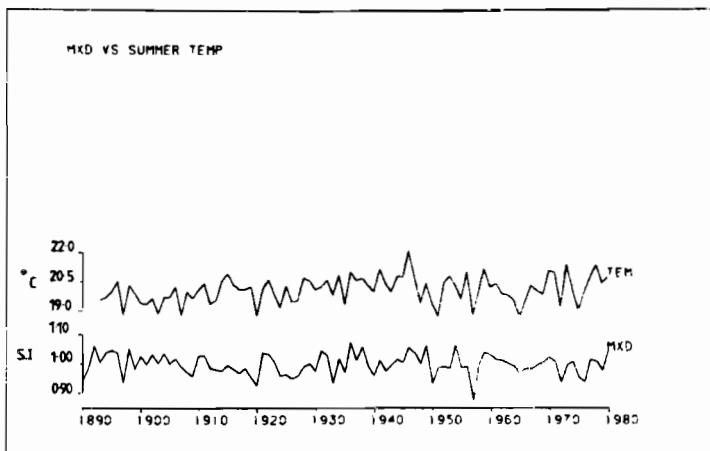
Figure 4 Mean maximum latewood density (MXD) for Kashmir *Abies* (see text for derivation) compared with mean April to September temperature (TEM) at Srinagar. The vertical axis for TEM is in degrees Celsius, for MXD in standardised indices.
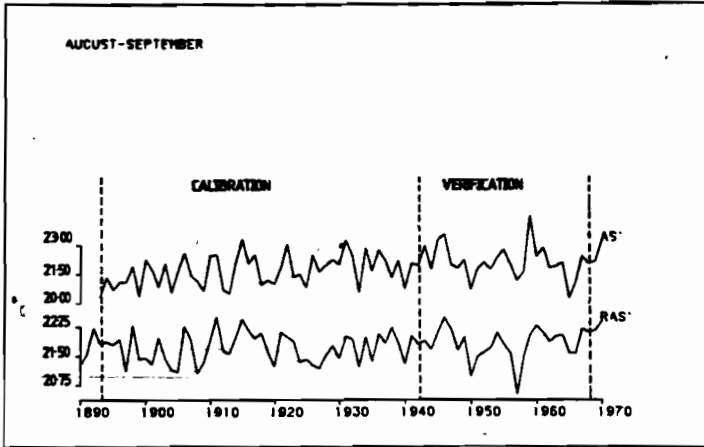
Figure 5 August-September mean temperature of Srinagar, Kashmir 1890-1970.
          AS - instrumental record
          RAS - as reconstructed using tree ring densities and widths.
The vertical axes are in degrees Celsius.
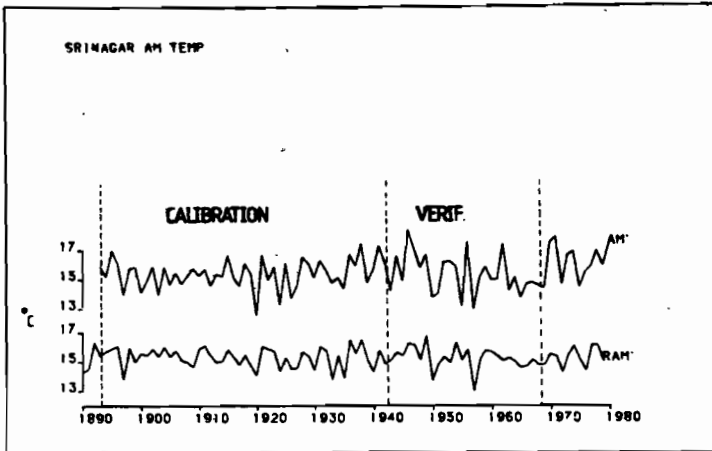
Figure 6 April-May mean temperature at Srinagar, Kashmir, 1890-1980
          AM - instrumental record
          RAM - as reconstructed using tree ring densities and widths.
          The vertical axes are in degrees Celsius.

Table 5 Calibration and Verification Statistics

Predictors: MXD and TRW at GUL, KHI, WSO, SON, THI, SAR, PAH, CHA for
             for years i-1, i, i+1
Predictands: Mean temperature at Srinagar for April-May and August-
             September

	April-May	August-September
Calibration period 1893-1942		
Multiple correlation coefficient	0.728	0.496
Predictors retained	5	3
F-value	11.6	7.0
Probability	0.0001	0.01
Verification period 1943-1968		
Correlation coefficient	0.663 ****	0.478 **
Reduction of error (RE)	0.381 +	0.389 +
Sign test[a]	15/25	19/25 *
Product means 't'[b]	2.385 *	4.060 ****

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*    - p<0.05          + a value of RE greater than zero
**   - p<0.02            indicates some skill in the model
***  - p<0.01            compared with the trivial
**** - p<0.001           persistence estimate
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a - the sign test involves a comparison of the signs of first difference
    of the two series.
b - A significant positive product mean indicates a tendency for both
    actual and estimated departures from the average to be large when
    the sign is correctly estimated and to be small when the sign is
    incorrectly estimated.

8. CONCLUSIONS

The project described here was envisaged as a study of the
feasibility of extracting information on past environments, especially
climate, from the annual rings of subalpine conifers in the Western
Himalaya. The relatively small collections of material made in 1980 and
1982 and subsequently analysed indicate that not only is this feasible,
but that there is very considerable promise for the successful
application of dendroclimatological techniques in Kasnmir and
neighbouring areas. One type of suitable material has been identified,
namely subalpine conifers from primarily temperature stressed sites.
The two example calibrations referred to in the previous paragraph
indicate the considerable potential of the network of multivariable
chronology sets from Kashmir as proxy records of past climate. The
possibility of using MXD chronologies from subalpine sites to
reconstruct spring and early summer temperatures, or even whole summer
temperatures might well increase the utility of dendroclimatology to
those interested in the effect of climate variability on systems such as
crops, rivers and glaciers in the Western Himalaya.

Preliminary work under the supervision of V.C. LaMarche
(A. Bhattacharya, pers.comm.) has shown that good material from
moisture-stressed sites in Kashmir is also available. Ramesh et al
(1985) have taken major steps towards the use of stable isotope ratios
in the annual rings of Kashmir trees as proxy climate records. Taken
with the positive outcome of the feasibility study reported in this
article, these developments augur well for the increase of our knowledge
of climate in this important region by means of dendroclimatology.

9.   ACKNOWLEDGEMENTS

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7.2 DENDROCHRONO-CLIMATOLOGY AT MARSEILLE, FRANCE

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The research at Marseille is devoted to the Mediterranean area *sensu stricto* and to the south-western part of the Alps where Mediterranean influences are still prevailing. Additional chronologies from the northern French Alps provide elements of comparison. Coniferous and deciduous species are analysed.

A comparative analysis of the response functions of *Quercus pubescens* Willd. in south-eastern France and of *Quercus canariensis* Willd. in Tunisia and Morocco is presented as an illustration of the relationships between tree growth and Mediterranean climate.

An outline is also given of temperature reconstructions already achieved, mainly regarding *Larix decidua* Mill. from the south-Western French Alps.

1. INTRODUCTION

During the last forty years dendrochrono-climatology has been developing in Europe, Scandinavia and Soviet Union, that is to say in regions situated roughly north of the 45° parallel (ECKSTEIN, 1972; ECKSTEIN and WROBEL, 1983; GRASLUND, 1984; FLETCHER and LINNARD, 1977, HUGHES *et al.*, 1982). Great progress in that field has also been made during the last fifteen years in the Mediterranean area (HUGHES *et al.*, 1982; SERRE-BACHET, 1985b).

In France, few laboratories are directly concerned with dendrochronology or dendroclimatology, they are essentially : the Research Laboratory on Wood Quality at the National Center of Forestry Research (CNRF) at Nancy Amance (H. POLGE, F. HUBER), the Technical Center of Wood (CTB) in Paris (Y. TRENARD), the newly created Laboratory of Chronology at Besançon (G. LAMBERT), the Research Center of Medieval Archaeology at Caen (L. LEBOUTET, E. CHARLES) and the Laboratory of Historical Botany and Palynology at Marseille (F. SERRE-BACHET, L. TESSIER, J. GUIOT) (Fig.1). In most of these laboratories, only dendrochronological researches are conducted and often jointly with archaeology. But at the Laboratory of Marseille mainly dendroclimatological and dendroecological researches are carried on and long ring-width series from living trees are now available which make possible climatic reconstructions.

Owing to the geographical situation of Marseille, the researches have been devoted, since 1966, to the French Mediterranean area *sensu stricto* and other Mediterranean countries such as Italy, Morocco, Algeria, Tunisia or Syria as well as to the southwestern part of the French Alps where Mediterranean influences are still prevailing. Specific studies (tree form, air pollution) are also made in the northern French Alps.

Thus, at the Laboratory of Marseille many coniferous or deciduous tree species have been and still are analysed: some species are restricted to the Mediterranean area, but as a whole they have a wider geographical distribution :

Pinus halepensis Mill.
Pinus pinea L.
Pinus leucodermis Ant.
Pinus laricio Poir.
Pinus pinaster Sol.
Pinus silvestris L.
Abies alba Mill.
Picea excelsa Lamk.
Larix decidua Mill.
Cedrus atlantica Manetti
Cedrus libani Barr.
Tetraclinis articulata Vahl.Mast.

Quercus ilex L.
Quercus canariensis Willd.
Quercus afares Pomel
Quercus suber L.
Quercus cerris L.subsp.*pseudocerris*
Quercus pubescens Willd.
Quercus toza Bosc.
Quercus sessiliflora Salisb.
Fagus silvatica L.
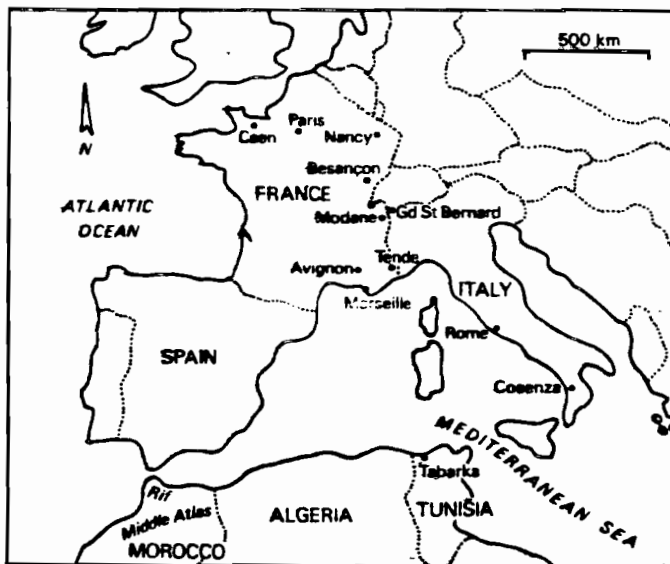
Fig.1 : Dendrochrono-climatological laboratories in France and location of the sites studied at the laboratory of Marseille

Dendroclimatological results obtained for *Quercus* and temperature reconstructions for the last millenium will be presented now.

2. DENDROCLIMATOLOGICAL RESULTS FOR *QUERCUS*

Analyses have been made of 18 populations of *Quercus pubescens* Willd. from various sites in southern France (TESSIER, 1984). 13 populations of *Quercus canariensis* Willd. from North Africa : 6 near Tabarka in North-western Tunisia (ALOUI, 1982), 7 in Morocco : 4 in the Rif, 3 in the Middle Atlas (RAOUANE, 1985). The response functions were established on a 30 to 50 years period, using the October to September precipitation and temperature parameters as predictors, ring-widths as predictands. The response functions were successively calculated for each site with precipitation-mean minimum temperature, precipitation-mean maximum temperature and precipitation-averaged mean temperature. In order to obtain the best signal to noise ratio, the predictands were corrected either by only removing the influence of the preceding year or persistency (ALOUI, 1981) or by applying the ARMA modelling (GUIOT *et al.*, 1982b) to each tree core or ray measurements (TESSIER, 1984; RAOUANE, 1985).

2.1. *Quercus pubescens* in France

The analysis of the response functions obtained for *Quercus pubescens* in southern France shows for that species a dominant sensitivity of growth to summer temperature. Precipitation is also involved in the variations, especially April or May precipitation on the one hand, depending on the date of the burst of annual tree growth, and June and accessorily July and August precipitation on the other hand. The relationships are always positive, *i.e.* direct, for these months.

A negative, *i.e.* inverse, relationship in September found in northernmost populations seems to be related to fructification.

As regards temperature, direct or positive relationships are evidenced from February to May, probably corresponding to cambial reactivation - since the more southern the sites are, the earlier do these relationships occur. In fact, mostly April temperature is concerned during this period.

Negative relationships between June-July temperature and growth are evidenced in nearly all the sites analysed. They suggest an important physiological activity of trees during a period when the water supply in the roots may suffer from drought, and confirm what has been observed by AUSSENAC and VALETTE (1982) in their measurements of *Quercus pubescens* sap pressure. One should note that these negative reactions mostly concern relatively old populations, whose well developed root system enables them to resist long dry periods.

2.2. *Quercus canariensis* in North Africa

The analysis of the response function obtained from *Quercus canariensis* in North Africa shows a marked heterogenity in the species behaviour. In Morocco, the oak is much more sensitive to precipitation and to temperature than in Tunisia; in Tunisia the species is markedly more sensitive to precipitation than to temperature. The relationships with precipitation are nearly always positive, whatever the region may be.

In Morocco the relationships essentially concern the months of December and March, as well as May, June and August, with differences between the Rif and the Middle Atlas (for example, there are more negative relationships in the Rif).

In Tunisia they concern the months of October, November, April as well as May, June and August; however variations may occur depending on elevation (October and April at low elevation, November at high elevation). Relationships with the precipitation of May are found in all the sites.

A negative relationship between September precipitation and the ring of the year at a low elevation and between October precipitation and the ring of the following year at high elevation is related to fructification. No similar relationship was found in Morocco for *Quercus canariensis* but it has been evidenced in a population of *Quercus toza* sampled in this country (RAOUANE, 1985).

Either positive or negative, but more frequently negative in Morocco than in Tunisia, the relationships with temperature in Morocco mainly concern December (+) and February (-) during the period prior to the formation of the ring, whereas in Tunisia they distribute quite irregularly from November to May depending on the sites. In Tunisia the summer period of July to September does not play a great role, contrary to Morocco where reversed relationships are found in the Rif and in the Middle Atlas (RAOUANE, 1985).

	June	July	August	September
Rif	-	+	+	+
Middle Atlas	+	-	-	+

2.3. Discussion

Owing to their geographical situation, altitude, exposition and bedrock, all the sites of *Quercus* studied are different as regards mean sensitivity (MS), percent variance related to prior growth (R2s)) or percent variance related to climate R2cl (R2cl = (1-R2s). R2c, with R2c = percent variance explained by the response function). The range of variation of these parameters is large :

	Quercus pubescens	*Quercus canariensis*
MS	0.15 to 0.27	0.13 to 0.21
R2s	05 to 79	0 to 85
R2cl	19 to 76	08 to 61

Nevertheless the values of M.S. vary around 0.20, the mean value for central Europe (HUBER and von JAZEWITSCH, 1956; MUNAUT and SERRE-BACHET, 1982), and there appears no close relationship between high values and altitude, though the sites in the Middle Atlas, with an elevation higher than 1500, show a better MS than the four sites in the Rif at 150 m or 1100-1200 m elevation.

R2s is less marked in Tunisia than in Morocco for *Quercus canariensis* or in France for *Q. pubescens* : 0.18 in average against 0.52 and 0.38.

The frequency distribution of all the R2cl reaches a maximum in the 0.31-0.40 class for *Quercus pubescens* and in the 0.41-0.50 class for *Quercus canariensis*. However in the last group, the R2cl from Tunisia concentrate on 0.41-0.50 and 0.51-0.60 classes with the highest frequency in the second class.

A comparison of the detailed results obtained from the response function shows an almost similar sensitivity to precipitation of May and June and quite complex or heterogeneous relationships with temperature from June to September.

It is obvious that the elevation more than the bedrock, the exposition or the geographical situation is implicated in the relationships with climatic parameters - as was also evidenced for *Quercus cerris* in Syria (CHALABI and SERRE-BACHET, 1981) - and in the more or less early occurrence of relationships with precipitation or temperature from February to May. This earliness is also related to the cambial reactivation of the trees whatever the species. For *Quercus* just as for *Pinus halepensis* (SERRE, 1976), the need of water is the greatest during the March to June period; it continues until september with an interruption in July for *Quercus canariensis*.

Fructification has a part in the negative relationship with the precipitation of September n or October n-1, depending on the altitude or latitude of the populations.

The negative relationship with the June and July temperature which characterizes *Quercus pubescens* in France, is also found in *Quercus canariensis*. It involves a dominant limiting effect of temperature on precipitation. In both cases it indicates a relatively strong cambial and physiological activity in spite of drought. Other species such as *Cedrus atlantica* Manetti introduced in Southern France (GUIBAL, 1985) show the same type of relationship, whereas *Pinus silvestris* (TESSIER, 1984) or *Pinus halepensis* (SERRE, 1976) may stop their activity during this period.

Sometimes absent or limited to one month only in France, occurring in June in the Rif, in July or August in the Middle Atlas, and hardly present at all in Tunisia, the relationship with summer temperatures reflects well the topographic and edaphic conditions of the sites colonized by *Quercus* in the Mediterranean area.

The comparison between the results obtained for the two species and those obtained for *Quercus robur* L. in the North of Germany (ECKSTEIN and SCHMIDT, 1974) or in England (HUGHES *et al.*, 1978; PILCHER and GRAY, 1982) highlights the needs of the genus regarding water, especially in May, and shows how for a same species these needs vary from one site to another. However, it seems that in the Mediterranean area, as compared with more northern regions, the reaction towards summer temperature characterizes the two species studied, whereas the percent variance of the ring-widths related to climate as a whole is about the same or lower (Schleswig-Holstein : 26; England : 34, 61 and 64).

3. CLIMATIC RECONSTRUCTIONS

Climatic reconstructions from tree rings imply that long series of tree-rings are available, of course longer than the longest series obtained from meteorological records.

The long tree-ring series used for reconstructions in Europe are either composite series obtained from living trees for the more recent time and from manufactured or fossil wood for older periods (ECKSTEIN and ANIOL, 1981; JONES *et al.*, 1984, BARTHOLIN, 1984) or series exclusively provided by more or less old living trees : BEDNARZ, 1984 : HUGHES *et al.* 1984: ANIOL and ECKSTEIN, 1984: GUIOT, 1981: 1984a; GUIOT *et al.* 1982a. Special mention should be made of researches performed in Switzerland which, on the basis of the variations of the maximal density of wood and of its close relation to the summer temperature, try to trace the holocene climatic

trends from wood remains buried in moraines (SCHWEINGRUBER *et al.*, 1978: ROTHLISBERGER, 1976, 1980: ROTHLISBERGER *et al.*, 1980: BIRCHER, 1982).

3.1 The material used at Marseille

At Marseille, four tree-ring series have been recorded from living trees sampled in four different sites at high elevation. The shortest series (323 yrs, 1653-1975) comes from *Abies alba* Mill in Mont Ventoux near Avignon (44°10′ N, 5°15′E, 1750-1800m elevation : SERRE-BACHET, unpublished). The three other series are longer than 600 yrs : a series obtained from *Pinus leucodermis* Ant. in Calabria near Cosenza (39°26′ N, 16°12′E, 1900 m elevation : SERRE-BACHET, 1985a) covers 827 yrs (1148-1974a); two series from *Larix decidua* Mill., one from the Orgère massif in Savoie near Modane (45°13′N, 6°40′E, 1900-2300 m elevation : TESSIER, 1981; TESSIER *et al.*, 1986), the other from the Vallée des Merveilles in the Maritime Alps near Tende (44°03′N, 7°27′E, 2150-2180 m elevation : SERRE, 1978, 1979) cover 621 yrs (1353-1973) and 1042 years (933-1974) respectively.

These series have been used several times together or separately on various periods (371, 775, 825 yrs) in tentative climatical reconstructions at the meteorological stations of Grand St-Bernard in the Pennine Alpes, Nice and Marseille in France, Rome in Italy (GUIOT, 1984a, b, 1985, 1986, SERRE-BACHET and GUIOT, 1986). Only ring-widths were considered. The meteorological station were chosen on account of the time covered by the instrumental records they provided. In the computation of the transfer functions used in reconstructions (GUIOT, *ibid.*), the time span of the instrumental records is of prime importance for calibrating the relationships between tree-ring and climate, verifying the calibration on an independant period and then proceeding to the reconstruction of meteorological data for a period longer than that covered by the instrumental data, which itself depends on the length of the available tree-ring series.

3.2. Results

Because of the elevation of the sites and of the main relationship between ring-width and summer temperature evidenced in them, we chose to reconstruct the summer temperature so as to obtain statistically reliable results. Among the studies made at Marseille, the following reconstructions were achieved : 1) the low frequencies of the mean temperature of August, December, Summer (June+July+August) and Autumn (September+October+November) as well as the interannual variation of the mean summer temperature at Grand St-Bernard (GUIOT, 1984a), 2) the interannual variation of the mean June-July temperature at Nice (GUIOT, 1984b), 3) The pluriannual and interannual variation of the mean June+July temperature at Marseille (GUIOT, 1985, 1986), 4) The interannual variation of the mean Summer temperature (June+July+August+ September) at Marseille, Rome and Grand St-Bernard (SERRE-BACHET and GUIOT, 1986).

A tentative reconstruction of precipitation at Nice did not provide reliable results because temperature was also involved in it (GUIOT, 1984b)

It would be of interest to reconstruct precipitation in a place such as the Mediterranean region, where summer drought is one of the main climatic factors. It is remarkable that the only reliable reconstructions of riverflow related to precipitation made in Europe are based on

deciduous trees (*Quercus petraea* Liebl. and *Quercus robur* L. : JONES *et al.*, 1984). Up to now, at Marseille, we have only used conifers in a particular geographical situation; deciduous species would perhaps be more suitable than conifers for reconstructions of precipitation; however, in view of the results presented in the first part of this paper concerning the Mediterranean *Quercus*, it is likely that such reconstructions would involve the vernal period rather than the estival period, during which *Quercus* growth is not markedly affected. The tree-ring series from deciduous species now available at Marseille are far too short; long series remain to be constructed before any attempt at climatic reconstructions.
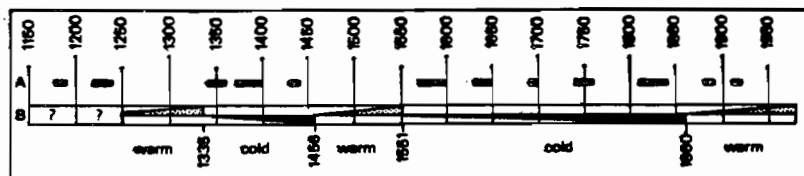
FIG. 2 : Particularly cold episodes (A) and evolution of the mean Summer temperature (B) at Marseille during the last millenium.

Meanwhile the evolution of the mean summer temperature (June to September) at Marseille during the last millenium (1150-1970 : SERRE-BACHET and GUIOT, 1986) can be schematized as in Fig. 2. A succession of alternately cold and warm crises rather than a continuous trend characterizes the analysed period. The longest cold phase, interrupted by a warm episode at the beginning of the XVIII century, corresponds to the so-called Little Ice Age; the XIXth century warming is also evidenced.

The same schema is found in meteorological stations as distant from one another as Marseille, Rome or Grand St-Bernard. A detailed analysis of temperature in the two mediterranean stations and a study of their peculiarity (supposing that they are peculiar) as compared with more northern stations, are now in progress.

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7.3 MODERN CHRONOLOGIES OF *ABIES ALBA MILL.* IN POLAND

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The European Silver fir in Poland reaches the north-eastern boundary of its natural range. This boundary runs approximately along the latitude of 52° North. In the Polish Tatra Mountains, firs grow up to 1450m above sea level (Myczkowski, 1966) (Figure 1). Beside the Norway spruce and European beech, the fir tree belongs to the most important forest forming trees in these mountains. Unfortunately, the decrease in fir covered area has been observed for quite some time. This is the result of mismanagement in forestry on the one hand, and the tragic and rapidly increasing phenomenon of fir dieback, especially in older stands, on the other. The cause of this phenomenon has not been unequivocally explained, as yet. It is sought in abiotic (Bernardzki, 1967; Dengler, 1944; Jedlinski, 1922; and Krzysztofik, 1963) as well as biotic factors (Wiedemann, according to Bernardzki, 1970). The complex nature of fir dieback requires comprehensive studies aimed at a thorough knowledge of its biology and its silvicultural requirements (Jaworski, 1973; Bialobok, 1983) as well as its sensitivity to environmental factors. In order to attain these aims, a wide range of environmental studies have been undertaken on fir trees in Poland. These are a continuation of Ermich's study (Ermich, 1951) on the dendroclimatology of fir in the Tatra Mountains. This paper reports on a part of these studies. It aims at the presentation of ring width chronologies of fir trees growing contemporarily in Poland, as well as an illustration of spatial differentiation of increment fluctuations.

Materials for the dendroclimatological studies have been collected in several dozen localities in the mountain regions (Sudetes, Carpathians, Saint Cross Mountains) as well as in the lowland areas situated mainly at the boundary of the fir trees' natural range in the localities placed under reserve protection. Some data represents several commercial fir stands, including one from outside the fir natural range, situated in the Manowo Forest Management Unit in northern Poland (52° N latitude). Each locality is represented by the dendroclimatological curve developed on the basis of ring width measurements taken along two stem radia of at least twenty trees. Before the development of the average curve, the material was verified in detail by comparing the chronology of increments of each radius and each tree. Itr was thus possible to eliminate all abnormalities and all measurement errors. The average curves were smoothed through the calculation of percent deviations from 10-year average values of ring widths for consecutive increments. The longest annual growth series
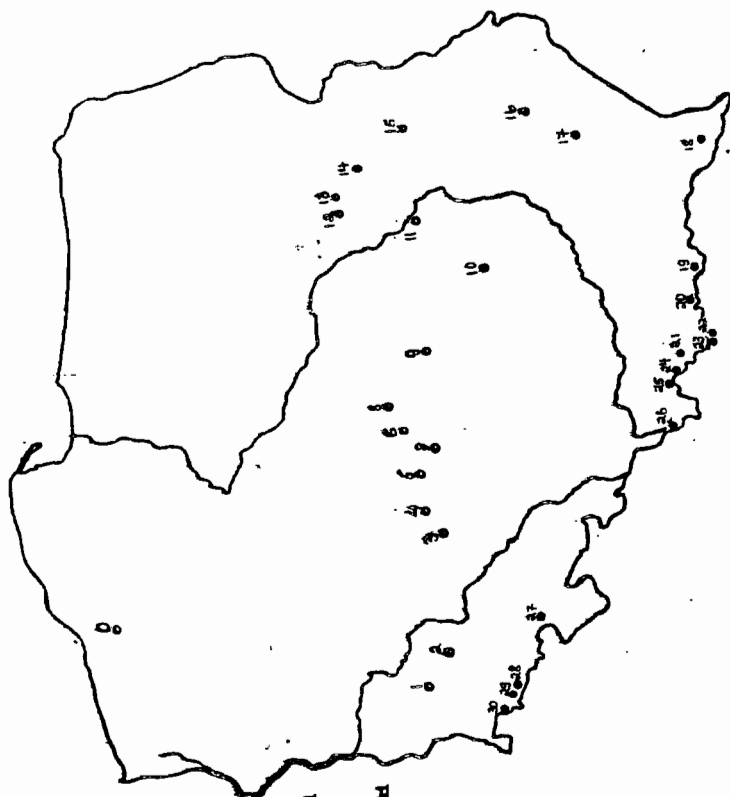
0. Namsos Dolne
1. Lasto Dolne
2. Chociebuda
3. Rez.,Gola
4. Arcoda
5. Rez.,Olbina
6. Rez.,Jamno
7. Nowa Wieś
8. Oleśnica
9. Lubańczów
10. Ss. Kryst
11. Rez.Grabie
12. Rez.Jedlina
13. Rez.,Rudka Sanatoryjna
14. Rez.Jata
15. Simdel
16. Rez.Buksowa Odra
17. Radzik
18. Przesmyki - Blesmowaty
19. Dol.Pusta (Krynica) - Beskid Sądecki
20. Pielniy
21. Babia Góra
22. Petry Zamachnis
23. Petry Dol.Białego Potoku
24. Rez.Cenzat (Ujsolry) - Beskid Żywiecki
25. Rez.Rytimka - Beskid Śląski
26. Rez.Bukoviec
27. Jupor
28. Dol.Szklarki
29. Jagniątków
30. Osłr Izerskie

Figure 1.   Study localities in Poland.

were obtained for fir growing in the mountain nature reserves, e.g., Zazadnia in the Tatra, Dolina Szklarki in the Karkonosze Mountains, Babia Góra and Rysianka Reserve in the Beskids. Some series comprise 200 years, but unfortunately they originate from single trees.

After development of mean growth curves for fir trees from individual localities, an interesting problem known in dendrochronology as "teleconnection" (E. De Ger, 1935) has arisen. It was possible to observe the variations in the rhythm of tree width fluctuations within the area of Poland, and to determine what factors decide these variations. Thus, the curves representing the individual fir localities were compared with one another utilizing the percentage index of curve similarity used by Huber (1943) and Bitvinskas (1965). It was assumed after Huber that 0% measn the highest similarity, i.e., the curves are identical. The index equal to 50% means a complete lack of similarity between curves under comparison. The higher values, e.g., 100% means a "negative simiarity" – the curves are a mirror reflection for each other. Only the most interesting resutls of this comparison have been included in this paper.

A most distinct similarity between dendrochronological curves was observe din the case of fir trees from the mountain localities (Table 1). The similarity index there varied from 15% for the neighboring localities (Zazadania-Dol. Bialego Potoku) as well as for the localities further away but from the same elevation (Zadadnia-Rez. Oszast), to 30% for the localities situated very far awy from each other (Zazadnia-Góry Izerskie).

The severe climate of the mountain regions decidedly affects tree growth, marking its variations in annual rings. The similarity of curves decreased with the increasing distance of the lowland localities from the mountains, but most frequently, it was as low as 58% (e.g., Zazadnia-Leszno). But there were also cases where the similarity index between curves for fir from the mountains and the lowlands reached 74% (Zazadnia-Lubaszów, Zazadnia-Antonin, Babia Góra-Szadek).

In the case of curves representing fir trees from the lowland areas, the following simple regularity was usually observed: the greater the distance between localities, the lesser the similarity of curves. However, there were exceptions from this rule. It seems that this phenomenon is connected with the uniformity of sites with respect to soil, phytosociological composition of plant communities and also with the extent and duration of anthropogenic effects, the degree of environmental pollution, etc. These problems will be studied in subsequent stages of the investigations. Generally speaking, the spatial variability of growth curves is of a continuous character. When comparing the curves from the localities arranged successively from West to East, it was found that the curves of consecutive localities are characterized by a high similarity, e.g., 9 and 10, 10 and 11, etc. Curves for the extreme localities, i.e., from West and East are less similar (Table 2). This results not only from the distance between extreme localities, but it appears that it is connected with an

Table 1. Percentage similarity indices for curves representing firs from mountain regions.

Number and name of localities under comparison	Distance between localities	Elevation above sea level	Percentage curve similarity
22 Zazadnia		1100 - 1200	
- 23 Dol.Białego Potoku	10 km	1200 - 1300	15,6
22 Zazadnia		1100 - 1200	
- 21 Babia Góra	55 km	800 - 900	20,8
22 Zazadnia		1100 - 1200	
- 24 Rezerwat Oazast	65 km	1100 - 1200	15,0
22 Zazadnia		1100 - 1200	
- 26 Rezerwat Bukowiec	100 km	700 - 750	20,0
22 Zazadnia		1100 - 1200	
- 19 Krynica	80 km	800 - 850	18,2
22 Zazadnia		1100 - 1200	
- 18 Pszczeliny	200 km	700 - 800	26,0
22 Zazadnia		1100 - 1200	
- 10 Święty Krzyż	190 km	550 - 580	23,4
22 Zazadnia		1100 - 1200	
- 27 Jugów	330 km	700 - 750	28,7
22 Zazadnia		1100 - 1200	
- 29 Jagniątków	400 km	600 - 700	28,7
22 Zazadnia		1100 - 1200	
- 30 Góry Izerskie	450 km	900 - 1000	30,0

increasing degree of continentalism in the climate towards the East. It is expected that this conclusion will be confirmed by further detailed analyses of ring chronologies.

Interesting results were obtained from the comparison of the growth curve representing 90—year fir stands of artificial origin (Manowo—North Poland) with the remaining curves (see Table 3).

On the basis of results obtained by the comparison of growth curves it may be concluded that fir trees growing in Poland are strongly affected by macroclimatic factors, the variability of which is expressed by a similar rhythm of annual oscillations in ring width of fir wood in Poland as a whole.
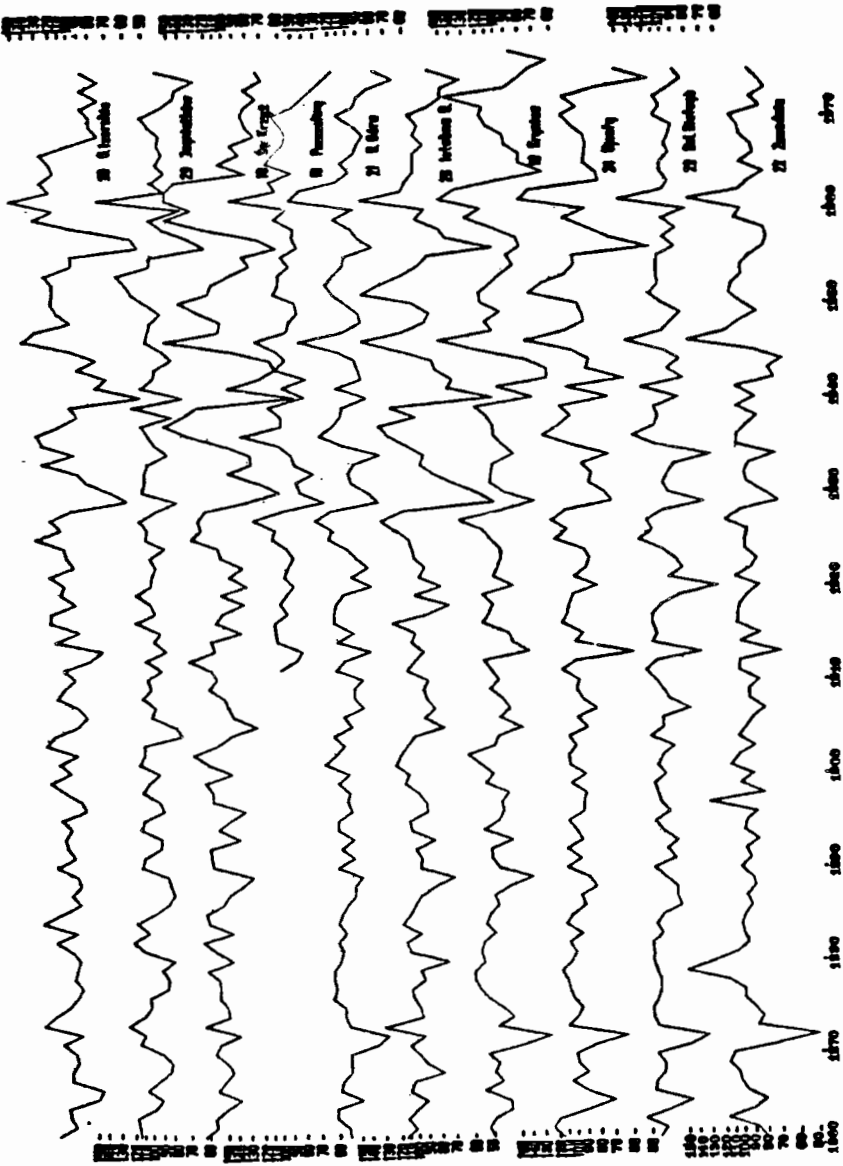
Figure 2. Curves representing chronology of annual increments of firs in the mountain regions

Table 2. Percentage similarity indices for curves representing firs
from lowland regions.

Number and name of localities under construction	Percentage of curve similarity
1 Leszno - 2 Chocianów	20,3
1 Leszno - 3 Rezerwat Goła	24,7
1 Leszno - 4 Antonin	23,0
1 Leszno - 5 Rezerwat Olbina	26,6
1 Leszno - 6 Rezerwat Jamno	22,2
1 Leszno - 7 Rezerwat Nowa Wieś	29,5
1 Leszno - 8 Oleśnica	32,0
1 Leszno - 9 Rezerwat Lubiaszów	29,5
1 Leszno - 10 Św. Krzyż	33,6
1 Leszno - 11 Rezerwat Grabie	28,3
1 Leszno - 13 Rezerwat Rudka	34,2
1 Leszno - 14 Rezerwat Jata	36,2
1 Leszno - 15 Siemień	38,6
1 Leszno - 16 Rezerwat Bukowa Góra	35,3
1 Leszno - 17 Rudnik	34,2

Fir trees from mountains areas are characterized by the highest
similarity of growth curves. In that case, the value of the similarity
index depended not only on the distance between the localities, but
above all, on the elevation above sea level. A high similarity was
observed between curves representing localities of fir situated at
similar elevations. In the lowland, the similarity between curves
decreases with increasing distance between the localities.

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Table 3. Percentage indices of similarity percentage between curves for firs from Manowo and other localities.

Number and name of localities under construction				Percentage of curve similarity
0	Manowo	-	4 Antonin	16,0
0	Manowo	-	7 Rezerwat Nowoa Wieś	28,0
0	Manowo	- 13	Rezerwat Rudka	28,0
0	Manowo	-	5 Rezerwat Olbina	30,6
0	Manowo	-	3 Rezerwat Goła	30,6
0	Manowo	- 14	Rezerwat Jata	32,0
0	Manowo	-	6 Rezerwat Jamno	33,3
0	Manowo	-	2 Chocianów	33,3
0	Manowo	-	9 Rezerwat Lubiaszów	33,3
0	Manowo	- 17	Rudnik	33,3
0	Manowo	-	1 Leszno Dolne	37,3
0	Manowo	-	8 Oleśnica	38,6
0	Manowo	- 22	Zazadnia	34,6
0	Manowo	- 29	Jagniątków	36,0
0	Manowo	- 24	Oszast	37,0
0	Manowo	- 26	Rezerwat Bukowiec	37,3
0	Manowo	- 19	Krynica	37,3

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**7.4   TREE-RING INVESTIGATIONS OF *PICEA ABIES* FORESTS IN THE
       PARANGALITSA BIOSPHERE RESERVE**

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1.   INTRODUCTION

Complex ecological studies on the structure and functioning of the most important forest ecosystems have been carried out in Bulgaria over the past two decades. Investigation on changes of radial growth of forests of the principal forest species under the influence of ecological factors were a part of the investigation programme. The need of such data has grown substantially recently, as it is linked with the historical approach in the study of forest ecosystems, in particular over several centures, as well as with possible variations over the following decades.
The application of the tree-ring analysis best meets these requirements in particular when the studied forest stands are of considerable age. The purpose of this paper is to outline the changes of radial growth of representative forest ecosystems in Bulgaria by means of the tree-ring method.

2.   EXPERIMENTAL MATERIAL AND SITES

Subject of the experiment were Picea abies Karst forests of great economic significance. In order to obtain observations from a longer period the source material was drawn from the Paranglitsa biosphere reserve known for its spruce stands. The Parangalitsa reserve is situated along the western slopes of Rila Mountain in the central part of the Balkan Peninsula. Spacious spruce forests grow on rich dark brown forest soils lying on basic rock (granite) in the lower parts of the reserve between 1450 and 1650 m a.s.l., at coordinates 42°02' N and E 23°20'. Mean annual temperature is 4.9° C; the growing season continues about 115 days; precipitations approx. 933.7 mm (Raev, 1986). The site is on the border of a cool and moderate mountain climate and part of the "zone of optimums" for the growth of coniferous vegetation in Bulgaria (Raev, 1983).

Outlined is a spring precipitation maximum (April- May). connected with continental climatological influence, however a secondary increase of precipitation (December - February) - a indication of a Mediterranean climate influence is also noted, and strengthened by the Struma valley. Minimal precipitations were measured between July-October.

Under these ecological conditions spruce forests of the Parangalitsa reserve noted a exceptional wood-mass above ground up to 1434 m^3/ha. The forests are of uneven age, trees between 150-250 years pravailing, while separate specimens reach an age of 350 years and more and a height up to 55 - 60 m.

3. METHODE

Twenty six trees with a mean diameter 60.5 cm (from 41 to 92 cm) were selected for analysis with a mean height of 40.5 m (from 21 to 54 m) - Table 1.

One stem disc was taken from each tree at a height of 1.3 m from the ground, half the tree (1)- from the bufferr zone of the reserve , while the remaining 13 trees came from fallen trees in the reserve (d). Each stem disc was processed after the methods described by Stokes, Smiley (1968). Two radiuses were measured on each disc, by means of a binocular microscope type MБC-9, magnification 16 times and precision 0.05 mm. Growth indices for each sample were calculated after the method of Fritts, Mosiman, Bottorff (1969) and Fritts (1976) by means of the expression

$$y = a.e^{-bx} + K$$

where y = width of annual ring; x = age of annual ring; a and b - parameters; e - Naper's constant (e 2.7182...); K - free right hand side.

In these studies we used formula (1), ommitting the member K as it is used with shorter periods. The data was processed on a personal computer type PRAVETZ-82 in order to study the distribution of rows of indices and all remaining analyses statistical studies on the normal distribution of the obtained rows of indices we carried out and are given in Table 2. (n - number of observation $\bar{x}$ - average; SE - standart error of the mean CV - coefficient of variation; σ - standart deviation; As -sqewness; Ex - kurtosis.

According to the results from this table normal distribution was evident in 16 tree samples, which provided data for the establishment of Parangalitsa tree ring chronology.

The method of non linear regression analysis was applied in the search of a link between changes of growth indices and certain important ecological factors (temperature, precipitation, solar activity). An attempt was made to work out approximation and extrapolation curves: using periods of years (3,7,15, 25,35), after the method empoyed by Douglas (1933).

Climatic data was drawn from the neighbouring Ecological station of the Forest Research Institute of the Bulgarian Academy of Sciences, located the same elevation and in similar forests at the Govedartsi stationary (1550 m a.s.l), some 30 km from the investigated site (the period 1964-1982). Wolf's numbers were taken from Vitinskii (1973) for the 1784-1971 period and from the Institute of Geophysics at the Bulgarian Academy

of Sciences, Sofia for the 1971-1981 period.

4.   RESULTS

Table 3 provides the mean values of the variation of the width of annual rings in mm., obtained from 26 treees of Picea abies from the Parangalitsa biosphere reserve, Rila Mountain. A period of 200 years is examined; from 1783 to 1982. Mean annual radial growth with these spruce foresets vary between 1.08 mm (1929) and 3.37 mm (1837), i.e. it retains a hight growth rate, which corresponds to the favourable ecological conditions of the reserve. The data on growth can be employed for various scientific purposes in forest science, dating in archeology etc.

This data assumes greater importance when growth indices are used i.e. arriving at a standardized chronology. The values thus obtained are not affected by the biological peculiarities of tree aging and can serve as an objective model of various ecological factors, as well as for the establishment of cycles, dating various phenomena etc.

Fig. 1. shows tree ring chronology in the Parangalitsa reserve given in indices. The index curve is reprecented in 6 variants; O - without smoothing of indices; variant 3,7,15,25,35 - by moving average smooting values for sets of 3,7,...35 years.

A rhythmic pattern occurs within a cycle of 11 to 24 years through smoothing of the curve of indices:

I	:	from	1784	to	1795	= 11 years
II	:		1795	-	1806	= 11 years
III	:		1806	-	1820	= 14 years
IV	:		1820	-	1834	= 14 years
V	:		1834	-	1858	= 24 years
VI	:		1858	-	1874	= 16 years
VII	:		1874	-	1896	= 22 years
VIII	.:		1896	-	1908	= 12 years
IX	:		1908	-	1929	= 21 years
X	:		1929	-	1947	= 18 years
XI	:		1947	-	1963	= 16 years
XII	:		1963	-	1981	= 18 years

With certain reservations it is possible to point to a rhythmical pattern of approximately 16 years for the 1784 - 1981 period.

A rhythmic pattern of a higher degree, between 33-36 (from 1796 to 1832, from 1832 to 1865 etc) appears with smoothing of 7 years.

The greatest smoothing 25-35 years brings out a fluctuation of about 85 years for the 1835-1920 period as well as parts of other large cycles.

What is the connection between changes in the growth of spruce forests and ecological factors? Table 4. offers to a certain extent an answer to this question through the mathematical link between indices (y) and ecological factors (x): temperature (T), precipitation (P), and Wolf's number(W), R - multiple correlation coefficient, V_1, V_2 degree of freedom; F - the test satisfies F = will have degrees of V_1, V_2 with critical value of F-distribution and confidence level = 0.05.

The analysis of the obtained results shows that the best link between indices of growth and air temperature is obtained when the "mean month temperature variant" is used for the period May previous year (n-1) up to September current year (n), where R = 0.93 and F = 42.29. A very good relation is also observed during the periods October-September and January-December; January-September etc. showed the weakest relation with variant 7 of the studies cases. Hence not only temperatures during the vegetation period are of importance for the explanation of the annual radial growth , in this

case but also previous summer, autumn and winter temperatures. A similar me-
thod was used for the study of the relation with precipitations (P). The
best correlation with precipitation was over the January-September period
(n), where R = 0.79, F = 21.75;a good correlation also occurs for the follo-
wing periods: May-September and October-July, it is weak for the remaining
variants. Hence precipitations is of substantial importance for annual
growth not only during the vegetation period, but also during the winter
season (January - September). The weakest correlations appear with Wolf's
number, however. this rather indicates an absence of direct evidence of this
impact and does not exclude the inderect of solar activity. The results
of attempt to arrive at an approximated curves of smoothed series of indices
3,7,15,25 are given in Table 5.
Particulary good results are obtained for smoothed curves over 15 years (R=
0.94), 35 years (R=0.90) and others. The values obtained through these fun-
ctions are used for plotting of aproximation curves, as well as for extra-
polation of the results up to the year 200 (Figure 2.). Some trends have
been worked out for smaller and larger cycles of the growth indices. Inter-
vals of decreased growth are outlined (over the 1980-1987; 1994-2000 peri-
ods),together with the possibility of increased growth (1985-1994). Through
the smoothing of 3,7,15 years. With the greatest smoothing (25,35 years)
large cycles of gradual increase of growth (from 1980) are outlined.
       This study indicates that intersting results can be obtained not only
from forest ecosystems of the zones with limithing ecological factors, but
also from zones of optimal natural conditions for a given species.

5. CONCLUSIONS

       The experiments carried out for tree-ring analysis of 26 trees of Pi-
cea abies in the Parangalitsa biosphere reserve, Rila Mountain established
the following conclusions:
5.1. Obtained tree-ring chronology - Parangalitsa (given in mm) covers the
1783-1982 period, and can be employed for archelogical dating and other
purposes.
5.2. Tree-ring chronology Parangalitsa (in indices) allows the establish-
ment of cycles of growth over a cycle of 16 years, over 33-36 years, and a
century long cycle with a duration of approx. 85 years.
5.3. A good relation has been established between the change of indices and
certain principal climatic factors. Not only temperature and precipitation
during the current vegetation period is of substantial importance to annual
growth but also that the preceeding winter, autumn, even summer.
5.4. The results obtained from statistical analysis of the rows of indices
allow some extrapolation and prognosis of growth in the studied spuce
forests.

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ACKNOWLEDGEMENT

TABLE 1.

BIOMETRIC CHARACTERISTICS OF TREES FROM THE
PARANGALITSA BIOSPHERE RESERVE SUBJECTEDTO
TREE-RING ANALYSIS

No	Begining	End	n.	h	$d_{1,3}$	Note
	year		years	m	cm	
1.	1854	1982	129	42	62	1
2.	1793	1982	190	49	72	1
3.	1697	1979	286	54	86	d
4.	1805	1980	176	41	49	d
5.	1866	1982	117	39	48	1
6.	1813	1978	166	43	59	d
7.	1815	1982	168	47	65	1
8.	1797	1982.	186	50	82	1
9.	1826	1982	157	47	65	1
10.	1844	1982	138	44	63	1
11.	1856	1982	127	42	64	d
12.	1836	1972	137	46	67	d
13.	1840	1974	135	43	60	d
14.	1851	1980	130	44	67	d
15.	1799	1981	183	51	92	d
16.	1839	1967	129	40	58	d
17.	1850	1972	123	41	48	d
18.	1860	1982	123	36	47	d
19.	1841	1978	138	38	46	d
20.	1783	1963	181	42	60	d
21.	1940	1985	46	24	62	1
22.	1837	1985	138	30	49	1
23.	1872	1985	113	29	60	1
24.	1904	1985	82	28	46	1
25.	1922	1985	64	30	41	1
26.	1903	1984	82	34	54	1

TABLE 2.

STATISTICAL CHARACTERISTICS OF THE LINES OF
INDICES OF PARANGALITSA TREE-RING CHRONOLOGY

No	n	$\overline{X}$	C.V	SE	σ	As	E_x	Distribution
1.	129	105.97	0.33	0.41	35.45	0.40	-0.31	normal
2.	190	107.70	0.34	0.35	36.96	-0.23	-0.59	normal
3.	194	105.55	0.38	0.34	36.97	-0.43	-0.20	normal
4.	176	104.68	0.29	0.36	30.70	0.23	-0.34	normal
5.	117	110.53	0.47	0.43	51.53	0.83	-0.55	abnormal
6.	166	102.63	0.22	0.37	23.02	0.29	0.06	normal
7.	168	107.98	0.35	0.37	37.97	-0.13	-0.71	normal
8.	186	109.65	0.41	0.35	44.50	0.66	1.66	abnormal
9.	157	106.90	0.37	0.38	40.04	1.05	1.57	abnormal
10.	138	106.14	0.34	0.40	35.63	0.42	0.01	normal
11.	127	101.93	0.20	0.41	20.05	0.40	0.04	normal
12.	137	100.34	0.21	0.40	21.21	1.23	2.19	abnormal
13.	135	103.82	0.28	0.40	28.84	1.12	3.97	abnormal
14.	130	102.52	0.22	0.41	22.62	0.21	-0.33	normal
15.	183	106.51	0.34	0.35	36.58	0.28	-0.59	normal
16.	129	104.95	0.32	0.41	33.53	0.75	-0.06	abnormal
17.	123	105.09	0.32	0.42	33.72	0.67	-0.14	abnormal
18.	123	103.82	0.27	0.42	28.33	0.39	-0.19	normal
19.	138	105.34	0.32	0.40	33.29	0.70	1.43	abnormal
20.	181	108.71	0.48	0.35	51.85	3.04	15.34	abnormal
21.	46	109.59	0.37	0.64	40.67	0.00	0.30	normal
22.	138	141.45	0.66	0.40	93.95	0.26	-0.66	normal
23.	113	127.40	0.71	0.44	90.00	2.00	7.13	abnormal
24.	82	110.63	0.40	0.51	43.80	-0.17	-0.78	normal
25.	64	104.13	0.28	0.56	29.21	0.00	-0.11	normal
26.	82	104.68	0.30	0.51	31.11	0.38	-0.19	normal

TABLE 3.

TREE-RING CHRONOLOGY, PARANGALITSA, OBTAINED THROUGH 26 SPECIMENS OF PICEA ABIES (IN mm), OVER THE 1783 - 1982 PERIOD, RILA MOUNTAINS.

Years	0	1	2	3	4	5	6	7	8	9
1780	-	-	-	1.65	2.42	1.75	2.37	2.20	2.75	2.47
1790	2.20	1.67	2.25	1.83	1.88	1.58	2.20	1.96	1.73	2.05
1800	2.26	3.37	2.33	2.33	2.48	2.13	2.09	2.32	2.60	2.54
1810	2.69	2.80	2.67	2.31	2.59	2.54	2.65	2.16	2.09	2.13
1820	1.95	2.12	2.04	1.88	1.91	1.80	2.08	2.31	2.01	1.94
1830	1.71	1.82	2.00	1.77	1.90	1.82	2.10	2.20	2.20	2.42
1840	2.34	2.48	2.40	2.52	2.44	2.48	2.61	2.46	2.53	2.52
1850	2.81	2.96	2.74	3.01	2.71	2.66	2.53	2.45	2.39	2.45
1860	2.53	2.47	2.28	2.04	2.08	2.21	2.23	2.11	2.18	2.27
1870	2.37	2.46	2.35	2.15	1.89	1.95	2.29	2.05	2.08	2.09
1880	1.98	2.16	1.98	2.02	2.11	2.27	2.19	2.09	1.90	1.79
1890	1.92	1.72	1.85	1.66	1.69	1.56	1.47	1.53	1.63	1.66
1900	1.60	1.58	1.67	1.52	1.40	1.36	1.24	1.26	1.26	1.22
1910	1.38	1.37	1.45	1.47	1.59	1.53	1.45	1.55	1.43	1.35
1920	1.41	1.21	1.20	1.14	1.21	1.24	1.26	1.17	1.10	1.08
1930	1.20	1.15	1.21	1.19	1.48	1.34	1.45	1.42	1.39	1.47
1940	1.39	1.42	1.48	1.37	1.78	1.64	1.62	1.48	1.74	1.72
1950	2.21	2.10	2.14	1.78	1.91	2.10	2.12	1.99	1.99	2.05
1960	2.05	1.73	1.66	1.67	1.72	1.82	1.70	1.89	2.15	2.09
1970	2.20	2.21	2.38	2.36	2.33	2.49	2.31	2.33	2.32	2.60
1980	2.07	1.99	2.22	-	-	-	-	-	-	-

TABLE 4

RELATIONSHIP BETWEEN INDICES OF THE GROWTH OF CERTAIN ECOLOGICAL FACTORS (T - TEMPERATURE, P - PRECIPITATION, W - WOLF'S NUMBER) ON THE CHRONOLOGY OF PARANGALITSA, RILA MOUNTAINS

No	Period (months)	years	Type of Function	ν_1	ν_2	R	P
1. **T**			**TEMPERATURE - INDICES OF THE GROWTH**				
1.1.	T_v^{n-l} : T_m^n	1966 - 1981	$y = 40.78 \sin x + 88.85 \cos x + 52.32$	2	13	0.93	42.29
1.2.	T_f^{e-l} : T_m^e	1966 - 1981	$y = -90.16 \sin x - 4.83 \cos x + 57.12$	2	13	0.89	25.31
1.3.	T_f^n : T_m^n	1965 - 1981	$y = -72.31 \sin x - 5.62 \cos x + 72.49$	2	14	0.85	18.58
1.4.	T_f^n : T_m^e	1965 - 1981	$y = -32.57 \sin x + 45.09 \cos x + 90.07$	2	14	0.71	7.06
1.5.	T_f^e : T_m^e	1965 - 1981	$y = -29.53 \sin x + 4.62 \cos x + 116.12$	2	14	0.69	6.41
1.6.	T_{v-m}^{e-l} + T_m^{-m}	1965 - 1981	$y = -40.48 \sin x + 19.13 \cos x + 103.12$	2	14	0.60	3.91
1.7.	T_v^{n-l} : T_m^{n-l}	1966 - 1981	$y = -49.43 \sqrt{x} + 305.33$	1	14	0.48	4.18
2. **P**			**PRECIPITATION - INDICES OF THE GROWTH**				
2.1.	P_f^n	1965 - 1981	$y = 0.09 \sqrt{x^2 + x} + 70.55$	1	15	0.79	21.75
2.2.	P_f^e	1965 - 1981	$y = 0.13 \sqrt{x^2 + x} + 71.1$	1	15	0.67	18.17
2.3.	P_x^{n-l}	1966 - 1981	$y = 3.9 \sqrt{x} + 26.41$	1	15	0.63	9.84
2.4.	P_x^{n-l}	1966 - 1981	$y = 8.55 \sin \frac{x}{2} + 4.42 \cos \frac{x}{2} + 134.66$	2	13	0.49	2.03
2.5.	P_r^n	1965 - 1981	$y = 2.91 \sin x + 8.96 \cos x + 134.77$	2	14	0.48	2.04
3. **W**			**PRECIPITATION - WOLF'S NUMBER**				
3.1.	I - XII	1784 - 1981	$y = 474.11 \, e^{-x} . \sin \frac{x}{2} + 129.38$	1	196	0.20	8.13

TABLE 5.

FUNCTIONS OF GOOD APROXIMATION OF DATA SMOOTHED LINES OF
GROWTH INDICES OVER DIFFERENT PERIODS (3, 7, 15, 25, AND
35 YEARS) IN THE CHRONOLOGY OF PARANGALITSA

No	Smoothed Curves Over	Years	Type of Function	V_2	V_1	R^2	F
1.	3 years	1962-1981	$y = -21.34 \sin \frac{x}{3} + 130.3$	1	18	0.87	59.46
2.	7 years	1964-1979	$y = -13.95 \sin \frac{x}{3} + 132.83$	1	14	0.76	18.80
3.	15 years	1960-1975	$y = -10.74 \sin \frac{x}{3} + 125.06$	1.	14	0.94	106.86
4.	25 years	1929-1970	$y = -17.54 \sin \frac{x}{6.4} + 104.14$	1	40	0.73	46.19
5.	35 years	1915-1965	$y = -18.23 \sin \frac{x}{9} + 96.18$	1	19	0.90	218.6
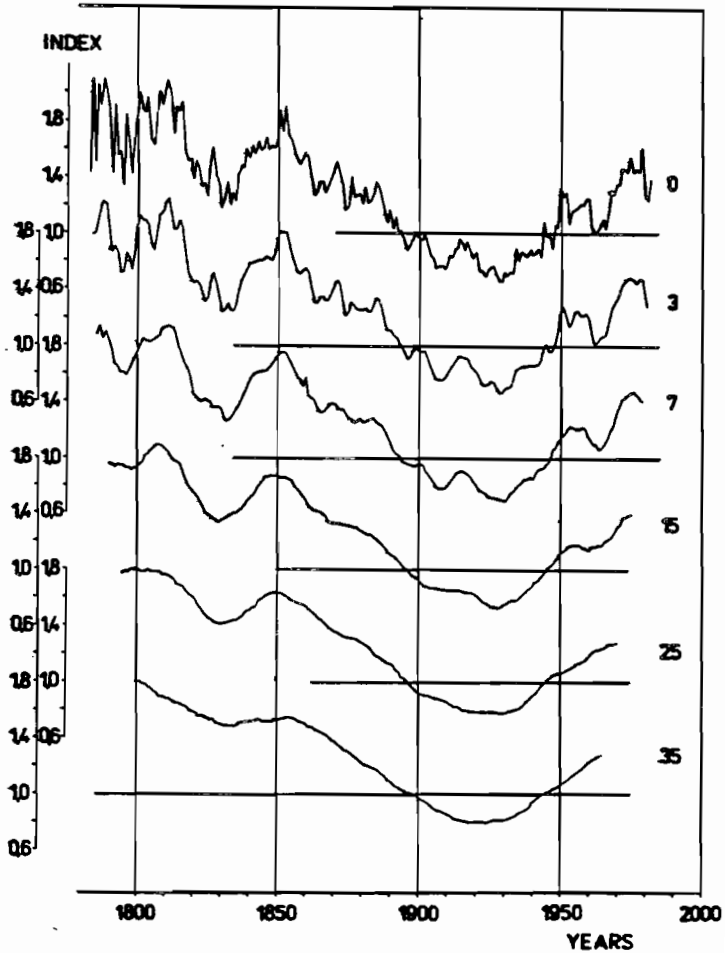
FIG.1 PARANGALITSA TREE-RING CHRONOLOGY FOR PICEA ABIES KARST.(IN INDICES) WITH DIFFERENT SMOOTHING CURVES (FOR 3, 7, 15, 25, 35 YEARS) FOR THE 1783-1982 PERIOD
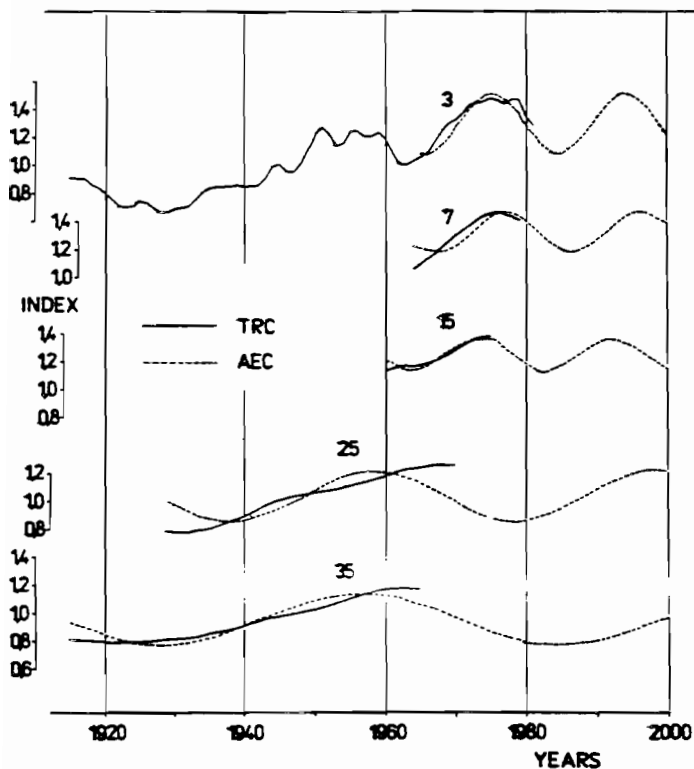
FIG. 2 APPROXIMATION AND EXTRAPOLATION CURVES (AEC) OF PARANGALITSA TREE-RING CHRONOLOGY (TRC) WITH DIF-FERENT SMOOTHING CURVES (FOR 3,7,15,25,35 YEARS)

7.5 DENDROCHRONOLOGICAL STUDIES OF RECENT DRIFTWOOD ON SVALBARD

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1. INTRODUCTION

The Eurasian and North American rivers draining into the Arctic Ocean and its approaches carry huge quantities of driftwood. Much of this wood is caught by ocean currents and eventually deposited along the barren shores of the Arctic, figure 1 (e.g. Murchinson 1855, Agardh 1869, Ingvarsson 1903, Kindle 1921, Eurola 1971, Häggblom 1982). Contingent on the exposure of these coasts to the currents, the sea ice conditions, and the local topography, etc., the driftwood can be found ashore as scattered pieces, or the beaches may be quite literally covered with it, on occasion by thick piles of logs. In addition to the logs there may be old barrels, pieces of wrecked ships, wooden boxes, beer cases, etc., on the lower beaches. Depending on the local climate the driftwood can remain for a substantial length of time. The drier and less vegetated the area is the longer the wood can be preserved and driftwood several thousand years old is not uncommon (e.g. Häggblom 1982).

This driftwood represents a very useful and valuable geological aid, particularly if the coastline, as is usually the case in the Arctic region, has been rising for most of the last 10,000 years. For instance:
1)   The driftwood may be used for dating the elevated beaches (usually done with ^{14}C method), and for constructing shoreline displacement curves. These curves, among other things, reveal the speed of the relative rise of the land throughout time.
2)   Increased amounts of driftwood within certain altitude zones on the beaches may indicate marine transgressions, when younger wood from lower zones is redeposited upwards by the rising sea (increasing the spread of ages within the sampled material), or it could reflect changes in the general influx of driftwood. The latter may be caused either by climatic changes in the source areas, e.g. leading to increased erosion there, or by changes in forestry practices (relevant for the youngest beaches only). Moreover, it can also depend on changes in the ice cover on the Arctic Ocean, as much of the driftwood is actually transported for long periods on the ice (Häggblom 1982). The final deposition can also be compounded by the varying accessability of the shores, as delimited by the extent and duration of open water along the coast (e.g. Blake 1972, Häggblom 1982). If, however, the primary

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factor behind increased accumulation of driftwood on certain beach levels is
an increasing influx rather than a redistribution, then the age spread within
the sampled material should be small.
3)   A knowledge of the geographical distribution patterns, within the Arctic
region, of driftwood from different source areas, and of time-dependent varia-
tions in those patterns, can also tell us much about the dynamics of currents
in the Arctic Ocean (Nansen 1897, Eurola 1971). This information has hereto-
fore been derived either from genetic and specific identification of the wood
(e.g. Eurola 1971), or from markings on anthropogenic driftwood and flotsam
found on the beaches (e.g. Häggblom 1982).

FIGURE 1   An example of driftwood concentrations (Glenhalvöya, Nordaustland,
Svalbard). Photo: A. Häggblom 1980.

2.   THE PRESENT STUDY

     This study is a pilot project aiming at evaluating the potential for
constructing dendrochronological series on samples of Arctic driftwood. Such
a chronology could give valuable information on the rhythm of driftwood
production in the source areas, as well as data on the rates of driftwood
influx onto the Arctic shores. The viability of a driftwood chronology will
naturally be enhanced if it can be supported and complimented with dendro-
chronological samples collected from the source areas.
     A driftwood dendrochronology can also greatly reduce expenses for the
scientific study of raised beaches. For example, the ages of samples from
different beach altitude could be quantitatively studied at much lower cost,

and much more precisely, than if each log has to be ^{14}C dated. A driftwood chronology would also improve the internal coherence and general reliability of the shoreline displacement curves, especially in areas rich in driftwood, and once available would almost completely dispense with the need for ^{14}C datings.

3. METHODS AND MATERIAL

In 1984 geologists from the University of Lund arranged an expedition to the Bohemanflya peninsula in Isfjorden, 40 km northwest of the town of Longyearbyen on Svalbard's main island, Spitzbergen, (78°25'/14°30'E), an area known for its concentrations of driftwood. This expedition offered an excellent opportunity to initiate a pilot study in dendrochronology on Arctic driftwood, with a minimum of cost and organization.

The results from the construction of a long-time chronology on Pinus silvestris from Swedish Lapland (Bartholin and Karlén 1983) had revealed a high correlation with a similar series from Finnish Lapland. A t-value = 9.36 was found even as far as the Kola Peninsula (locality 2, figure 2). This indicated that a strong dendrochronological similarity might be expected even over very long distances in the Sub-arctic zone, where Arctic driftwood would have its origins.

It was nonetheless decided for the project's initial phase to restrict the first sampling to modern driftwood alone, in order to limit the spread in time of the samples. For this purpose the Isfjord area was ideal. Human presence has been regular there since the 17th century (whaling), and until as late as the 1920's collected driftwood played a vital role as both fuel and building material. For this reason, and due to a relatively humid local climate which promotes natural decay of the wood, much of the driftwood older than circa 1920 can be expected to have disappeared from the area.

There was in fact a considerable assortment of driftwood available within a distance of only 1 km from the camp on the shore of the fjord: a few whole logs, many butt and top logs, some longer and shorter logs with nails and cut-outs once possibly used in rafting, and a variety of sawmill materials in different stages of preparation. Samples exhibiting obvious signs of secondary useage were for the most part deliberately avoided to ensure source representability. Most of the logs had been felled with a chain saw, and no naturally fallen whole trunks from river bank erosion were observed. There was, of course, also great amounts of plastic mixed with the wood, from countries all over the world.

A disc was sawn from each of 145 randomly selected beached logs, which were also paced to determine length and thoroughly examined visually. The diameter was later measured in the laboratory from the sawn disc. The length of the logs varied from 1.5 to 7 meters for both Pinus and Picea, with concentrations of lengths at 4 and 6 meters (table 1). The shorter logs seem to have been cut in accordance with the above-mentioned functions. The diameter varied from 10 to 40 cm for Pinus, and 10 to 25 cm for Picea. The 43 top logs of Pinus had an average diameter of 16.6 cm, and the 45 butt logs 19.6 cm. For Picea the 30 top logs averaged 15.2 cm and the 26 butt logs 17.3 cm.

A wood anatomical investigation of the samples gave the following distribution of the species:

Pinus sp. (Pinus silvestris type)	88 samples
Picea sp.	56 samples
Larix sp.	1 sample

Length of the logs, meter.

Year of Cutting	Pinus sp. 0	1	2	3	4	5	6	7	Picea sp. 0	1	2	3	4	5	6	7
1930																
1																
2																
3					x											·
4			x													
1935					x											
6																
7				x												
8						▼ ⋅										
9													x			
1940																
1				x												
2																
3			·	────												
4																
1945	·				x						x					
6							x			x	x		x			
7						x					x		x			
8			x											x		
9			x													
1950					·	x							x		x	
1							x						x			
2				x												
3					x											
4				x	x		x									
1955					x	x	x				x		x		x	
6					xx x		x						x	x	xxx	
7													x			
8				x	x								x			
9					x x								x	x	x	
1960					x								x			
1				x									x		x	
2																
3					x x x	x x									x	
4					x x x							xx				
1965		x		x								xxx xx			x	
.6			x	xx xx	x xx	x				x		xxx xx			x	
7				x	x					x		xxx				
8				xx	x								x	x x		
9			x	x	x										x	
1970				x x												
1					x							x				
2				x								xx				
3												x x				
4																
1975																x
6												x		x		
7														x		
8												x				
9										x						
1980													x			

TABLE 1. Length of the dated logs.

The method described by Bartholin (1979) was used to distinguish the anato-
mically similar Picea and Larix.
  A radius about 2 cm wide was cut with razor blades into the surface of
the sawn discs in preparation for measurement on an ADDO Tree Ring Measuring
Machine. Only one radius was measured on most samples, and the ring widths
were recorded in 0.01 mm. Semilogarithmic curves for visual synchronization
were drawn from the measured data. The tree ring series were correlated with
the help of t-values (Baillie and Pilcher 1973) and 'percentages of agree-
ment' (Eckstein and Bauch 1969), and by optical evaluation.
  Of the Pinus samples 62 could be synchronized, and 41 of these were
used to construct a relative mean curve for that species. For Picea, 51 were
synchronised and 25 used in the Picea curve. The mean curves were calculated
as a mean of the measured ring widths for each year of selected samples, and
dated samples not chosen for use in the mean series generally had serious
anomalies, such as missing rings, that precluded their use.[2]
  Many of the Pinus samples gave very high significant values in correla-
tion with the Picea mean curve, and vice versa. The two mean curves could
also be synchronized, but the values were relatively low (table 4). The
relative datings of the material are shown in table 2.
  The relative year of cutting was presumed to be identical with the
dating of the outermost registered ring, even in cases where no bark was
found. The influence of the elements can have eroded a few rings on some
samples, but no such absences were noted in the field or laboratory. The
undatable samples were not subjected to continued investigation. Many of
these had very few rings, evidenced atypical growths, or were obviously
missing rings, and therefore rejected.

4. RESULTS

  The large number of relatively datable samples was a welcome surprize.
It apparently indicated that the driftwood originated in a region (of yet
undetermined size) with very homogenous growth conditions, and deliberately
exploited to supply uniform logs for the timber industry.
  The first attempt to obtain an absolute dating was made on a chronology
for Pinus from Lapland (Bartholin and Karlén 1983). No significant correla-
tion was found. The Svalbard Pinus mean curve gave a value of t = 2.30 and
a percentage of agreement = 57.4. However, it was unlikely that the end
year could lay more than a few years in the past, and a good, visual syn-
chronization was eventually discovered for the year 1979; continued investi-
gation proved this dating to be correct. Nevertheless, the most recent sample
was dated to 1980, a Picea log with one unmeasureable outer ring representing
that year. The Pinus mean curve terminated at 1969, but some Pinus samples
contained up to three unmeasureable rings after that date.
  There presently exists an extensive Russian literature in dendrochrono-
logy, and the published mean curves represent many different forest types
from all over the Soviet Union. A survey of the Russian series used in the
efforts to localize the provenance of the Svalbard driftwood is given in
table 3.
  The first attempt to locate the origin of the Svalbard driftwood to
within the Soviet Union was made by correlating an open network of localities

Relative year	Number of samples x = 1 Pinus sp	Picea sp	Calender year
186	x		
187	x		
188			
189			
190			1920
191			
192			
193			
194			
195			
196			
197			
198	x		
199			
200		x	1930
201			
202			
203	x		
204	x		
205	x		
206			
207	x		
208			
209		x	
210			1940
211	x		
212			
213			
214			
215	x	x	
216	x	xxx	
217	x	xx	
218		x	
219	x		
220	x	x	1950
221	x	x	
222	x		
223	x		
224	xxx		
225	xxx	xx	
226	xxxx	xxxxx	
227		x	
228	xx		
229	xx	x	
230	x	xx	1960
231	x		
232		x	
233	xxxxx	x	
234	xxx		
235	xx	xx	
236	xxxxx xxxx	xxxxx x	
237	x	xxxx	
238	xxx	xxx	
239	xxx	x	
240	xx		1970
241	x	x	
242	x	xx	
243		xx	
244			
245		x	
246		xx	
247		x	
248		x	
249		x	
250		x	1980

TABLE 2. Dated samples of Svalbard driftwood.

Tree species	Mean curve			Reference
	No.	Locality	Length	
Pinus	1	Svalbard	1731-1969	
"	2	Kola	1698-1971	Bitvinskas, ed. 1979 fig. 5, p. 58, tab. 1
"	3	Karelia 3	1648-1973	Bitvinskas, ed. 1979 fig. 5, p. 59, tab. 3
"	4	Karelia 5	1697-1973	Bitvinskas, ed. 1979 fig. 5, p. 61, tab. 5
"	5	Karelia 7	1684-1973	Bitvinskas, ed. 1979 fig. 5, p. 62, tab. 7
"	6	Karelia 9	1617-1971	Bitvinskas, ed. 1979 fig. 5, p. 64, tab. 9
"	7	Karelia 11	1755-1969	Bitvinskas, ed. 1979 fig. 5, p. 65, tab. 11
"	8	Karelia 13	1744-1968	Bitvinskas, ed. 1979 fig. 5, p. 66, tab. 13
"	9	Karelia 15	1823-1969	Bitvinskas, ed. 1979 fig. 5, p. 67, tab. 15
"	10	Karelia 17	1720-1968	Bitvinskas, ed. 1979 fig. 5, p. 68, tab. 17
"	11	Archangelsk $63°49'N\ 40°39'E$	1832-1975	Anikejeva et al., 1984 p. 52, tab. 1
"	12	Rep. Komi	1862-1975	Jevdokimov, 1984 p. 44, tab. 1
"	13	Rep. Komi	1861-1975	Jevdokimov, 1984 p. 44, tab. 2
"	14	River Taz Arctic circle $85°E$	1642-1969	Sijatov, 1984 a p. 63
"	15	Celjabinsk $55°N\ 62°E$	1857-1968	Komin, 1981 p. 66, tab. 68
"	16	Ural Mountain ca. $60°N$ ca. $60°E$	1557-1969	Bitvinskas, ed. 1979 fig. 8, p. 110, tab. 4
Picea	17	Svalbard	1753-1979	
"	18	Archangelsk $65°43'N\ 41°20'E$	1788-1979	Semenov et al. 1984 p. 47, tab. 1
"	19	Archangelsk $63°49'N\ 40°39'E$	1822-1975	Anikejeva et al. 1984 p. 52, tab. 2
"	20	Rep. Komi	1881-1975	Jevdokimov, 1984 p. 45, tab. 3
"	21	River Taz Arctic Circle $85°E$	1604-1969	Sijatov, 1984 a p. 59
"	22	River Ob/Sob $66°N\ 66°E$	1727-1973	Sijatov, 1984 b p. 71, tab. 7 (43)
"	23	Nemzen	1707-1968	Siyatov, 1981 tab. 1 (31), p. 82
"	24	Nemzen	1713-1968	Siyatov, 1981 tab. 2 (32), p. 82
"	25	Nemzen	1716-1968	Siyatov, 1981 tab. 3 (33), p. 83

TABLE 3. Survey of the investigated localities.

(Nrs. 2, 11, 14, 15, 16, 18, 21, 22) representing both Pinus (silvestris) and Picea (obovata), see table 4 and the map, figure 2. No correlation was found between the Svalbard mean curves (1 and 17) and the Siberian mean curves (14, 15, 16, 21, 22), which with the exception of locality 15 show a high similarity to each other, nor was there any noticeable correlation between the Siberian and the European (2, 11, 18) mean curves. However, high significant values were found to exist between Svalbard and the European curves.

To expand and continue the effort, the network was increased by 15 sites, table 3 and the map, figure 2. Locality 18 was excluded from further investigations because its high correlation values with localities 19 and 20 indicated that the series was dated one year too young, and/or that it was calculated without cross-dating the component curves. This demonstrated error was necessarily taken into account when considering some of the other mean curves used in the investigation. For instance, it is remarkable that the locality 8 mean curve (Karelia) did not show similarity with any of the other tested curves. Similar problems can be experienced with other single curves used in the mean curves, when localities close to one another correlate with high t-values but very low values for percentage of agreement; see, for example, mean curve 3 as compared to mean curve 4. The value of t = 7.19, yet the percentage of agreement is only = 59.6 (table 4).

The results of the correlation tests between all localities in the expanded network are shown in table 4. Where no figures are registered the percentage of agreement was below the 95% limit of probability, and therefore not printed. It cannot be seen from the table that the subsequently added mean curves for European Picea (23, 24, 25) were the only ones to show strong correlation with the Siberian mean curve (22), t = 8.10 and percentage of agreement = 67.6. Similar values were registered with the other Siberian localities. In figure 3 the t-values from table 4 are plotted to allow a comprehensive view of the Svalbard curves in relation to the European curves. As can be seen, the correlation values in certain cases are exceptionally good.

5. CONCLUSIONS

When one considers: 1) the mutual correlations between the European mean curves, 2) the non-homogenous network of localities east of Archangel, and 3) the few localities west of Archangel with Picea, it can be concluded that the driftwood from Isfjorden on Spitzbergen, Svalbard, originated in an area north of the 60th parallel and between longitude 35° and 60° E. This conclusion is augmented by the fact that the Soviet saw and paper mill industry is centered on the Archangel region, and that judging by the log dimensions (see above and table 1) much of the driftwood was originally intended as pulp. This finding is also well in accordance with the primary counter-clockwise surface current system in the Barent's Sea (figure 2).

The limited number of dated logs does not permit us to draw extensive conclusions at this time, but several observations can be made with regards to the year of cutting for the dated samples, table 2:
1) The oldest samples are all Pinus, only one Picea sample is dated to before 1945. No Pinus is dated to after 1972, and no finds have been dated to the years after 1980. The year of sampling was 1984.
2) The concentrations of datings in the middle of the 1950's and 1960's might be explained by a higher level of logging activity, and/or special conditions such as intensive spring flooding and changes in the ice cover in the Barent's Sea.
3) The increasing concentrations of datings in these decades is first

Tree species	Mean curve No.	Locality / Length	1	2	3	4	5	6	7	8	9	10	11	12	13	17	19	20	23	24
Pinus	1	Svalbard 1731-1969	3.85/60.7																	
"	2	Kola 1698-1971		6.70/63.0																
"	3	Karella 3 1648-1973	2.54/63.0	6.53/67.2	7.19/59.6															
"	4	Karella 5 1597-1973	3.18/60.3	3.57/62.3	4.89/57.9	7.28/64.7														
"	5	Karella 7 1684-1973	3.38/60.7	5.96/65.2	7.59/64.4	6.72/65.9	8.19/67.2													
"	6	Karella 9 1617-1971	3.76/64.1		7.59/65.5	2.83/62.6	3.17/59.8	7.17/68.7												
"	7	Karella 11 1755-1969	4.83/68.5	4.71/59.3	2.39/65.2			4.01/57.1	3.57/64.0											
"	8	Karella 13 1744-1968	–/–																	
"	9	Karella 15 1823-1969	4.76/64.0	3.04/65.4	2.17/62.3	3.43/63.0	2.41/61.0	4.47/58.2	4.76/61.5		4.72/52.1									
"	10	Karella 17 1720-1966	–/–									2.99/61.4								
"	11	Archangelsk 1832-1975	6.33/67.9	6.23/63.3	3.31/63.5	4.28/62.4	3.17/62.8	6.25/67.3	6.86/67.5		4.25/60.9		3.44/61.0							
"	12	Komi 1 1862-1975	5.42/66.4								3.66/63.6			5.67/65.9						
"	13	Komi 2 1861-1975	4.27/68.1	2.27/61.4	2.47/64.7				1.91/63.9		2.48/61.6	1.70/60.3		4.54/63.3	2.20/61.0					
Picea	17	Svalbard 1753-1979	3.1/61.1					2.44/58.4			2.92/63.0		4.76/65.4			7.41/69.9				
"	19	Archangelsk 1822-1975	3.67/62.9				2.74/60.6				1.77/60.3		3.96/66.1				3.52/65.4			
"	20	Komi 1981-1975	–																	
"	23	Memzen 1707-1968	2.25/59.1						1.86/56.8					2.70/61.8		5.66/65.8	4.25/65.8			
"	24	Memzen 1713-1968	2.66/59.9											2.49/61.3		5.63/62.1	4.13/63.0		24.2/83.5	
"	25	Memzen 1716-1968	2.18/58.2											3.92/62.7		4.84/61.2	4.00/61.6		14.4/74.4	14.0/77.2

TABLE 4. Correlation between the investigated localities.
T-values listed above, percentage of agreement below.
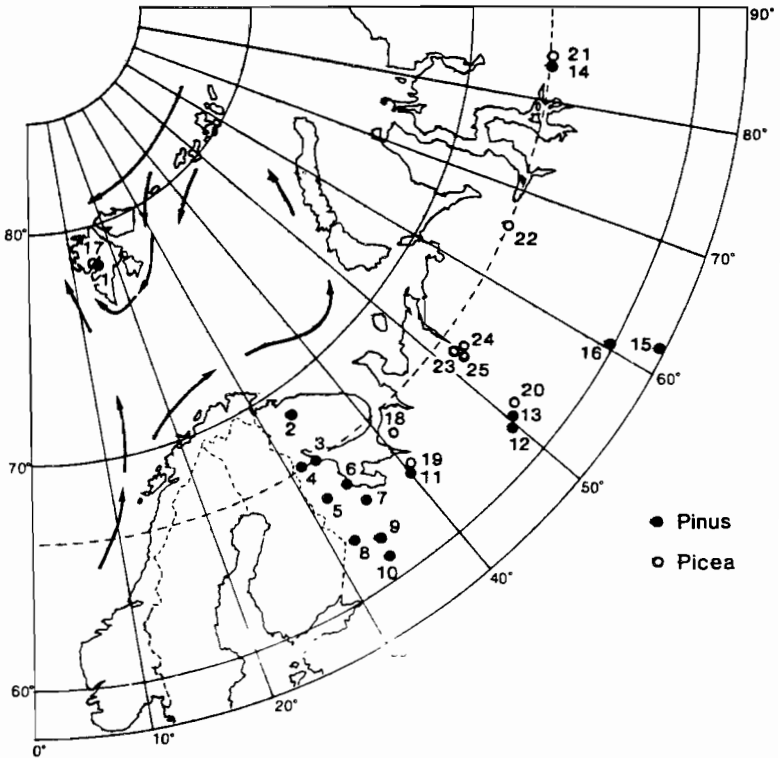
FIGURE 2. Map of the investigated localities on Svalbard (nrs. 1, 17) and of the reference localities in the Soviet Union. Direction of the major surface currents are indicated by the arrows.
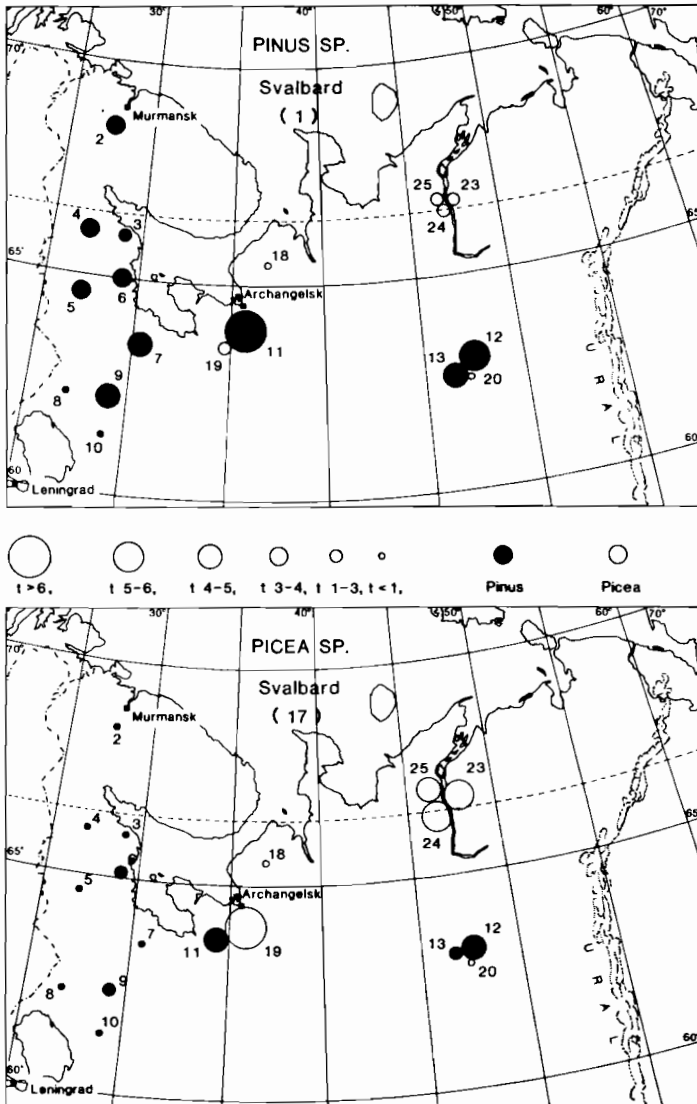
FIGURE 3 (a+b) Correlation of _Picea_ sp. and _Pinus_ sp. from Svalbard and the European part of the northern Soviet Union (t-values).

detected in the Pinus material, and after a few years delay in Picea.
4)   No datings are found for the growing seasons 1942-1944.
     The results hereto demonstrate the feasibility of applying dendrochrono-
logy to Arctic driftwood, but much work remains before the full potential of
the investigation can be ascertained. Additional studies on modern-beach
driftwood must be performed, also including shores more exposed to the trans-
polar drift, and thus to even larger source areas than those merely feeding
the Barent's Sea. It is absolutely necessary to extend the chronologies
further back in time, and to eventually establish curves for dating raised
beach sequences. An enhanced knowledge of the dendrochronology, hydrology,
forestry, etc., in the source areas is imperative for the future success of
the project, and this requires much closer cooperation with Soviet colleagues
than has been the case in the past.

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7.6 SOME RESULTS OF DENDROCLIMATOLOGICAL RESEARCH IN HUNGARY

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1.

Over the period of the latest 40 years, the percentage of Hungary's forested area has increased from 12 % to 17.3 %, whereas the total area of forests has been expanded from 1 100 ha to 1 610 ha. Nowadays multipurpose silviculture is generally expected to meet the following requirements:

- full exploitation of natural resources
- complex utilization of timber-growing stock
- permanent augmentation of timber crops
- increase of value production.

Wood represents a kind of reproduceable raw material, thus, research focused on exploitation of correlations between stand development and growth rate of individual trees on one hand and factors exerting influence on them such as climatic conditions on the other is of great importance in respect of our endeavours aimed at increasing the productive capacity of Hungary's forests.

The system of Hungary's site types is based on three environmental factors: climate, hydrological conditions and genetic soil type. In the course of evaluation and systematization of forest sites we determine climatic factors - with the exception of one - indirectly by means of tree species and forest associations, respectively.

Accordingly, we differenciate the following climatic zones:

- zone of beech-forests
- zone of hornbeam - oak-forests
- zone of European oak-forests
- zone of Turkey oak-sessile oak-forests
- zone of forest-steppe forests.

About 23 % of our woods are situated in the climatic zone of forest-steppe forests. However, for tree growth this type of climate is the most disadvantageous of all, mainly because average annual precipitation is as little as 400-500 mm. This is why the majority of dendroclimato- logical studies carried on in Hungary have been chiefly limited to forest stands of the above-mentioned climatic zone.

The main results achieved in this domain of science by Hungarian research workers of forestry can be summed up - without aiming at completeness - as follows.

II.

In Hungary ROTH (1935), Z.FEKETE (1951) and KOLTAY (1953) were the first to point out that changes in an- nual rings provide important information on interre- lationships between tree growth and environmental fac- tors.

Comprehensive studies were carried out by SZÖNYI (1958) on the Great Hungarian Plain in order to in- vestigate factual relationships between the diameter increment of locust trees (Robinia pseudoacacia L.) and the quantity of precipitation fallen during the vegetation season.

On the evidence of detailed analysis performed on 122
sites he established a definite correlation between the
two factors in 8 %, a moderate one in 21 %, a poor one
in 39 %, whereas neutral relationship was found in 32 %
of the cases.

Cases indicating distinct correlation originated from
sites principally suitable for safe and profitable growing
of commercial forests: i. e. in such sites locust trees
possessed the best precipitation-utilizing capacity
resulting from favourable effects of other ecological
factors.

The fact in itself that a particular area was sup-
plied with larger quantities of precipitation did not
result in increased diameter increment of locust trees.
It has also been proved that locust groves beyond fel-
ling age and those having been coppiced more times than
expedient are incapable of utilizing precipitation
originating from the atmosphere satisfactorily.

In the course of his studies on the growth of Scotch
pine (Pinus silvestris L.) SOLYMOS (1963) ascribed
differences in growth not only to climatic conditions
but also to factors of stock composition as well as to
methods of silvicultural treatment.

HALUPA (1967) performed stem analyses on Populus
euramericana Dode (Guinier)' cv. robusta' and compared
the results achieved in this respect with data on pre-
cipitation. He found that both diameter growth and basal
area increment were significantly influenced by the
quantity of precipitation fallen during the vegetation
season. If the quantity of precipitation was less than
during the preceding year, diameter growth decreased,
and so did generally basal area increment as well.

The studies of MAJER (l973) accomplished in the
scope of Hungarian dendroclimatological research are
also of great importance. From the results of his in-
vestigations concerning annual ring chronology and
dendroclimatology the following major conclusions can
be drawn:

Between breast height diameter and quantity of pre-
cipitation a moderate correlation is provable. (Linear
correlation being taken for granted.)

Determination coefficient of correlation between
diameter increment and precipitation fallen in May and
June is l5.2, whereas that of correlation between dia-
meter increment and precipitation fallen during the
total vegetation season amounts to l9.5.

Determination coefficient of correlation between the
quantity of precipitation fallen in May-June calculated
for 1° C and diameter increment was found to be l7.1:
that of correlation between the quantity of precipitation
fallen during the total vegetation season calculated for
1° C each proved to be 21.9.

MAJER pointed out the following as well: in the years
preceding those of crucial importance in respect of beech
tree (Fagus silvatica) growing, quantity of precipitation
was favourable: however, in the year that was directly
followed by abundant seed-crop it was necessary that
midsummer should be sunny and warm in order to permit
a plentiful crop.

Correlation was also provable between individual
climatic factors on one hand and major biotic damages
on the other.

BABOS (1984) performed year ring analyses on stems of Turkey oak (Quercus cerris L.), elm (Ulmus sp.) and various cultivars of Populus euramericana. The total number of specimens on which ring widths were measured amounted to 54. On the evidence of his studies on correlations between average ring widths and the quantity of annual precipitation as well as the quantity of precipitation fallen during the vegetation season, Babos stated the following:

- values of the correlation coefficient may vary within a very wide range (0.0142-0.4915):
- significant correlation between the two variables ranges from P= 1 % to P= 10 %.

RÉDEI (1984) performed dendroclimatological studies on stems of locust trees and proved that a close correlation exists between the following variables:

- rate of diameter increment and quantity of precipitation fallen during the vegetation season:
- rate of diameter increment and humidity index based on joint effects of precipitation and temperature.

Taking linear relationship for granted, he found significant correlation (r= 0.43) only between the humidity index and the annual increment of breast height (1.3 m) diameter.

Rédei also studied correlations between the rate of annual ring increment and the climatic factors of the year preceding the period under survey. However, methematically verifiable correlations were not to be found.

III.

The chief objective of our present study was to out-
line some results achieved in the scope of dendroclima-
tological research, directly related to practical timber
growing. In our brief account we did not deal with
theoretical and methodological questions of dendrochro-
nology and dendroclimatology, neither did we treat several
far-reaching possibilities of research provided by the
above-mentioned discipline.

The function and importance which dendroclimatology
possesses in revealing the causes of inviromental
contamination getting more and more extensive and serious
all over the world and of forest destruction closely
donnected with environmental contamination are not referred
to in our paper, either.

In the near future some research bases are going to
be established in Hungary in order to facilitate in-
vestigations on forest ecosystems. It will be their task
to expand research in order to explore the causes of
damages as accurately as ever possible.

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7.7 DENDROCHRONOLOGY OF OAK IN POLAND

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INTRODUCTION

Dendrochronology in Poland can be traced back until 1938 when some bronze aged wooden samples from Biskupin were sent to Ebba Hult de Geer at the Institute for Geochronology in Stockholm. She placed two pieces of wood in the 7th century B.C. using the then existing tree-ring chronology of Sequoia in N.-America and the Scandinavian varve-chronology. These results gave rise to some doubts.

More serious dendrochronological work in our country started after the Second World War. For example, Zinkiewicz (1946) studied the influence of climate on tree growth and Ermich (1960) compared polish and bavarian oaks to test the possibility of teleconnection. In the 60ies and 70ies dendrochronology was several times applied to date timber from archaeological excavations, above all by Dąbrowski (1972) and his coworkers in Opole and Lublin and by Gorczyński and Molski (1965) in Szczecin. But these investigations should rather be considered as preliminary. More recently Bednarz (1984) and Feliksik (1972) elaborated essential dendrochronological contributions.

OWN STUDIES

Since 1983 dendrochronological research on oak is being carried out as a common project of the Academy of Fine Arts in Warsaw and the University of Hamburg. The aim of these studies is to establish a reference chronology for Poland. The sampling started in Gdańsk and the surrounding region because of the significance of this town for the polish history and culture. This area will be gradually extended in order to include Pomerania, the delta region of the rivers Vistula and Nogat, and the Wysoczyzna Elbląska, that means from the Żarnowieckie Lake in the west as far as Frombork in the east (Fig.1). From a climatic point of view the region is fairly homogenous and is determined both from oceanic and continental influences.

LIVING OAKS

The Gdańsk-chronology for living oaks is 24-times replicated and covers the period from 1984 to 1780. In order to check the geographical range of this chronology, further sites were sampled. The chronology for the Warsaw region represents a transition zone to less precipitation, whereas the chronology for Białowieża contains stronger continental influences. However, the Gdańsk-chronology is rather similar to the Warsaw-chronology and even to some chronologies from Lithuania (Kairaitis 1979). The regions around Warsaw and Białowieża were chosen since they played an important role for the supply with timber in the so-called Gdańsk timber trade during the 13th to the 17th century. Additional sites for living oak trees are Wolin, Poznań, Krakow, Wrocław, eventually Opole. With the same material a dendroclimatological evaluation is planned.

DATING EXAMPLES

Besides of living oaks, timbers from architectural monuments, art-historical objects and archaeological excavations are being dendrochronologically analysed. From 16 sampled buildings 13 could already be dated, the oldest one to the second half of the 14th century, the youngest one to the second half of the 19th century. The large scattering of the felling years of the trees and the long tree-ring series enabled the establishment of a chronology as far back as 1100 A.D.(Fig. 2). Two dating results should be shown as examples:

- The St. Nikolaus Church in Gdańsk has been built by the Dominicans in the 13th century and is one of the oldest churches of the town. Its roof is one out of few which have survived the last War. The bell tower is constructed with oak timber, the dendrochronological dating of which is 1398 A.D. (Fig.3).

- In Gdańsk-Lipce there is still an old-fashioned farmhouse, the oldest one of this type in the Vistula delta region and the only representative of the early developmental stage of this type in Poland. The building has been dated by architectural historians to the middle of the 17th century. However, the dendrochronological analysis resulted in 1571 as the cutting year for the oaks used for the timber frames (Fig.4).

In addition to the historical monuments art-historical objects of Gdańsk painters were included. Up to now 32 panels of paintings of one to five boards each were measured. All paintings were created between the 14th and the 17th century and mostly contain more than 200 tree rings.

An extension of the Gdańsk chronology into the past was made possible by means of archaeological objects:

- The excavations in Elbląg try to get the oldest traces of settling and therefore concentrate on those areas within the old town which were destroyed through the War. Out of 27 samples 15 could be absolutely dated covering the time between 996 and 1332 A.D. and thus belonging to the first settling phase (Fig. 5). These excavations will be continued for several years and will also be extended to new areas. Afterwards the old town of Elbląg will be rebuilt.

- In the Puck bay some 4 meters below the water and some 100 meters off-shore big wooden constructions were found. They cover an area of 12 hectares and represent the remnants of the former fortification of the early medieval harbour. The ship wrecks are carbon-14 dated to be from the 6th to the 12th century. Out of 10 samples from various parts of the harbour only one could be dated dendrochronologically, that is to the middle of the 13th century. There are no archival sources at all about the harbour of Puck.

At the time being the dendrochronological analysis of the archaeological timber finds from Wolin is performed. Wolin is located at the mouth of the river Odra and was one of the most important trade centres of North Europe during Medieval times; today a small town with the same name is located there. The wooden samples are assumed to belong to the 8th to 10th (eventually 11th) century according to archaeological and carbon-14 datings. Wolin is situated outside of the initially defined study area, but its location just between Gdańsk and Lübeck in North-Germany may enable a teleconnective cross-dating between these sites along the Baltic Sea.

A further material worthwhile to be dendrochronologically
evaluated are subfossil oak trunks from the Gardno-Łeba Lowland
close to the Baltic Sea. Some of the trunks were already
carbon-14 dated to be from 1115 ± 60 BP. It is planned to
intensify the project, also in order to compare dates derived
by means of C 14-analysis and dendrochronology.

CONCLUSION

To conclude, the dendrochronology of oak in Poland makes some
promising progress with regard to the establishment of a dating
tool as well as the dendroclimatological analysis. There is one
by-product to be mentioned. By means of the Gdańsk-chronology
coming into existence, a tree-ring chronology from paintings of
Dutch and Flemish masters being floating up to nowadays could
be placed in time and thus a long-lasting puzzle as to the
provenance of the timber used solved (Eckstein et al. 1986).

Last but not least it has to mentioned that besides of oak also
pine is dealt with dendrochronologically since few years by
common efforts of the Universities of Torun and Lund/Sweden.

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Fig.1 Dendrochronological study area within Poland.
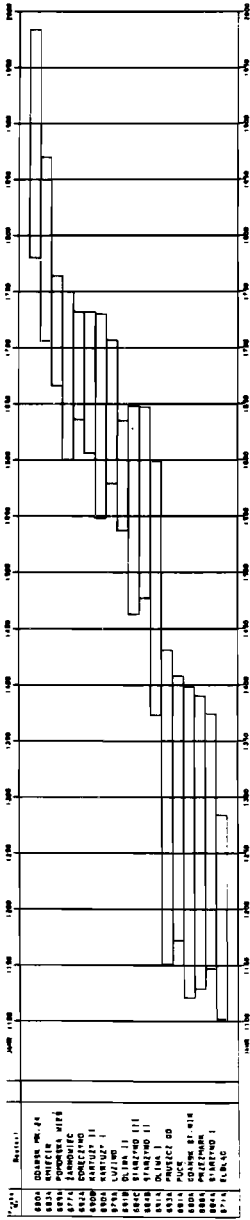
Fig.2 Tree-ring chronology for oak in North Poland.
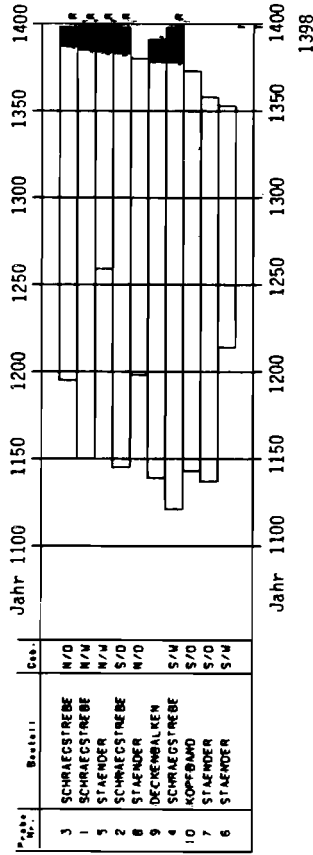
Fig.3 Gdańsk, St.Nikolaus Church, dendrochronological dating of ten beams from the bell tower; black areas mean sapwood, R stands for bark; cutting year 1398/99.
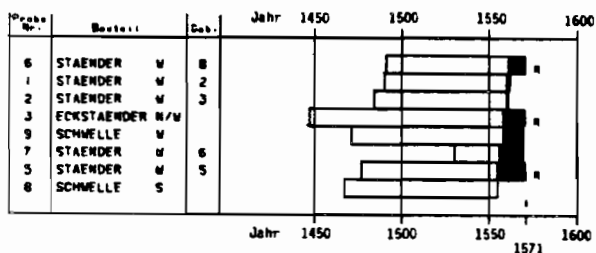
Fig.4 Gdańsk-Lipce, farmhouse, dendrochronological dating of eight beams; cutting year 1571/72.
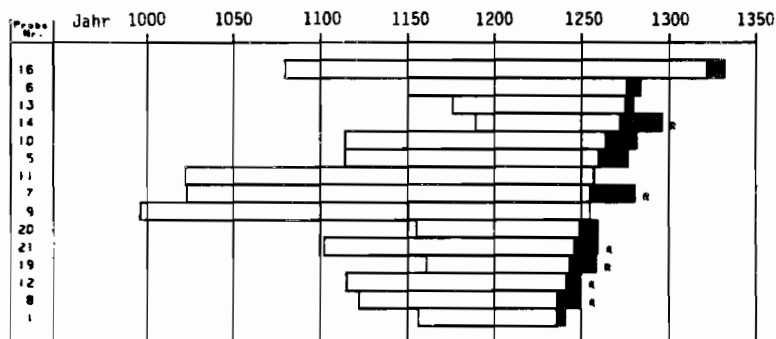
Fig.5 Elblag, excavation, dendrochronological dating of 15 samples with cutting years between 1250 and around 1332.

8. APPLICATION OF DENDROCHRONOLOGY ASSESSMENT DEVIATIONS OF FOREST GROWTH

8.1 DETECTING THE EFFECTS OF ACIDIC DEPOSITION AND CO_2 FERTILIZATION ON TREE GROWTH

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ABSTRACT

    In recent years there has been growing interest in and concern about the need to identify pollution effects on tree growth, both the detrimental effects of acidic deposition and related industrial pollution, and the enhanced productivity expected to result from increasing atmospheric CO_2 concentrations. These are complex problems involving the detection of uncertain signals in the presence of considerable noise, i.e. the variability that results from the other factors which influence tree growth. Many of the problems to be faced in detecting these effects have already been addressed in the CO_2-climate issue, where the unequivocal detection of a CO_2-induced warming is a major concern of climatologists. Climatic change detection methods and problems are reviewed and their analogues in the tree growth cases are described. A framework for the rigorous identification of acidic pollution or CO_2-fertilization effects is proposed, which, if followed, will help to ensure the credibility of future work in this area of dendrochronology.

1. INTRODUCTION

    In recent years, the possible effects of pollution on tree growth have become major environmental concerns. There are two distinct issues. The first is the direct influence of increasing atmospheric carbon dioxide (CO_2) on plants, the "CO_2-fertilization" effect, thought to increase plant productivity; and the second is the problem of "acidic deposition" where a host of pollutants associated with industrialization have been implicated as causal factors in forest "die-back".
    Dendrochronological interest in these problems centres around the effects on tree ring characteristics, width, density, etc. Both issues, as far as the dendrochronologist is concerned, are detection problems; i.e. we are attempting to detect a significant change in tree rings that can be unequivocally attributed either to CO_2-fertilization or to acidic deposition. A considerable effort has recently gone into a similar problem, that of detecting the effects of increasing CO_2 and other trace gas concentrations on global climate (e.g. MacCracken and Luther, 1985). In order to make these climate studies and their implications for dendrochronological studies more accessible, we present here a review of the CO_2-climate detection problem and demonstrate the parallels with the two dendrochronological issues. Guidelines for studies of CO_2-fertilization and acidic deposition effects are presented that, if followed, will help to ensure the credibility of future work on these issues.

Although these three detection problems have many similarities, there are many conceptual differences. In the CO_2-climate and CO_2-fertilization cases, causal factors have been identified and their qualitative effects established using models and/or small-scale experiments. The aim is to identify these effects in the real world. In the climate case, models of the climate system predict that increasing concentrations of CO_2 and other trace gases (methane, nitrous oxide, ozone, chloroflurorcarbons) will have a "greenhouse effect" which will be manifest as a warming of the lower layers of the atmosphere, a predicted "signal". The current magnitude of this predicted signal is small, partly because the CO_2 changes experienced so far are relatively small and partly because the oceans cause a damped response (Wigley and Schlesinger, 1985). Because the models are only simplified representations of the real climate system, empirical verification of the greenhouse effect is required, i.e. we need to detect the small predicted signal in the observational record. This is difficult because any signal tends to be obscured by the large "noise" level of natural climatic variability. The signal has not yet been convincingly demonstrated (Wigley and Jones, 1981; Wigley et al., 1985a).

In the CO_2-fertilization case, small-scale growth chamber experiments have shown that large CO_2 changes can cause large changes in plant growth rate (the signal), at least for C-3 plants, a category that embraces all but a few species of tree (for reviews see Strain and Cure, 1985, and Warrick et al., 1986). The projected real-world effects to date are probably too small to be immediately obvious (an ~10% increase in growth rate for the observed ~25% increase in CO_2 concentration that has occurred since ~1850) and are obscured by the background noise of natural growth fluctuations. Further-more, just as climate models only approximate the real world, so the results of growth chamber experiments need not apply in the real world where plant growth is influenced by many factors which are not simulated in the growth chamber environment. Empirical verification is therefore required.

In the acidic deposition case we have a fundamentally different situation, essentially an effect looking for a cause. The effect is the extensive forest die-back which has become increasingly evident in both Europe and North America in recent years. The cause is thought to be air pollution, probably the synergistic effects of a number of different pollu-tants and not simply "acid rain". However, because of the complexity of the biological processes involved, the cause-effect link is still controversial. There is no accepted specific pollutant-related causal mechanism, and the observed symptoms have other possible causes unrelated to pollution. Although the main evidence of forest die-back is visible external damage to trees, dendrochronologists suspect that acidic deposition should also cause growth changes. However, although there is no doubt that high pollutant levels have growth effects, there is no definite evidence of significant effects on mature trees at the lower regional-scale pollution levels that prevail today in Europe and North America. In other words, the strong theoretical or small-scale experimental basis that firmly underlies the CO_2-climate and CO_2-fertilization cases is far less conclusive in the acidic-deposition case. Attempts to detect an acidic deposition effect on tree growth are therefore less well-defined than in the other two cases.

1.1. Direct versus indirect effects

One other factor links the CO_2-fertilization and acidic-deposition cases to the CO_2-climate case, the existence of both direct and indirect effects. In the former two cases, most discussions tend to focus only on identifying the direct effects, although we believe that there may be both

direct and indirect effects. Let us consider the three cases separately.

For CO_2-fertilization, we know that, not only do plants tend to grow faster at higher CO_2 levels, but they also use water more efficiently. Thus, in a high CO_2 environment, one might expect plants (and this applies to both C-3 and C-4 plants) to be less subject to moisture stress. Use of nitrogen is also more efficient, so growth limitation through nitrogen deficiencies could be reduced. Finally, any climatic change caused by increasing CO_2 levels could well be in a direction that improves plant growth. In principle, these indirect effects might be distinguishable from the direct fertilization effect. In practice, however, they are likely to be indistinguishable. Does this matter? Probably not, but seekers after a CO_2-fertilization effect should be cognisant of the fact that attribution of growth changes to the direct effects alone is likely to be much more difficult than attribution to the sum of both direct and indirect effects.

The indirect effects of acidic deposition are more subtle, and less easy to describe explicitly. In fact, since the mechanisms involved are so poorly understood, one might say that all of the effects are indirect. To clear this semantic hurdle, we give an example of what we mean here by "indirect". Just as changing CO_2 levels may alter the susceptibility of plants to water stress, so too may acidic and related forms of industrial pollution alter the way plants respond to climate. For example, a pollution stressed plant is more likely to be adversely affected by spring cold or summer dryness. On the other hand, higher nitrate fluxes from large-scale pollution may counteract nitrogen deficiencies in some soils and allow plants to capitalize better on the positive climatic resources of a good growing season. As for the CO_2-fertilization case, such indirect effects may be distinguishable from more direct effects in principle, but probably not in practice. In the acidic deposition case, however, distinguishing direct and indirect effects is rather more important. For example, if someone were able to show that forest die-back in Europe was a result of climate stress, then it is clearly important to know whether or not this is due to a pollution-induced increase in the susceptibility to such stresses.

In the CO_2-climate case, it is actually the indirect effects that are most important. The greenhouse warming due directly to changes in carbon dioxide and other trace gas concentrations is amplified by a variety of feedbacks within the climate system. For example, CO_2-induced warming causes an increase in the atmosphere's water vapour content which, because water vapour is also a greenhouse gas, causes further warming. Although there is some small uncertainty in the direct effects, the main uncertainties lie in these feedbacks. In other words, the focal point in the detection of CO_2-induced climatic change is actually the detection of the indirect effects, which are thought to be around 2 to 5 times stronger than the direct effect.

2.   THE CO_2-CLIMATE ISSUE

The atmospheric concentration of carbon dioxide even under normal circumstances is not constant. Since about 1750, however, and particularly since the middle of the 19th century, CO_2 concentrations have increased steadily as a result of the activities of Man (Wigley, 1983; Neftel et al., 1985; Raynaud and Barnola, 1985). The global-mean CO_2 concentration in 1985 was 345ppmv, approximately 25% more than the level that existed before about 1850. In recent years the climatic importance of other radiatively active trace gases such as CH_4, N_2O, O_3 and CFCs has been recognized. These gases have greenhouse effects like CO_2 and may be considered in equivalent CO_2 terms. Based on projections of future energy use and accounting for the

contributions of these other greenhouse gases, it is widely accepted that the equivalent atmospheric CO_2 concentration will reach double the "pre-industrial" level by as early as 2030 (Bolin et al., 1986). The importance of the other trace gases is such that, when they are included, the equivalent doubling time is some 50 years earlier than would be expected from CO_2 alone.

Both simple and complex models of the global climate system have been used to estimate the global-mean surface air temperature changes that might result from the increases in greenhouse gas concentrations. The latest numerical models indicate that the equilibrium global-mean temperature increase due to a CO_2 doubling would be between 1.5 and 4.5°C (N.R.C., 1983; W.M.O., 1986). The greenhouse gas signal, however, is not this doubling temperature change, but the varying, transient response change that has occurred since the late 19th century. Wigley and Schlesinger (1985) estimate that this lies in the range 0.3-1.1°C for today's greenhouse gas concentrations. Observed global mean temperatures have risen by about 0.5°C (Wigley et al., 1985b; Jones et al., 1986) since the late 19th century. The change to a warmer climate should occur, if the theory and models are correct, with increasing rapidity over the next 50-100 years. The projected rise in temperature over the next two decades is 0.2-0.5°C (Wigley et al., 1986), noticeably more than that which has occurred over the last two decades.

In the CO_2-climate case, therefore, we have a theoretical signal (based on highly sophisticated models of the real-world climate system) and observational evidence (based on a near-global network of meteorological data and many hundreds of millions of observations) that there has been an observed warming which agrees well with theory. However, even though some individuals have claimed to have positively identified the CO_2 effect on climate, proof of detection has not been accepted by the scientific community (see MacCracken and Luther, 1985, for a recent review). The reason for this conservatism is partly because of the signal-to-noise ratio (where the signal is the expected anthropogenic warming and the noise is the background variability of natural climate fluctuations) is not yet high enough. However, the main reason is that the causes of climatic change are not well understood, so we cannot be sure that the observed 100-year time scale warming trend is not simply a manifestation of natural climatic variability. In other words, the difficulty lies not so much in the statistical aspects of detecting a climatic change, but in attributing the observed change to greenhouse gas concentration changes. Similar difficulties await the investigators of CO_2-fertilization and acidic deposition effects. Before going further into these details, let us consider the ways in which the problems of detection in the CO_2-climate case have been approached.

3. CO_2 DETECTION STRATEGIES

In efforts to detect a CO_2 effect on climate two aspects may be distinguished, the statistical and the attribution aspects. In practice, the distinction is rather vague because some statistical approaches also contribute to the attribution problem, while attribution itself should be quantified using statistical techniques. Nevertheless, this separation helps to clarify some points. We begin with an outline of the basic statistical principle used in detection problems, the signal-to-noise ratio concept. Note that the general points discussed here apply, not only to the CO_2-climate detection problem, but also to the CO_2-fertilization and acidic deposition cases.

3.1. Signal-to-Noise Ratio (SNR) Analysis

In detection problems we speak of detecting the signal above some background noise level. But just what do we mean by "signal" and "noise"? The overall variability of a record is made up of part signal, part noise, so the noise is that part of the variability which is not signal.

From a statistical point of view, detection requires us to test a null hypothesis. The most appropriate null hypothesis is that there is no signal. Under this hypothesis, all aspects of variability must be considered as noise. The precise definition of the noise depends on the particular statistical test we use, and this must depend on the type of signal we are searching for. This in turn is determined by theory, i.e. by what we know of the expected signals based on theoretical or experimental grounds. In the CO_2-climate case there are many possible signals, (e.g., predicted rises in global-mean temperature, Arctic temperature, global-mean precipitation, etc.) each of which has some theoretical expectation. All these have varying theoretical levels of confidence and the best choice of signal variable would be one whose changes were most firmly established on theoretical grounds. In addition to this multitude of possible detection variables, each variable may be examined in different ways using different statistical parameters. For example, we could choose to search for a change in the mean between two time periods, or for a trend over a chosen time interval.

In general, the noise level is proportional to the standard error of the sampling distribution of the chosen detection parameter. The parameter under test is the observed signal (which is distinct from the theoretical or predicted signal). We now have two choices of statistical strategy. Either we can test the hypothesis that the observed and predicted signal are the same, or we can test the hypothesis that the observed signal is significantly different from zero. The former can only show whether observed and predicted signal are significantly different, and it is the latter null hypothesis that is most commonly used.

As an example, Wigley and Jones (1981) have examined changes in global mean temperature. The signal here is a mean value, the average temperature over, say, a thirty-year period, and the noise is proportional to the standard error of the sampling distribution of the mean ($SE(\bar{X})$), which in turn is determined by the variance of the data and by its autocorrelation structure. Autocorrelation cannot be ignored, since it can inflate $SE(\bar{X})$ considerably. In Wigley and Jones' analysis of Northern Hemisphere data, observed changes in the mean were judged not statistically significant, although with more recent and more spatially extensive data this conclusion may have to be modified. In the Southern Hemisphere, for example, there has been a statistically significant warming over the past 80-100 years. A parallel warming, punctuated by cooling between 1940 and 1970 has occurred in the Northern Hemisphere. But are these changes due to CO_2 and other greenhouse gases?

3.2. Attribution

Even if a statistically significant change were observed, this would still not be enough to claim that the theoretical signal has been detected. The observed signal must still be attributed to the proposed cause. This difficult task should also be approached statistically. One method that has been proposed is based on pattern recognition (where the pattern may span both variable-space and physical-space), and is essentially a quantification of the "fingerprint" method (see below). Further details are given by

Barnett (1986). However, we do not need to go into the statistical
complexities in order to see some of the difficulties that can arise in the
attribution phase of detection.

In the CO_2-climate case, as noted earlier, the magnitudes of observed
and expected signal are compatible. This compatibility must be the first
thing to examine in attribution. Large differences between observed and
expected signal (as in the work on CO_2-fertilization by LaMarche et al.,
1984) should lead one to re-examine the original hypothesis. The next stage
in attribution should be to examine other aspects of the data to search for
compatibility in greater depth (i.e. we must head towards a more complex
pattern). In the CO_2-climate case there are aspects of the global mean
temperature record (e.g. the 1940-1970 cooling in the Northern Hemisphere)
that are not immediately compatible with CO_2 and trace gas changes as the
only cause of warming. These require explanation. Finally, we need to
examine other hypotheses, since one way to strengthen the case for the
greenhouse effect is to eliminate other possible causal mechanisms.

The task of attribution is a difficult one, and the preliminary
statistical aspects that should precede it are easily misapplied. One item
is clear, however. For both phases of detection, the variables and
parameters that can be used are limited by two things, our confidence in the
expected signal, and data availability, particularly insofar as the way this
defines the low-frequency characteristics of the noise. Let us now consider
a number of strategies that have been developed to facilitate either the
statistical or attribution-aspects of detection.

3.2. Signal maximization

On the basis of the SNR concept, one way to improve the chance of early
detection is to choose a variable that has a large predicted signal.
However, a large signal alone is not enough, as an example will show.
Numerical climate models predict that, for surface temperatures, the largest
warming signal will occur in polar regions and the smallest in tropical
regions. However, in polar regions the level of natural variability is also
high, some 5 to 10 times greater than in low latitudes. Greater signal does
not necessarily imply greater SNR. The regions with highest SNR are, in
fact, the mid-latitudes, with the spatial and seasonal variations in the
noise rather than in the signal being more important in determining the SNR
(Wigley and Jones, 1981).

3.3. Noise-reduction studies

Noise-reduction studies are an alternative approach. These attempt to
reduce noise levels by attributing some of the climatic variability to other
causes (such as volcanic aerosols) and then factoring out these effects,
thereby reducing the background noise level. Of course, any attribution of
a part of climatic variability to a specific cause must be both physically
and statistically sound. Thus, both the past record and the theoretical
climatic signal of the non-CO_2 forcing factor(s) must be well understood,
otherwise we might actually increase the noise by introducing the additional
uncertainties that surround its estimated signal. For a number of reasons,
all attempts in this area to date have been unconvincing (Wigley et al.,
1985b).

3.4. The "fingerprint" method

Here, instead of using a single climatic variable, a number of variables are considered. The philosophy here is that the attribution aspect of detection may be facilitated if variables are viewed together. For example, the climatic signal of increasing CO_2 and a larger solar constant are the same for surface mean temperature, a warming. However, while an increase in CO_2 is expected to decrease stratospheric temperatures, a larger solar constant is expected to increase them. The two effects can be distinguished by using surface and stratospheric temperatures together (see, for example, Epstein, 1982). The ideal fingerprint is one that is unique to the proposed forcing mechanism (see Barnett, 1986).

The drawback of using more than one variable is that the predicted signal and observed noise must be well defined for all variables which make up the fingerprint. The method is therefore limited by the uncertainties which apply to the worst variable in the fingerprint group. For example, considering the above case, the length of the stratospheric temperature record is so short that its natural variability is not nearly so well established as is that for surface temperatures.

3.5. Unprecedented changes

The simplest, but least satisfying detection strategy in the CO_2-climate case is the "wait and see" strategy. If climate model predictions are correct, then it is likely that global mean temperatures will reach such a high level by some time in the early decades of the 21st century, that no-one will be able to deny the CO_2 and trace gas influence. The warming will have reached limits that have no parallel in the history of past climatic change and which could not feasibly be attributed to any other cause. However, whether or not temperatures can be judged to have reached unprecedented levels depends on how well we know the past record. Present global mean temperatures are certainly warmer than anything experienced in the instrumental record, which goes back some 130 years (Jones et al., 1986), but what about earlier conditions? The Medieval Warm Period ($\simeq$800-1200 AD), the early Holocene ($\simeq$6000-9000 BP) and the last interglacial (around 125,000 BP) are times when some authors believe the globe was warmer than today (see, for example, Webb and Wigley, 1985). Although the evidence for this is equivocal, we cannot yet say that the globe has already reached a level of unprecedented warmth. However, by around 2010$\pm$10 years it should have, if the models are correct.

4. THE TREE GROWTH CASES

In recent years, some dendrochronologists have sought to identify changes in tree growth that can be attributed to acidic deposition or to the biological effects of increasing atmospheric CO_2 concentrations. These detection problems are similar to the CO_2-climate case described above. In each case there is a predicted signal, a number of possible causal factors, and considerable natural noise on inter-annual, decadal and longer time scales. It is essential that the same degree of rigour should be applied to such studies as has been applied in the CO_2-climate case.

4.1. Basic requirements

In the CO_2-climate case the basic requirements were a knowledge of the time history of the forcing factors (i.e. CO_2 and other trace gas changes through time), some idea of the expected response based on theory or modelling studies, and suitable observations of the potential responding climatic variables. What are the parallels in the acidic deposition and CO_2 fertilization cases?

In both tree growth cases, the responding variables (ring widths, density, etc.) have long records from a number of individual sites widely scattered around the globe outside the tropics. These individual site series are analogous to individual site climate records (such as temperature series). The analogy is not perfect, however, because the site growth-variable series are generally averages based on a large number of trees. There is no analogue for tree-to-tree variability in temperature observations, and this variability adds a new and important complicating factor.

For the forcing history and the predicted signal, the CO_2 fertilization and acidic deposition cases must be considered separately. We consider the CO_2 fertilization case first. Direct CO_2 effects on plant growth are well understood at the small-scale experimental level. Based on such experiments, the expected signal as CO_2 levels rise is an increase in the tree growth. One might also expect indirect growth changes as described in section 1. The history of the rise in CO_2 concentration since 1850 is generally assumed to be the same as for the climate question. In fact, this need not be the case in densely vegetated areas where the CO_2 level differs markedly from that in the ambient atmosphere and is, in part, controlled by the biological activity in the local environment. We can, of course, use the global CO_2 curve as a proxy for local variations (just as, in the climate case, we use the history of volcanic eruptions as a crude proxy for the associated forcing by stratospheric radiation balance changes). The links between large-scale CO_2 changes and changes in the forest environment require further study.

For acidic deposition the problem is much more complicated. First, it is very unlikely that there will be a long record of the forcing variable. Indeed, for large-scale pollution effects in general we don't even know with any confidence what the forcing factors are! Second, we do not have an accepted model or theory from which to determine the expected signal. It has even been argued that the signal may change with time, with the initial effects being beneficial (e.g. in the generally nitrogen deficient high latitude forest areas) and later effects detrimental. The effects may also vary from site to site depending on such factors as soil type, and from species to species. To exacerbate the problems, any CO_2-fertilization "signal" would represent "noise" as far as acidic deposition effects are concerned, and vice versa.

4.2. Detection variables

In the CO_2-climate case selection of the most suitable detection variable is based on knowledge of the expected signal and of the background noise. Consider first the signal.

In tree growth studies there are a number of possible variables that characterize different aspects of growth - total ring width, early and late wood widths, mean density, maximum and minimum densities, and various combinations of these (such as total width times mean density as an indicator of net biomass productivity changes). The predicted signals for

most of these variables are, at best, highly uncertain. For example, will increasing CO_2 concentrations increase or decrease maximum late-wood density? Do low levels of acidic pollution enhance or reduce growth? In some cases, the signal may vary both with time and with spatial location, just as in the CO_2-climate case. In the climate case, spatial variations in the signal are eliminated by using large-scale area averages. There are problems in trying to do this in the tree-ring case because of our lack of understanding of species-related and temporal differences in response.

In general, the noise is any variability not related to the signal. The noise in the tree-ring cases is therefore the manifestation of the effects of climate, age, pests, disease, management, competition, etc. In the CO_2-climate case our knowledge of the noise is often limited by the length of the available record. Tree rings are often less limited in this way, although in many commercially managed stands trees may be relatively young.

4.3. Noise reduction

The large number of noise contributors demands that some strategy be adopted to reduce the noise level. The noise level, however, depends on the spatial scale being considered. Many tree growth studies have used data from a single site or small region. In the CO_2-climate case the parallel would be trying to detect a CO_2 signal in a single-site climate record. There are two reasons why single-site climate data are of little value in the detection context; the regional-scale signals are unknown and the noise levels at this scale are too high. The latter problem also applies to the tree-growth cases. Since a large part of the noise in a single-site meteorological record is specific only to that site, the noise level may be reduced by area-averaging. The same applies to tree-ring data, and a similar averaging strategy would seem to be mandatory for such data. However, as noted above, spatial averaging may distort the signal, and the strategy requires more thought than in the climate case.

In ring-width time series from a single site, averaging is commonly used to reduce the noise that exists at the individual tree level. In the dendroclimatological context, the raw data are also generally filtered ("standardized" or "indexed") in some way beforehand to remove unwanted low-frequency variations. This procedure may be considered as one which takes advantage of the frequency dependence of different forcing factors in trying to reduce the noise level (Briffa et al., 1986). The filtering strategies normally used in dendroclimatology, however, are clearly inappropriate in the pollution and CO_2-fertilization cases, since, in these cases, the forcing factors act primarily at lower frequencies (although acidic deposition may also have high frequency effects). In this context, we must concentrate on the parts that are rejected in most dendroclimatological analyses. In the pollution and CO_2-fertilization cases, however, we need to be much more careful in the chosen method of filtering. It may even be preferable to consider the raw data directly (cf. LaMarche et al., 1984).

If we are primarily interested in the low-frequency characteristics of a time series, a filtering method must be chosen which does not distort the low-frequency data characteristics. The importance of knowing how the indexing process affects the frequency characteristics of a ring-width time series is discussed by Briffa et al. (1986). Works which fail to consider the possibility of spurious low-frequency variance being introduced through the use of an inappropriate indexing procedure, should be viewed with skepticism.

Because of this focus on low-frequency effects, obfuscating aspects of tree growth that can be largely circumvented in dendroclimatology may present real difficulties in the CO_2 fertilization and acidic deposition cases. For example, both effects are likely to be obscured by aging and management effects. By considering the low frequency characteristics of a number of chronologies from different aged stands the effects of age and, perhaps, management might be minimized.

For dendroclimatological analysis there is a certain minimum number of trees that need to be averaged together in order to produce a statistically well-defined average. There is also an upper limit to the required number of time series, above which the addition of more samples does not significantly affect the high-frequency chronology. The number of trees required to reach a certain level of confidence in a high-frequency chronology depends on the common variance, or mean inter-series correlation $\bar{r}$ (Wigley et al., 1984a). The variance of the hypothetical population chronology that is explained by a size-n sample chronology is

$$R_n^2 = n\bar{r}/(1+(n-1)\bar{r}).$$

This formula allows the strength of a chronology to be assessed as a function of the number of cores in the dendroclimatological, high-frequency case, but its application in the low-frequency chronology case (i.e. the case that is more appropriate to the CO_2-fertilization and acidic deposition problems) is not straightforward (see Briffa et al., 1986). In fact, $\bar{r}$ itself may be affected by pollution or increasing CO_2 and could perhaps be considered as a possible detection variable.

We note finally that the noise reduction strategy of factoring out known effects, which has been applied (albeit rather unconvincingly) in the CO_2-climate case, is much more difficult to apply in the tree-ring cases. For the factors that may contribute low-frequency effects, neither the time histories of the forcings, nor the expected effects are generally known - except perhaps for the effects of low-frequency climatic change on tree growth.

In principle, the idea of factoring out low-frequency climatic effects may seem attractive, but it has great practical difficulties. The statistical problems are the same as those for the CO_2-climate case, discussed at length by Wigley et al. (1985b). In dendroclimatology, success in relating tree growth to high-frequency climate variations using response function analysis has been limited and few such relationships stand up well to independent testing (Briffa, 1984). Low-frequency response function relationships are much more difficult to establish, and almost impossible to test because there is never enough climate data to permit adequate statistical validation. One must, therefore, either assume that a high-frequency response function relationship can be applied with equal confidence to the low-frequency data, or avoid the use of response functions completely. If response functions are used, then due allowance must be made for the uncertainty in the response function relationship. Response functions rarely account for more than 50% of the variance in calibration, or 30% in verification, so the climate-dependent factor that is removed as part of the noise reduction strategy must have wide confidence limits. Given this uncertainty, an alternative approach would be simply to filter out the high frequency variability, making use of the fact that most local climate variance is in the high frequency range. This would, of course, remove any high-frequency pollution effects which may, themselves, be of considerable interest.

To compound these problems, both CO_2-fertilization and air pollution may actually change the way tree growth responds to climate - this is almost

certainly true in the former case because of the effects of CO_2 on water use efficiency. Thus, even if a growth- or density-climate relationship could be developed using unperturbed tree data, this may simply not be applicable to the perturbed case. Most analyses in the literature that have adopted this particular noise-reduction approach have failed to adequately address the above-mentioned problems.

We noted above that pollution may also have high frequency effects on tree growth. This is likely because of the episodic nature of strong pollutant concentration events. The complex nature of the pollution influence, involving many chemical agents with high spatial and temporal variability and numerous hypothesized damage mechanisms, is such that growth (including density) effects can be expected on all time scales. Identifying short time scale effects is no easier than identifying long time scale effects. Although some statistical problems may be reduced because of larger effective sample sizes, other problems arise through the synergistic interactions of the effects of climate and pollution. As noted in section 1, if a tree is stressed by climatic conditions, a severe spring or dry summer for example, then one would expect it to be more vulnerable to pollution. Similarly, pollution stress may well increase the vulnerability of trees to climatic damage. To compound this synergism, at least in Europe, high pollution levels often occur during those weather situations which are thought to be stressful to trees, namely anticyclonic conditions which are generally accompanied by high temperatures and minimal precipitation. Unravelling the interactions between the influences of pollution and climate is a formidable task, one that has no clear parallel in the CO_2-climate detection issue.

4.4. Signal maximization

In climatology it has been suggested that the best place to look for a CO_2 effect is in regions where the expected signal is high. Similarly, in the CO_2-fertilization case, it has been suggested that the signal. i.e. an increase in growth, might be maximized in high elevation trees (LaMarche et al., 1984, 1986). Although this seems to be a direct parallel, there are important conceptual differences. In the climate case, the regions of high signal were established a priori using climate models. In the CO_2-fertilization case, however, reasons for an enhanced effect seem to have been proposed a posteriori. Although science doesn't always follow the strict principles of the scientific method, and a posteriori arguments do sometimes turn out to be correct, this is certainly not a very satisfactory situation.

As an example, consider the growth changes in high-elevation Bristlecone pine noticed by LaMarche et al. (1984). These authors argue that CO_2-fertilization effects might be enhanced at high elevations. They need to do this because their reported growth enhancements, 75-100% over the past ~100 years, are so much larger than expected from small-scale CO_2-fertilization experiments (see Wigley et al., 1984b). Their arguments regarding the supposed amplified signal (LaMarche et al., 1986) are unconvincing. Rather than try to salvage their initial hypothesis that the observed growth changes are a result of CO_2-fertilization, an alternative step would be to reject the hypothesis and search for another mechanism that fits the facts better. Wigley et al. (1984b) note that other sites in the same area and of the same species show no enhanced growth. In the absence of an explanation for these site-to-site differences, this must be counted as evidence against the CO_2-fertilization hypothesis.

4.5. Fingerprint studies

Such studies require a considerable a priori knowledge of the multivariate nature of the signal, something that is distinctly lacking in the CO_2-fertilization and acidic deposition cases. Nevertheless, it is a strategy that may well be worth pursuing, particularly in the CO_2-fertilization case. Wigley (unpublished work) has shown, using the model of Francey and Farquhar (1982), how tree-ring delta C-13 should change as a result of CO_2-induced growth enhancement. Experiments could be carried out to investigate how wood density should change as CO_2 increas . The use of three variables, ring width, delta C-13 and density, should allow CO_2-fertilization effects to be, not only more easily identified, but also more readily attributed to the direct biological effects of increasing CO_2.

4.6. Unprecedented changes

This strategy can be applied in the CO_2-fertilization and acidic deposition cases, but it has the same drawback as in the CO_2-climate case, that of having to define "unprecedented". Most tree-ring records far exceed the length of available quantitative climate records. Nevertheless, care must be taken to examine all of the available data (not just the most recent parts, as in the study by LaMarche et al., 1984), and also to ensure that the "unprecedented" changes are not simply an artefact of the indexing method. In judging unprecedentedness, one can argue that data from a number of sites should be considered.

The basic premise here is that, if one or more characteristics of tree growth (physical properties such as ring widths and densities or statistical properties such as common variance, inter-annual variability, etc.), attains and sustains an unprecedented high or low level, then this must indicate that some new forcing factor has entered the scene. In Europe, there are certainly examples of growth characteristics that have reached unprecedented values in recent decades. Although air pollution is a possible explanation in these cases, there are alternative explanations which need to be examined. Perhaps management or recent unusual climatic conditions have caused these growth changes?

The possibility that future (or recent past) climatic changes may greatly influence tree growth must be considered. If CO_2 does cause a large global warming, unprecedented climatic conditions may occur leading to unprecedented growth effects which would obscure the effects of pollution on tree growth. These climatic changes are as likely to be noticeable in the frequencies of extremes as they are in changes in the mean. For example, although there are no obvious trends in mean rainfall in England and Wales, there is evidence of recent changes in the frequency of extremes (wet springs, dry summers, high growing season soil moisture deficits). Karl et al. (1984) have noted statistically unusual aspects of the recent U.S. climate record. However, even though climate cannot be discounted as a cause for recent highly anomalous growth changes observed in parts of Europe and North America, identifying the unusual climatic conditions that may be associated with these unusual features of tree growth is difficult.

The work of LaMarche et al. (1984) can be viewed as an example of the unprecedented change method. This work, however, would benefit from a more complete demonstration that the recent growth changes are, indeed, unprecedented. The authors also fail to consider the possibility of other explanations, except for a cursory attempt to "disprove" the possibility that climatic change was involved.

5. SUMMARY AND CONCLUSIONS

Determining the effects of large-scale pollution on tree growth have been considered as a problem of detecting an uncertain signal in the presence of considerable noise. The CO_2-fertilization and acidic deposition issues therefore have strong parallels with the problem of detecting the effects on climate of increasing concentrations of CO_2 and other greenhouse gases. Strategies for the tree-growth cases may be defined by drawing parallels with the greenhouse gas-climate case.

Detection has two aspects, the statistical detection of a signal in the observed data (generally based on signal-to-noise ratio arguments), and the attribution of this signal to the proposed causal factor. Attribution should also be approached statistically and this may be done by comparing the magnitudes of the observed and predicted signal and/or by pattern recognition techniques which rely on prescribing an expected multivariate signal.

The following strategies for facilitating detection were discussed: noise reduction methods, signal maximization, fingerprint studies and the identification of unprecedented changes.

Under noise reduction, area averaging is of the utmost importance in the greenhouse gas-climate case, but its application to the tree growth cases is less clear. In these cases, although the noise level may be reduced, averaging may also distort the signal. The main noise reduction method in the tree growth cases, therefore, must be based on attempts to factor out the effects of other causes of tree growth variability. The chief obfuscating factors are age-related growth effects, and the influences of climate, competition and management. Factoring out these effects is exceedingly difficult. For example, separation of the natural age-related growth curve from the effects of pollution is difficult because both operate at low frequencies. Standardization methods that are commonly used to remove growth trends cannot, in general, distinguish between different low-frequency forcings. To overcome this, standardization might be performed over a period of growth unlikely to be affected by large-scale pollution, and the results extrapolated into more recent years. Unfortunately, this introduces new uncertainties related to the validity of the extrapolated curve. Separating out the effects of climate is equally daunting and is generally severely limited by uncertainties in the statistically derived response functions that are usually used for this purpose. These uncertainties are rarely accounted for quantitatively. The problem is further complicated in the acidic deposition case by the possibility that such pollution may change the way tree growth responds to climatic variability, and by the fact that industrial pollution levels tend to be higher in precisely those circumstances when climate stresses are highest.

The signal maximization method relies on identifying some variable or location where the expected signal is much higher than elsewhere. An example here is the possibility that CO_2-fertilization effects may be amplified at high altitudes. There is a danger here of arguing a posteriori; ideally the maximized signal variable or location should be selected a priori in order to avoid circularity of argument.

Fingerprint studies aid in the attribution phase by identifying a specific combination of signals that is unique to the hypothesized forcing mechanism. In tree growth studies there is the possibility of using ring width, density and isotopic data (delta C-13 in particular) to form a multivariate signal whose variations can be attributed to only one forcing mechanism. Present understanding of the CO_2-fertilization and acidic deposition effects on density and isotopic values is insufficient to be able to employ this method, but further work is clearly warranted.

The unprecedented change method requires identifying changes in one or in a combination of variables which have no analogue in the past record. The influence of an entirely new forcing factor may then be hypothesized, but unequivocal proof of the existence of such a new factor would still be lacking.

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**8.2   ON THE C-13/C-12 RECORD IN TREE RINGS: ENVIRONMENTAL
        AND CLIMATIC EFFECTS**

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1. INTRODUCTION

CO_2 from fossil fuel burning and CO_2 released as a result of deforesta-
tion and agricultural manipulation of the soil are marked by a δC-13 deficit
of about 18 to 20°/oo with respect to atmospheric background CO_2 (PDB scale;
e.g. Freyer 1979c). Thus, parallel to the long-term increase of atmospheric
CO_2, the ratio of its stable carbon isotopes decreases with time. Measure-
ments by Keeling et al. (1979, 1980) show that the C-13/C-12 ratio of atmo-
spheric CO_2 has decreased from -6.69°/oo (PDB scale) in 1956 to -7.34 °/oo
in 1978. The C-13/C-12 ratio of preindustrial CO_2 is unknown. Since carbon
in wood is assimilated from atmospheric CO_2, a historical record of this
ratio could be stored in tree rings. For the recent period, mean C-13/C-12
tree ring data obtained from measurements on 22 free-standing trees of
different origin in the Northern Hemisphere (Freyer 1978, 1979a) compares
favorably (Freyer 1981) with the C-13/C-12 decrease found in atmospheric CO_2.
     Existing multi-tree records (Freyer and Belacy 1983; Stuiver et al.
1984; Freyer 1986) leave no doubt that the C-13/C-12 ratio in modern wood
has decreased significantly. However, whether the stable carbon isotope re-
cord in tree rings can be used for reliable determination of past C-13/C-12
levels of atmospheric CO_2 is a matter of some contention (Francey 1981;
Freyer 1981). Measurements have shown that the atmospheric C-13/C-12 infor-
mation in tree rings is often masked by scatter, which is supposed to depend
on local environmental and climatological as well as physiological factors
(Freyer 1980; Francey and Farquhar 1982). This paper summarizes some of
these effects and, in addition, gives a mean C-13/C-12 tree-ring trend for
the Northern Hemisphere which has been reported and interpreted elsewhere
in detail (Freyer 1986; Peng and Freyer 1986).

2. OTHER EFFECTS THAN INCREASING ATMOSPHERIC CO_2 LEVELS INFLUENCING THE C-13/C-12 RECORD IN MODERN WOOD

2.1 Choice of the wood constituent

The chemical form of carbon analyzed in wood is important. For examp-
le, a network of resin channels permeates the wood tissue and contains
soluble organic material that cannot be correlated to the age of the wood
structure. Furthermore, the components that form the wood (cf. TABLE 1)
differ in their isotopic content, and relative abundances of the components
may not be constant over the entire age of wood (Nikitin 1966). Therefore,
the preparation of one pure component is necessary, and in most tree-ring

records, cellulose was analyzed. The reproducibility of measurements, including sample preparation, is of the order $\pm$ 0.1 °/oo (1σ).

TABLE 1   C-13/C-12 data on 14 oak samples (Freyer 1979a)

lignin $\xleftarrow{\ -2.8 \pm 0.2°/oo\ }$ cellulose (δC-13 = -20.9 $\pm$ 0.6°/oo)

$\xrightarrow{\ \div 1.3 \pm 0.3°/oo\ }$ hemicellulose

2.2 Inner-ring variability

The carbon isotope data within the circumference of a single ring closely agree during the juvenile stage of a tree (Freyer and Belacy 1983), whereas those in the older wood show a variability of between 0.1 and 1°/oo (Freyer and Wiesberg 1975; Freyer 1979a; Harkness and Miller 1980; Mazany et al. 1980; Freyer and Belacy 1983; Long and Leavitt 1983), but sometimes as large as 4 to 5°/oo (Tans and Mook 1980). This later differentiation in the circumference of a ring is probably associated with the growth and development of the crown, indicating different environmental conditions around the tree. Some causes of this differentiation have been discussed by Francey and Farquhar (1982). Changes of the carbon isotope content with height, especially in the same wood fiber, seem to be negligible (Freyer and Wiesberg 1975; Tans and Mook 1980), and no consistent longitudinal gradients have been detected (Long and Leavitt 1983). To avoid inner-ring variations, Tans and Mook (1980), Leavitt and Long (1983), and Long and Leavitt (1983) have analyzed wood material from the full circumference of the ring. In other studies, mainly only one radial cut was analyzed for each tree, because nearly similar relative C-13/C-12 changes in different radial cuts have been found (Freyer 1979a; Mazany et al. 1980). Long and Leavitt (1983) have concluded from their careful studies that measurements of two radial cuts opposite in direction may provide a representative trend of the tree.

2.3 Site selection

During the juvenile stage of trees, increasing trends in C-13/C-12 data have been observed in several studies, which were explained as a result of the partial uptake of C-13-depleted soil respiration CO_2 (Freyer 1979a). This effect lasts for about 50 years at most (Freyer and Belacy 1983) and disappears at a certain height or age of the tree, indicating that the C-13/C-12 record of an older tree is more representative for the free-atmospheric C-13/C-12 signal. The same effect has also been observed in forest trees after clearing of neighboring trees (Freyer 1979b). Similar canopy effects could result from death or regrowth of trees in a forest stand adjoining the sample tree. It has been found by Freyer and Belacy (1983) that sudden jumps and nonsystematic variations of C-13/C-12 data with a set of forest oak trees (from the Spessart, Germany) occur, but no correlation is observed with respect to time. In contrast to forest trees, most of the pairs of C-13/C-12 records from free-standing Scots pine trees (from Muddus National Park, Northern Sweden) correlate at confidence limits of $\geq$ 99.5 % (cf. TABLE 2). The scatter for the coefficient of regression of each record on the mean C-13/C-12 trend of the time series amounted to $\pm$ 51 % for the forest trees and to $\pm$ 26 % for the free-standing trees. The

latter scatter is comparable to $\pm$ 20 % observed as inner-ring variations in a free-standing Scots pine (from the Black Forest, Germany), which was analyzed in four different radial cuts (Freyer and Belacy 1983). From these facts, it has to be concluded that forest tree records are not usable for either C-13/C-12 changes of free atmospheric CO_2 or climatic variations. The effects should be minimized by proper selection of free-standing trees.

TABLE 2   Coefficients r for linear correlation of C-13/C-12 data between each pair of records from forest oak trees and free-standing Scots pine trees (Freyer and Belacy 1983)

r^a				

Spessart oak trees (1741-1940 time interval)

	Qu 17	QU 18	QU 19	Qu 20
QU 16	0.16	0.10	0.50	0.22
Qu 17		-0.20	-0.04	0.23
Qu 18			0.01	0.33
Qu 19				-0.16

Muddus National Park Scots pine trees (1780-1969 time interval)

	Pi 8	Pi 9	Pi 10	Pi 11	H + M
Pi 7	0.82	0.86	0.67	0.78	0.55
Pi 8		0.90	0.86	0.74	0.82
Pi 9			0.77	0.67	0.76
Pi 10				0.57	0.76
Pi 11					0.35

[a]Measurements of C-13/C-12 data were performed on 10-year blocks of wood. The number of data points differ in the sets. With 17 degrees of freedom for the 1780-1969 data in the Muddus National Park series the 95, 99, and 99.5 % confidence limits for linear correlation are r = 0.39, 0.53, and 0.58, respectively.

2.4 Pollution effect

Tree-ring studies of C-13/C-12 have shown that heavy air pollution (e.g. from SO_2) lowers the photosynthetic carbon isotope fractionation (Freyer 1979b). This effect was explained by a known inhibition of photosynthesis in plants exposed to air pollution; however, the mechanism of this inhibition is still unproven. It could be caused by the reduction of stomatal conductance, which, according to the model of Francey and Farquhar (1982), would cause increasing C-13/C-12 data in the plant material. Similar effects have been observed by Leavitt and Long (1983) in Juniper trees from Arizona. Trees taken from open sites in rural localities showed a decreasing

C-13/C-12 trend during the last 20 years, whereas a tree in the vicinity of a copper smelter showed an increasing trend approximately coincident with the opening of the smelter. Another example of C-13/C-12 variations in a diseased and a till now visible non-diseased tree from the same site is given in FIGURE 1, showing that the C-13/C-12 pollution effect is one way for early assessment of a damage to a tree.
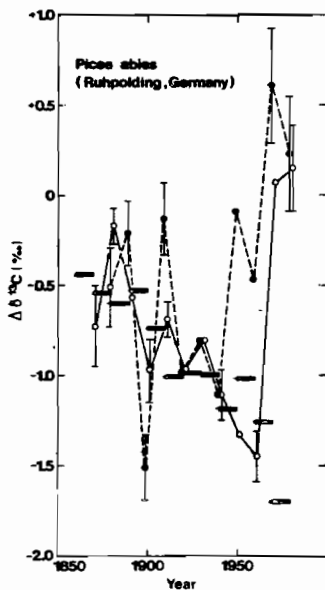
FIGURE 1   C-13/C-12 variations in a diseased (full dots) and a till now visible non-diseased Norway spruce (open dots) from an open site at Ruhpolding, Germany (Freyer, unpublished). The diseased tree shows a rapid C-13/C-12 increase since 1940. The reference tree shows a delayed increase since 1960. Decreasing C-13/C-12 tree ring data at other periods correspond to data of the mean C-13/ C-12 trend of the Northern Hemisphere (full bars; cf. CHAPTER 3)

It has been pointed out (Freyer 1979b) that trends of C-13/C-12 data in trees during the 19th century similarly decrease, whereas the C-13/C-12 records of individual 20th century trees exhibit larger variations. This may partly reflect the increase in ambient pollution levels or in acidity of rain during this century, which could cause changes even where the trees had not been exposed to local pollution sources.

2.5 Climatic effects

A summary on C-13/C-12 temperature effects in trees and other nonwoody plants has been given recently by Long (1982). In addition, other climatic effects have been reported by Freyer and Belacy (1983) and Leavitt and Long

(1983). These effects may disturb the atmospheric C-13/C-12 signal in tree-ring records, especially during the 1920 to 1960 period, in which larger climatic variations have occured. Freyer and Belacy have observed in Scots pine trees from Muddus National Park (Northern Sweden) that first differences of C-13/C-12 and combinations of seasonal climate data correlate significantly (i.e., differences between following 10-year blocks of data, which take into account the sign and magnitude of change in the C-13/C-12 and climate series; the measurements of C-13/C-12 data were performed on 10-year blocks of wood). Correlations at the highest confidence limit ($R^2 = 0.89$) gave a mean temperature effect of +0.18 °/oo ($\Delta\delta C$-13)/ΔT(°C) for autumn and a mean precipitation effect of +0.019 °/oo ($\Delta\delta C$-13)/Δmm (mean monthly) for spring. Leavitt and Long have observed in Juniper trees from Arizona negative responses of -0.27 °/oo (δC-13)/T(°C) and -0.04 °/oo (δC-13)/mm for December temperature and precipitation, respectively. It has been shown in both studies that when applying climate corrections on the original C-13/C-12 data, unexplained variations of the tree-ring records were reduced and a smoother trend was obtained (cf. FIGURE 2).
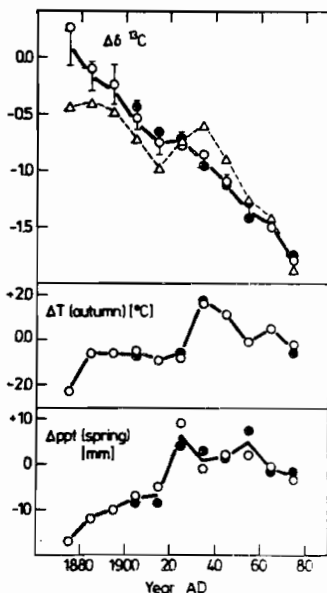
FIGURE 2   (Upper figure) Uncorrected C-13/C-12 record of the Scots pine trees from Muddus National Park in 10-year blocks from 1871-1979 (open triangles, broken line) compared to the weighted corrected record (full line), using autumn temperature and spring precipitation coefficients from climate data of two near-by meteorological stations, Jokkmokk (open dots) and Gällivare (full dots). The bars give the range of data if other significant seasonal climate coefficients are used for corrections. The scale is adjusted to the 1600-1800 mean of the record. (Lower figures)

Autumn temperatures (in °C) and spring precipitation (in mean monthly mm) in 10-year blocks from 1871-1979 as deviations from the 1901-1979 mean for Jokkmokk (open dots, -6.78 °C, 38.0 mm) and Gällivare (full dots, -6.18 °C, 37.7 mm) (Freyer and Belacy 1983).

The response of C-13/C-12 data on temperature and precipitation is complex and even opposite in sign. A change in sign of the temperature effect is not unreasonable for both sites. Data for C-13/C-12 should be maximal at the temperature optimum for photosynthesis, as discussed in the model of Farquhar (1980) and Francey and Farquhar (1982). Therefore, in cooler climates (Northern Sweden), C-13/C-12 data should increase with increasing temperatures favoring optimal conditions for photosynthesis, whereas in warmer climates (Arizona), the reverse effect should result. A similar positive and negative correlation of temperature with growth is also observed in ring-width studies (Fritts 1976).

3. MEAN C-13/C-12 TREND OF THE NORTHERN HEMISPHERE FROM TREE RINGS

It is assumed, that to first order, the C-13/C-12 trend obtained from average tree-ring studies represents C-13/C-12 changes of atmospheric CO_2. However, some effects discussed above may be included in the trend. The choice of the wood constituent could not cause large variations, because cellulose was analyzed in most of the studies. Effects of inner-ring variability, although important within a single tree-ring record, should also be negligible, because data from about 65 trees have been used. Data from obvious forest trees were rejected, as well as data for evident juvenile effects in the trees. Some other canopy effects and effects due to ambient air pollution may be included in several records. All of the records, however, include climatic effects, since only uncorrected data have been used or have been published. Climatic effects should influence the C-13/C-12 data, especially during the 1920 to 1960 period.

All known published C-13/C-12 records for trees from the Northern Hemisphere were used for calculating a mean trend, which has been reported elsewhere in detail (Freyer 1986). The data were first reduced into 10-year block averages. A normalization procedure was performed for construction of 13 different regional trends. The long-lasting record during the 1800-1979 period was used as reference record. The other records for the same region were included by center-of-gravity coordinates. Data measured before 1800 were added without normalization. The same procedure was performed for construction of the mean trend of the Northern Hemisphere from the regional trends. The regions of analyzed trees, recorded years and tree species are summarized below (references are given as footnotes).

Record A: Sweden, Norway (1530-1979), Scots pines (Pinus silvestris), five trees from Northern Sweden[1], one tree from Norway[2].
Record B: California, Oregon, Washington/USA (1530-1969), two Bristlecone pines (Pinus longaeva) from California[3,4], two Douglas firs (Pseudotsuga menziesii) from Oregon[5] and Washington[5].
Record C: Arizona/USA (1700-1981), nine Pinyon pines[6].
Record D: Arizona/USA (1710-1969), one Ponderosa pine (Pinus ponderosa)[7].
Record E: Arizona/USA (1930-1979), six Juniper trees[8].
Record F: Black Forest, Eifel/FRG (1800-1975), two Scots pines (Pinus silvestris)[1,9,10], one chestnut tree (Aesculus hippocastanum)[9,10],

four oaks (Quercus robur)[9,10], two ash trees (Fraxinus excelsior)[9,10].
   Record G: Netherlands (1850-1969), three oaks (two Quercus robur, one Quercus rubra)[11], one beech tree (Fagus sylvatica)[11].
   Record H: Massachusetts, North Carolina/USA (1880-1975), one American elm from Massachusetts[12], four oaks (two Quercus rubra, two Quercus alba)[9], two pines (Pinus serotina and Pinus virginiana)[9] and one poplar (Populus alba)[9] from North Carolina.
   Record I: Ural/USSR (1890-1959), two spruces[13].
   Record J: Wisconsin/USA (1900-1978), three Bur oaks (Quercus macrocarpa)[14].
   Record K: England, Scotland (1900-1968), one oak (Quercus robur)[15], one larch (Larix decidua)[15].
   Record L: Hawaii/USA (1920-1978), two False sandalwood trees (Myoporum sandwicense)[1].
   Record M: France, Spain (1920-1969), four oaks (two Quercus robur, two Quercus lusitanica)[9,16,17], two pines (Pinus maritima)[9,16,17].

   TABLE 3 summarizes mean C-13/C-12 trends found in the regional records. Whereas no trends or slightly decreasing C-13/C-12 data are observed during the preindustrial period from 1550 to 1800 in three regional records, the data in all records decrease since 1800. The mean decrease from 1800 to 1850 and from 1850 to 1920 amounts to about 0.2 and 0.6 °/oo, respectively. Without exception, all regional records exhibit this decrease. From 1920 to 1960, however, the data fluctuate strongly.
   The fluctuations in record A were found to be correlated with climatic factors (Freyer and Belacy 1983; cf. FIGURE 2). Variations in seasonal temperature of about 2 °C and in monthly mean seasonal precipitation of about 15 mm were observed at the site of record A trees from 1920 to 1960. By using a temperature coefficient of +0.2 °/oo ($\Delta\delta$C-13)/ΔT(°C) and a precipitation coefficient of +0.02 °/oo ($\Delta\delta$C-13)/Δmm, a total shift of 0.7 °/oo would be obtained (if temperature and precipitation effect coincide), for which the measured C-13/C-12 data could be corrected. If other tree-ring records were also influenced by climatic effects of this magnitude, much of the disagreement between regional trends from 1920 to 1960 might be explained. In other periods, less regional and global climate variations were observed.

References: [1]Freyer and Belacy (1983); [2]Harkness and Miller (1980); [3]Grinsted et al. (1979); [4]Wilson (1978); [5]Stuiver (1978); [6]Long and Leavitt (1983); [7]Lerman and Long (1980); [8]Leavitt and Long (1983); [9]Freyer (1979a); [10]Freyer (1979b); [11]Tans and Mook (1980); [12]Farmer (1979); [13]Galimov (1976); [14]Bender and Berge (1981); [15]Farmer and Baxter (1974); [16]Freyer and Wiesberg (1973); [17]Freyer and Wiesberg (1975).

TABLE 3 Mean δC-13 change in the regional trends from preindustrial time up to 1960

Record	Change in ΔδC-13*			
	1550-1800	1800-1850	1850-1920	1920-1960
A	-0.3°/oo (Variable. + 0.3°/oo)	-0.1°/oo	-0.7°/oo	-0.5°/oo
B	-0.4°/oo (Variable. + 0.5°/oo)	-0.2°/oc	-0.6°/oo	-0.1°/oo
C	-0.7°/oo (1710-1800)	-0.2°/oo	-0.5°/oo	+0.4°/oo
D	(Variable. + 0.3°/oo) (1720-1800)	-0.4°/oc	-0.6°/oo	+0.6°/oc
E				-0.5°/oo (1940-1960)
F		-0.2°/oo (1810-1850)	-0.8°/oc	-0.9°/oo
G			-0.8°/oo (1860-1920)	+0.4°/oo
H			-0.3°/oo (1890-1920)	+0.1°/oo
I			-0.6°/oo (1900-1920)	+0.8°/oo (1920-1950)
J			-0.2°/oc (1910-1920)	+0.1°/oo
K			-0.6°/oo (1910-1920)	-0.2°/oo
L				-0.6°/oo (1930-1960)
M				-0.5°/oo (1930-1960)
		-0.2 ± 0.1°/oo	-0.6 ± 0.2°/oo	-0.1 ± 0.5°/oo
Mean record	-0.4°/oc (variable. + 0.4°/oo)	-0.2°/oc	-0.6°/oc	-0.1°/oo

*The changes were calculated from means between following 10-year block data (e.g. data for 1800 are the 1790-1799 and 1800-1809 means).

Polynomial fits of the trends during the last two decades from 1960 to 1980 covering the last decade closely agree with the C-13/C-12 decrease in atmospheric CO_2 of -0.65+0.13°/oc for 1956 to 1978, as measured by Keeling et al. (1979, 1980). In contrast, some records without data for the last decade would extrapolate to increasing trends. The agreement of the more detailed record (2-year blocks of data) reported by Freyer (1979a), with the atmospheric C-13/C-12 change, has been shown elsewhere (Freyer 1981).
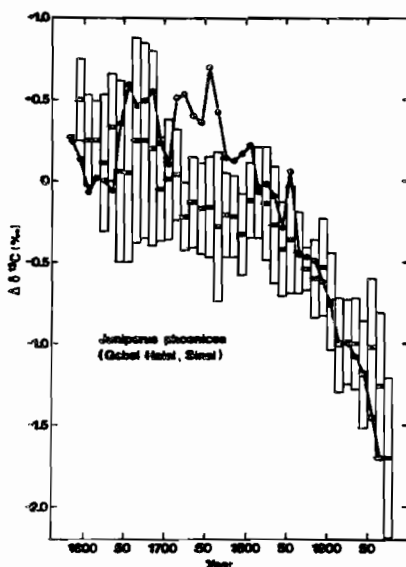
FIGURE 3   C-13/C-12 variations from 1580 to 1970 in a Juniper tree from the
            Sinai (full dots, Freyer unpublished) compared to the mean
            C-13/C-12 tree-ring record of the Northern Hemisphere (Freyer
            1986). Heavy marks of the mean record are mean data for each
            10-year block; the vertical extension of blocks represents one
            standard deviation (1σ) of scatter of individual from mean data.
            The scale is adjusted to the 1600-1800 mean of the mean record.
            The data of the Juniper tree are adjusted by center-of-gravity
            coordinates in the 1800-1970 time period.

        The mean C-13/C-12 trend of the Northern Hemisphere, as calculated from
the regional tree-ring trends, is shown in FIGURE 3, which also gives com-
parable C-13/C-12 variations observed in a desert tree. This revised trend
(Freyer 1986), including new C-13/C-12 tree-ring measurements, shows a lower
C-13/C-12 decrease than the trend reported by Freyer and Belacy (1983). After
completion of this calculation, Stuiver et al. (1984) have published an ad-
ditional trend based on C-13/C-12 measurements of six trees from the Pacific
coast, four of the trees were of forest origin. This trend shows a C-13/C-12
decrease since 1800, which is still 0.5°/oo less than that obtained from the
revised trend of Freyer. One argumentation of Stuiver et al. is that increased
soil acidity in Europe and the eastern United States, from which most of trees
considered by Freyer and Belacy and Freyer are orginiated, and increased
fossil fuel CO_2 contributions as well, could cause a steeper C-13/C-12
gradient than in their Pacific coast trees. This argumentation seems to be
invalid. FIGURE 4 shows that the 20th century data of the Stuiver et al. and
Freyer trends very closely correspond to each other. The main reason for the

deviations of trends is the jump of the Stuiver et al. data between the years 1891/1900 and 1901/1910, which is observed in none of the regional trends used by Freyer.
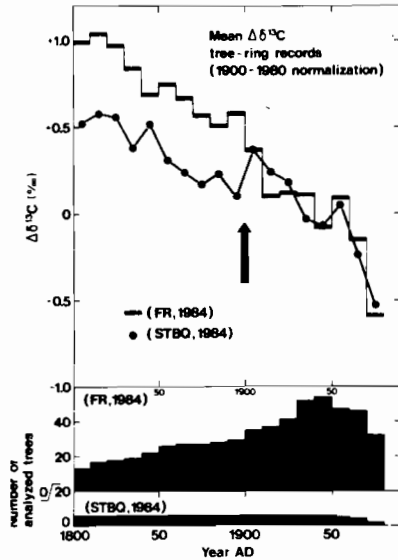
FIGURE 4   Mean C-13/C-12 tree-ring variations in the Stuiver et al. (1984) and Freyer (calculation 1984; in press 1986) records from 1800 to 1980. The scale is adjusted to the 1900-1980 mean of both re-cords. The histograms in the lower figure stand for the number of analyzed trees at quoted time intervals.

A controversy also exists with Southern Hemispheric tree-ring records, which should be expected to give the same C-13/C-12 trend, although with a decrease of some tenths of a mil less than Northern Hemispheric trees (Francey and Farquhar 1982). In fact, measurements by Rebello and Wagener (1976) on a free-standing Brazilian tree agree with the trend for the Northern Hemi-sphere. Also C-13/C-12 trends obtained on whole wood from three Tasmanian trees, and published by Pearman et al. (1976) and Fraser et al. (1978), are consistent with those of some Northern Hemispheric trees used in the calcu-lation of Freyer (1986). Francey (1981), however, using the cellulose frac-tion of wood of the same three Tasmanian trees and including measurements on four additional trees in his record, has reported the absence of any C-13/C-12 trend in tree rings. This is contrary to the findings for Northern Hemispheric trees. However, five of the Tasmanian trees were of forest origin. From measurements on trees within forests, Freyer and Belacy (1983) have observed neither correlation of C-13/C-12 data between individual records nor trends, and they have concluded that forest trees record no C-13/C-12 changes of free atmospheric CO_2.

With inclusion of additional tree-ring data and also slight modifications for normalization of data, a smaller C-13/C-12 decrease from preindustrial time until now was obtained in the Freyer (1986) trend than in the trend published earlier by Freyer und Belacy (1983). The earlier trend has been adopted by Peng et al. (1983) for calculations of past atmospheric CO_2 levels and evaluation of the net biospheric CO_2 input. According to the model of Peng et al., fossil fuel CO_2 emissions would account for a C-13/C-12 change of about 1.1°/oo from 1860 up to 1980. The residual change from the tree-ring data has been attributed to the input of forest and soil CO_2 into the atmosphere. By deconvolution of the residual change using 20-year running means, the integrated forest-soil CO_2 contributions amounted to 22 x 10^{15} mol. Due to the smaller C-13/C-12 decrease obtained from tree-ring data in the calculation of Freyer (1986), these biospheric CO_2 contributions have to be reduced considerably and revised estimates are given by Peng and Freyer (1986).

The main conclusions from this study are summarized below:
a) The total release of CO_2 from the terrestrial biosphere (as of 1980) is estimated to be about 12 x 10^{15} mol, which is only 55 % of the previous estimate. Compared to the total fossil fuel CO_2 released, the biospheric CO_2 input since 1800 is about 90 % of the fossil fuel CO_2 input. Two maxima are observed for the biospheric CO_2 input, a smaller one centered at 1860 and a larger one centered at 1910. A similar time history of the biospheric CO_2 input follows from model calculations of Druffel (1985) based on C-13/C-12 studies of scelerosponges in surface waters.
b) The atmospheric CO_2 increase over the last 20 years is predominantly generated by the release of fossil fuel CO_2. The input from the biospheric source during that period is only about 15 % of that from fossil fuels.
c) The pre-1850 atmospheric CO_2 concentration is estimated to be about 266 ppm, which is consistent with data obtained from polar ice-core studies by Barnola et al. (1983) and Raynaud and Barnola (1985), but it is lower than the data reported by Neftel et al. (1985) and Pearman et al. (1986), which are in the 280 ppm range.

Considering the changes in the averages of the global composite C-13/C-12 record from tree-rings when more data became available, it is clear that C-13/C-12 based estimates of atmospheric CO_2 variations are highly volatile and that further changes are likely.

It has to be emphasized further, that the calculated trend, and thus any conclusions, are based on C-13/C-12 tree-ring data, that were not corrected for climatic influences. These corrections could be especially important for the 1920 to 1960 period, in which larger regional and global climate variations have occured. Further studies and calculations are required to improve the tree-ring usefulness during this period.

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8.3 THE USE OF CLIMATIC RESPONSE MODELS OF TREE RINGS IN THE ANALYSIS AND PREDICTION OF FOREST DECLINE

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1. INTRODUCTION

The recent decline and mortality of red spruce (Picea rubens Sarg.) in the northern Appalachian Mountains of North America (Johnson and Siccama, 1983) has lead to speculation that the cause of the decline is related to atmospheric pollutants. Although there is no shortage of hypotheses regarding the cause of the decline, no cause has yet been found (McGlaughlin, 1985). One of the principal impediments to the analysis of suspected forest declines is the lack of a long-term, pre-decline database for comparison to current conditions in the forest. Ideally, this database would be in the form of frequently remeasured permanent plots located randomly throughout a forest ecosystem. Without a database to provide expected values of tree and stand vigor as a function of tree age, stand density, and site character, it is extremely difficult to determine if a suspected forest decline is truly anomalous or a result of natural stand evolution.

The annual radial growth increments of trees provide an expression of tree and stand growth that can be used to investigate certain aspects of the forest decline problem. Such tree-ring series, which are usually obtained from the DBH region on the bole, are very complicated reflections of past and present stand conditions, competition, tree aging, and climatic influences on tree growth. See Cook (1986) for a detailed discussion of the complexities of interpreting tree-ring series in forest decline studies. In particular, tree-ring series can be extremely useful for modelling the influence of climatic variability on tree growth and vigor. Historically, such climatic response models were often computed as a prelude to reconstructing past climate from tree rings (e.g. Fritts, 1976; Hughes et al., 1982). In such studies, the purpose of predicting tree rings from climate was to discover which, if any, climatic variables could be reconstructed from the tree rings. The actual reconstruction or retrodiction of climate from tree rings involved reversing the direction of dependence in the equations relating tree rings to climate. These new equations were then used to estimate past climate from tree rings. The remarkable success of dendroclimatic reconstructions in many parts of the world (e.g. Cook and Jacoby, 1977, 1983; Fritts et al., 1979; Jacoby, et al., 1983; Briffa et al., 1983, 1986; Norton and Salinger, 198_) attests to the way in which climate can exert a strong and predictable influence on tree growth.

Climatic response models of tree-ring series have great application in the study of forest decline. Such models can be used to identify key climatic variables that are especially influential on the growth and development

of a declining tree species. Such information could reveal a change in climate that is, in some way, responsible for the observed decline (e.g. Johnson and Cook, 1986). The concept that changing climate could directly or indirectly initiate a forest decline was described by Hepting (1963) in a seminal paper. In that paper, Hepting discussed how climate could act as a secondary agent of forest decline by creating optimal conditions for the development of tree pathogen populations. This is a well known concept in forest pathology. More importantly, he advanced the idea that changing climate could be the primary agent of forest decline in those cases not associated with any identifiable primary pathogen. Hepting called such declines "physiogenic". The recent dieback of red spruce is an example of a physiogenic decline of that species, given the present lack of any primary pathogens (Johnson and McGlaughlin, 1986).

Climatic response models can also be used to search for a change or intervention in the operational environment of a tree species that causes an alteration in the trees' response to climate (Cook, 1986). When used in this way, climatic response models are used to predict tree rings from climate in much the same way that tree rings are used to retrodict climate. Significant departures of the actual tree rings from the climate predictions may indicate the intervention of a new, non-climatic stress agent into the trees' environment.

In the following sections, some estimation procedures for climatic response models will be briefly described, followed by some recent applications of this methodology to the red spruce decline problem. I will assume that the tree-ring series being analyzed have been cross-dated and transformed into stationary time series via some method of standardization (Fritts, 1976; Cook, 1985) prior to regression analysis with climate. In addition, is important that a sufficient number of trees be sampled to provide a reasonably precise estimate of the common ringwidth pattern among trees in the stand.

2. CLIMATIC RESPONSE MODEL ESTIMATION

Typically, climatic response models are estimated using ordinary least squares (OLS) or more complicated procedures, such as principal components regression (PCR), when certain OLS assumptions are violated. Since the more complicated techniques are all based on OLS, model estimation procedures based only on OLS will be described. A description of the PCR procedure and examples of climatic response models based on PCR can be found in Fritts (1976). Other potentially useful techniques, such as generalized least squares and ridge regression, are described in Koutsoyiannis (1977) and Draper and Smith (1981). In addition, the OLS procedure described here will be strictly linear in form. Non-linearity may be incorporated by transforming intrinsically linear variables or by allowing for multiplicative interactions between variables. Again, any regression analysis textbook will describe these operations.

Using OLS, we wish to create a regression equation to predict tree rings from climate. In its general form, a tree-ring series, Y_i, of length n will be modelled as a linear function of m climate variables, the X_i, also of length n. This multiple regression equation has the form

$$Y_i = b_0 + b_1 X_{i1} + b_2 X_{i2} + \ldots + b_m X_{i,m} + e_i$$

where b_0 is the y-intercept, the $b_1 \ldots b_m$ are the regression coefficients relating the X_i to Y_i, and the e_i is the error term that is assumed

distributed $N[0,\sigma^2_e]$ and serially random. In matrix notation, this relationship becomes

$$_nY_1 = {_n}X_m b_1 + {_n}e_1$$

and the b's are estimated as

$$_m b_1 = ({_m}X_n X_m)^{-1} {_m}X_n Y_1$$

Assuming that the assumptions of OLS are met, the difficulty in creating a valid climatic response model comes not in the actual computation of the b_i, but in the selection of the appropriate climatic variables, $X_{i,m}$, for predicting tree ring, Y_i. Clearly, for the above model to be useful in predicting tree rings from climate, the selected $X_{i,m}$ must have a time-stable relationship with the Y_i, which will enable the model to make accurate predictions or forecasts outside of the time period used for estimating the b_i. Although best-subset regression procedures, such as stepwise regression, can be used to reduce the number of spurious variables in the model, there is no theoretical method that guarantees the correctness of the regression model during its creation. Much of this problem stems from the a posteriori way that climatic variables are usually screened and entered into the model. Rarely is the general structure of the climatic response model for a tree-ring series known a priori. Hence, a large number of candidate climate predictors are usually included to allow for the search and development of the "correct" model. As the number of candidate predictors increases, the probability of spurious correlations between tree rings and climate likewise increases. See Rencher and Pun (1980) for a very sobering analysis of the problem of spurious regressions given a large number of candidate predictors.

Given that there is no theoretical method to always avoid spurious regressions during the estimation phase, dendroclimatologists traditionally verify the time stability of the regression equation (Fritts, 1976). This is done by withholding some of the actual data from the regression analysis and, the, testing to see if the regression estimates for the period of withheld data agree with the actual data. In the context of climatic response model development for forest decline studies, Cook (1986) advocated two verification periods: one prior to the start of the suspected decline period and one during the decline period. The model forecasts are estimated as

$$_{n1}Y_1 = {_{n1}}X_m b_1$$

for the [n+1...n1] pre-decline period, and

$$_{n2}Y_1 = {_{n2}}X_m b_1$$

for the [n1+1...n2] decline period. Of course, there is no inherent reason to constrain the pre-decline verification period to lie between the regression analysis and decline periods. In addition, if there is enough climatic data, more than one pre-decline verification period can be tried. If the amount of climatic data is very limited, subsample replication techniques, such as the "leave-one-out" method, can be used to verify the model (Gordon, 1982).

Numerous statistical tests are available for verifying model forecasts. These include the product-moment correlation coefficient, sign test, and reduction of error test (Fritts, 1976; Gordon, 1982). Other methods of evaluating forecasts are found in Granger and Newbold (1977) and Abraham and Ledolter (1983). Once the forecasts have been made, these values can be compared to the actual values using one or all of the above tests.

If the regression model verifies in the pre-decline period, the model can be accepted as time stable and extrapolated through the decline period. The decline period forecasts can then be tested for accuracy against the actual data to see if a breakdown in the climatic response model is indicated. Such a breakdown would strongly support the reality of a decline unrelated to "normal" climatic variability and may indicate the intervention of a non-climatic agent such as anthropogenic pollution. Failure to verify in the pre-decline period renders the climatic response model useless for forecasting purposes and highly suspect as a true expression of the climatic response even during the regression analysis period.

In the following section, some applications of the climatic response model to forest decline research will be reviewed.

3. EXAMPLES OF CLIMATIC RESPONSE MODELLING

The methodology of climatic response modelling, described above, was initially tested by Cook (1986) on a red spruce tree-ring chronology from Lake Arnold in the Adirondack Mountains of New York. This chronology was derived from the tree-ring series of 38 increment cores taken at DBH from 20 dominant and codominant trees in the stand. The cores were collected in 1976, several years before the red spruce decline was clearly recognized as a broadscale phenomenon. The stand is near the upper elevational limit of growth for the species (1150 meters) and has an average age of about 220 years.

The 38 tree-ring series were standardized as described in Cook (1986) and averaged into a mean-value function for analysis. Based on previous ndroclimatic studies of red spruce (e.g. Conkey, 1979; Cook, 1982), a mperature response model was developed using regional average monthly temperatures extending back to 1889. Two regression models, using stepwise screening, were developed for the period 1890-1950 using the original tree-ring chronology and the same after autoregressive persistence was removed. The models explained 43% and 48% of the tree-ring variance, respectively, and differed by one climate variable. A pre-decline verification periods of 1951-1960 and 1951-1967 were selected based on the timing of an extremely visable step-like decline in the tree-rings after 1967. Consequently, the decline period was chosen as 1968-1976.

In each verification period, the actual and forecast tree-ring data were compared using the correlation coefficient, reduction of error (RE), and an equality-of-means test. In the pre-decline verification periods, the forecasts significantly correlated ($p<.05$) with the actual data and had strongly positive RE's (a sign of forecast skill). In addition, the equality-of-means tests indicated no significant difference between the means of the actual and forecast values. Thus, there was no significant bias in the forecasts. However, in the 1968-1976 "decline" period, the correlations were not significant ($p<.05$) although the RE's were still positive. More importantly, the equality-of-means tests revealed a significant ($p<.01$) bias of overestimation in the forecasts. This means that the trees were growing much more poorly than the climatic response model forecast. Thus, there is evidence for a breakdown in the relationship between red spruce tree-rings and climate after about 1967. This may be due to the intervention of a new form of stress. Figure 1 shows the actual and estimated standardized tree-rings based on one of the temperature response models. Note the excellent quality of the forecasts up to 1967. The anomalous decline and lack-of-fit of the forecasts after 1967 is quite apparent.
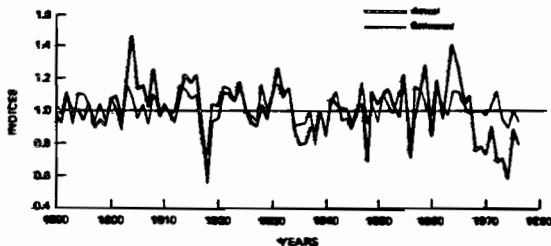
FIGURE 1 Actual and estimated red spruce tree rings at Lake Arnold
based on a temperature response model.

Although the case just described shows strong evidence for an anomalous
decline in red spruce tree rings at Lake Arnold, this finding cannot be ex-
trapolated to the red spruce ecosystem as a whole. In order to get a
regional picture of the red spruce decline in the northern Appalachian
Mountains, Johnson and Siccama (1983) surveyed stands of red spruce in
New York, Vermont, and New Hampshire. Except for low mountain sites, eleva-
tional transects on the east and west sides of the mountains were established
from the low elevation hardwood forest zone to the upper limit of red spruce
in the spruce-fir boreal forest zone. Along each transect at 50 meter inter-
vals, red spruce larger than 10cm DBH were cored at specified sampling points.
Only the more vigorous trees were selected for sampling to exclude trees that
were strongly declining and, perhaps, dying. See Johnson and Siccama (1983)
and Johnson and McGlaughlin (1986) for details concerning the sampling
design.

A total of 18 tree-ring chronologies from the survey data and 3 from
other collections were used in climatic response model analysis (Johnson and
Cook, 1986). The survey data produced chronologies corresponding to natural
elevational zones of red spruce habitat: hardwood forest (low elevation),
transition forest (medium elevation), and boreal forest (high elevation).
All of the chronologies began no later than 1854 and ended (except for 2) on
or after 1981.

Johnson and Cook (1986) were primarily interested in determining if the
climatic signal in the outer 20 years of growth was indeed anomalous compared
to earlier periods. For this reason, they removed as much of the actual
ringwidth reduction as possible by using tight-fitting cubic smoothing
splines (Cook and Peters, 1981) during the standardization process. In addi-
tion, they modelled and removed any remaining persistence in the tree-ring
chronologies through autoregressive modelling. The result was a suite of red
spruce tree-ring chronologies with virtually no persistence and no indication
of an anomalous decline as indicated in Figure 1.

In order to test the usefulness of the climatic response models in a
highly rigorous way, a long-term monthly temperature series extending back to
1820 was created for the Adirondack Mountain region of New York by linearly
interpolating nearby long-term records to the region. This enabled the cli-
matic response model to be based on the 1885-1940 time period with ample time
for two pre-decline verification periods: 1856-1884 and 1941-1960. The
1961-1981 interval was set aside as the decline period.

The results of the modelling are as follows. The temperature response
models explained between 9% and 55% of the tree ring variance, with the
majority in the 15%-30% class. Each result was statistically significant

(p<.10), but some were very marginal. The most consistent variables to enter the model were July and August of the previous growing season (negatively) and December and January (positively) prior to growth. That is, a cool prior summer and a warm late autumn—early winter results in above average radial growth for red spruce the following growing season. In the 1856-1884 verification period, 11 out of 15 cases verified at the p<.10 level, and 9 out of 15 passed the p<.05 level. In the 1941-1960 period, 20 out of 21 cases verified at the p<.10 level, and 18 out of 21 passed the p<.05 level. Thus, the climatic response models are, in general, quite time stable up to 1961 even though the variance explained by regression is sometimes low. However, for the 1961-1981 decline period, only 3 out of 21 cases pass verification at the p<.10 level. In every case, the verified sites were from the low-elevation hardwood zone, a result consistent with the observation that the red spruce decline becomes less severe with decreasing elevation (Johnson and Siccama, 1983).

These results provide convincing evidence that red spruce entered an anomalous period of radial growth around 1960, which changed the way in which the trees responded to climate. Although this conclusion seems to indicate that climate is ruled out as a cause of the decline, an additional examination of the temperature data suggests otherwise. Johnson and Cook (1986) examined the occurrence of extremes in the August and December temperature series by transforming each to standard normal N[0,1] deviates. Those years when either deviate exceeded ±1.64 standard deviations were tabulated and plotted as a "stress index". That is, positive August and December (with sign reversed) deviates were plotted to indicate climatically stressful times that should result in below-average radial growth the following summer. This stress index is shown in Figure 2, along with known periods of abnormal red spruce mortality in the past (Johnson et al., 1986).
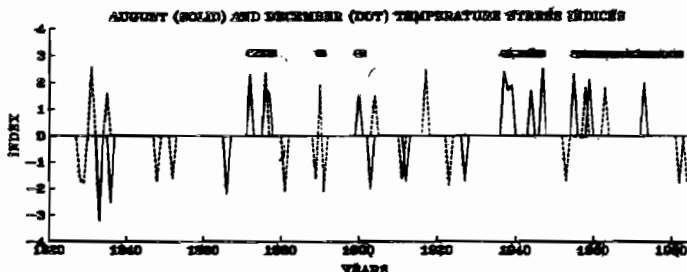
FIGURE 2 The August—December stress index for red spruce growing in the northern Appalachian Mountains. Positive values indicate more stress. Solid points are August and dotted points are December. Solid horizontal lines mark periods of notable red spruce mortality in the past.

There is a clear association between periods of climatic stress and spruce mortality. Most significantly, the 1870's mortality period, which is the only previous decline thought to be as severe as the current one, shows a conjunction of August and December stress similar to the near-conjunction in the late-1950's. The late-1950's is believed to mark the beginning of the

current decline based on field reports of wintertime foliar damage (Johnson et al., 1986; Johnson and Cook, 1986).

Thus, it is probable that abnormally high climatic stress acted as a "trigger" for the present decline. It is not clear at this time if anthropogenic pollution is intensifying the severity of the decline. However, any experimental exposures of red spruce to different pollutants should incorporate climatic stress in the experimental design.

4. DISCUSSION

The successful examples of climatic response model analysis cited above indicate that the method should have considerable utility in forest decline studies. The temperature response modelling of red spruce has resulted in new insights into the sensitivity of that species to climate. In addition, the stress index results, which were only possible through the climatic response model results, suggest that red spruce declines are related to a physiologically-based, temperature-related threshold phenomenon. This empirical result provides a clear hypothesis for tree physiologists to test experimentally.

The utility of climatic response modelling for other tree species and forest declines (e.g. in Central Europe [Schutt and Cowling, 1985]) has yet to be tested. However, judging from the success in reconstructing past climate from numerous other tree species, it is highly likely that the basic methodology presented here can be applied, and when necessary modified, to other forest decline problems.

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8.4   100-YEAR RECORDS OF FOREST PRODUCTIVITY AT HIGH ELEVATIONS IN WESTERN WASHINGTON, USA

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1.   INTRODUCTION

Recent variations in forest productivity are a major interest in North America and Europe as concern grows over reports of forest declines due to acid rain and atmospheric deposition (Johnson and Siccama 1983, 198, Krause et al. 1983, Morrison 1984, Prinz et al. 1983). The accurate assessment of production losses from these factors requires a knowledge of the productivity of forest stands in the absence of air pollution and the natural variability of production over time. Unfortunately, estimates of forest production require intensive research projects (Grier and Logan 1977, Sprugel 1984, Cooper 1981), and, as a consequence, the productivity of many forest types in these regions are not well known.

Net primary productivity (annual production of biomass per unit area) has studied more intensely in conifer forests than in any other forest type (Sprugel 1985). Emperical studies of several different species in different climatic and geologic settings have documented productivity changes following major stand disturbances (Grier and Logan 1977, Tadaki et al. 1977, Yarie and Van Cleve 1983, Sprugel 1984). Although the absolute rates of change differ among forest types depending on the lifespans of the species involved, all studies show generally similar trends during stand development and aging. These trends are summarized in the following below as described by Sprugel (1985).

Annual productivity decreases immediately after disturbance, but increases rapidly as new trees become established on the site. The largest component of production during early stages of stand development comes from the production leaf biomass. Following crown closure, leaf production stabilizes and the relative contribution of woody tissue increases. Total stand productivity stabilizes in mature stands, but generally decreases as stands reach old age. Production declines in old stands are presumably due to increased stand respiration related to the increasing biomass of woody tissue, or to a decrease in nutrient availability.

The objective of our study was to assess the natural variability of net primary production of old-growth conifer stands on upper slopes of the Cascade Mountains, Washington. We were particularly interested in the effect of annual variations in climate on the forest production, as prior work (Grier and Running 1977, Gholz 1979) suggests that these forests should be susceptible to annual variations in temperature. Our study also provides baseline information for assessing present and future pollution effects in these mountains.

2.   STUDY AREA

2.1 Geology

The Cascade Range, WA, is a north-south trending mountain chain with
maximum elevations typically reaching 2000 to 3000 m. Several volcanic
cones rise more than 1000 m above the major peaks of these mountains
(Highsmith 1973). This range was covered by extensive alpine glaciers
during the most recent glaciation (Porter 1984). Soils are generally thin
and developed in glacial till capped by numerous tephra layers originating
from nearby volcanoes (Franklin and Dyrness 1973).

2.2 Climate

Westery air from the Pacific Ocean dominates the western slopes of
the Cascades during all seasons of the year (Highsmithe 1973). Orographic
lifting of moist air results in high precipitation in the mountains,
particularly as snow in the winter. Annual snowfall is commonly more than
1500 cm at upper elevations (1500-2000 m) in these mountains. Snow often
remains on the ground at upper elevations until early July. Precipitation
is stongly seasonal, however, with only 20% of the average annual
precipiation occurring during the growing season.

The proximity of the Pacific Ocean has a mitigating effect on
seasonal temperature fluctuations in the western Cascades. At upper
elevations in these mountains minimum January temperatures are
approximately -10 to -15°C and average maximum July temperatures are
generally +15°C.

A recent dendroclimatic reconstruction for the west Cascade Mountains
shows a 1°C increase in mean annual temperature between the mid 19th and
20th centuries (Graumlich and Brubaker 1986). This warming trend has
caused a rapid recession of alpine glaciers (Burbank 1981) a and recent
increase in tree establishment at treeline (Franklin et al. 1971) in these
mountains.

2.3 Forests

Three major forest zones (Franklin and Dyrness 1973) cover the
western slopes of the Cascade Mountains. The *Tsuga heterophylla* zone
extends from lowland areas to approximately 700 m. Old-growth: forests in
this zone are dominated by *Pseudotsuga menziesii* (Douglas-fir) and/or
Tsuga heterophylla (western hemlock), with lesser importance of *Thuja
plicata* (western redcedar). These species are generally long-lived
(600-1000 years) and reach massive sizes (3m in diameter, 100m in height).
Stands within this zone have shown some of the highest biomass and annual
production rates recorded for coniferous forests in the world (Lassoie et
al. 1985).

The *Abies amabilis* zone, extending from approximately 700 to 1500
meters, is dominated almost exclusively by *Abies amabilis* (Pacific silver
fir). Trees in this zone are smaller than those of the *Tsuga heterophylla*
zone and net primary productivity is generally two-thirds that of the
Tsuga heterophylla zone (Lassoie et al. 1985). The lower productivity of
Abies amabilis forests is thought to result from the detrimental effects
of shorter and cooler growing seasons on rates of net photosynthesis and
nutrient release by decomposition and mineralization at high elevations
(Lassoie et al. 1985).

The *Tsuga mertensiana* zone (1000 to 1500 m) is the highest forest zone of the western Cascade Mountains. These forests are dominated by *Tsuga mertensiana* (mountain hemlock) with varing proportions of *Abies amabilis*, *Chamaecyparis nootkatensis* (Alaska yellow cedar) and *Abies lasiocarpa* (subalpine fir). Old trees (600-1000 yrs) are relatively common; however, tree sizes are generally small compared to those of lower forest zones. The productivity of these forests has not been previously studied, but is considered to be less than that of lower forest zones.

3. METHODS

3.1 Field sampling

The following criteria were used to select plots for sampling: 1) tree ages of at least 300 years, 2) no evidence of tree mortality within the plot and within 10 meters of the plot perimeter, and 3) no evidence of unusual crown damage to trees within the plot. In each plot, increment cores were collect at 1.4m height from all trees greater than 15 cm in diameter. The diameters of all sample trees were measured at 1.4m height. The locations of the plots analyzed in this study are shown in Figure 1.
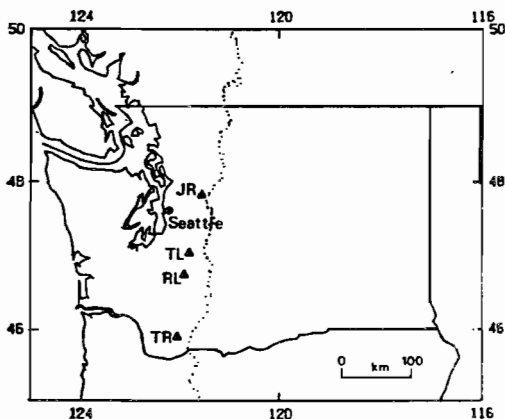
FIGURE 1 Locations of sites analyzed for net primary production and the Seattle climatic station. The dashed line represents the crest of the Cascade Mountain Range.

3.2 Laboratory analysis

All cores were mounted in permanent holders, sanded to a high polish and cross-dated with other cores from the plot and with existing tree-ring chronologies from the west Cascade Mountains (Brubaker 1980, Graumlich and Brubaker 1986). Annual ring widths were measured to the nearest 0.01mm using a Bannister incremental measuring machine.

3.3 Estimation of net primary production

Net primary production (NPP) is defined as the exess of annual gross photosynthesis over respiration (Odum 1969). In practice, gross photosynthesis and respiration are difficult to measure in field situations and few studies have attempted to quantify these processes in forest stands (Assman 1970, Sprugel 1984). More commonly, NPP is estimated by the equation (Grier and Logan 1977, Fujimori, et al. 1976):

$$NPP = B + D + G \text{ where,}$$

B = annual increment of living biomass of trees, shrubs and herbaceous plants

D = annual loss of living biomass of trees, shrubs and herbaceous plants due to natural mortality

G = annual loss of living biomass of trees, shrubs and herbaceous plants due to grazing.

Several simplifying assumptions enabled us to use this equation to reconstruct NPP back in time. Biomass losses to grazing were considered negligible because insect defoliation and grazing by mammals are unimportant in mature stands of western Cascade forests (Grier and Logan 1977). Similarly, the contribution of understory species and small trees (<15 cm diameter at 1.4 meters) to total primary production of old stands is negligible (Grier and Logan 1977). Estimating NPP was thus reduced to determining the biomass increment and mortality of large trees.

The major difficulty in assessing NPP by this equation is in determining the dates of tree mortality and sizes of such trees at the time of their death. In order to avoid the uncertainties of characterizing tree mortality, we selected plots free of signs of mortality (downed logs and raised linear surfaces). The death of trees less than 15-20 cm in diameter may have gone undetected, but trees of this size are unimportant in production budgets of old-growth forest stands (Grier and Logan 1977).

We were thus able to estimate past NPP solely by determining the past biomass increments of trees alive at the time of sampling. Biomass increments were calculated by substracting the estimates of total tree biomass of the plots between successive years. The components of tree biomass (foliage, stem wood, stem bark, and living and dead branches) for each year were calculated from standard regression equations (Gholz et al. 1979) relating stem diameters to tree biomass components. These equations are of the form:

$$\ln Y = a + b \ln X$$

where,

Y = biomass of foliage, stem wood, stem bark, or branches

X = stem diameter

a,b = regression coefficients

We used species-specific regression coefficients established in previous studies (Gholz et al. 1979), which had distructively sampled trees of each species and compared tree diameters to weights of tree biomass components. The total plot biomass for each year was calculated by summing the biomass

components across all trees in the plot, as calculated from the diameters
of trees in that year.

3.4 Comparisons of Productivity and Climate

The variations in NPP at the four sites were summarized by principal
components analysis. Factor scores of the first principal component,
representing the most important common variation in NPP among the series,
were used as a record of variations in regional forest productivity for
comparisons with climtic data. These scores were compared to climatic
data from Seattle, WA (47 39, 122 18) using simple correlation and
cross-spectral analyses. Seattle is the closest station to the sampling
sites having a long meteorological record (1983-1980). Climatic data were
summarized as average summer (June-September) temperatures and water year
totals (the sum of precipitation from the preceeding October through the
September of the growth year).

4. RESULTS

The sampled stands come from each of the three major forest zones of
the west Cascade Mountains, WA (Table 1). Stand ages, as indicated by the
age of the oldest tree, ranged from 370 to 630 years.

TABLE 1   Characteristics of sample plots.

Forest Zone	Tsuga heterophylla	Abies amabilis	Tsuga mertensiana	
Site	TR	TL	RL	JR
Latitude	4 52'	47°45'	47°02'	46°45'
Longitude	122°05'	121°15'	121°50'	121°56'
Elevation (m)	1200	1400	1440	1460
Plot size (ha)	0.032	0.046	0.051	0.026
No. trees	27	20	14	24
Oldest tree (yrs)	630	510	370	560
Percent of total biomass by species (1979) data:				
T. heterophylla	100	--	--	---
A. amabilis	--	52	27	4
T. mertensiana	--	48	69	96
Chamaecyparis nootkatensis	--	--	4	---

Current (1980) net primary production ranged from approximately 5 to 10 metric tonnes per hectare per year. The records NPP at all sites shows strikingly similar trends (Figure 2): 1) increasing from 1880-1980, 2) decreasing or remaining stable from 1910 to 1935, 3) increasing from 1935 to 1960, and 4) remaining relatively stable from 1960 to 1980. The average increase in NPP at each sites between the first three decades (1880-1909) and last three decades (1950-1979) of the record was 60%. Correlations of NPP among sites are positive and highly significant, ranging from .46 to .83. The first principal component explains 81% of the variation in the data and represents the positive correlation of NPP among all sites.
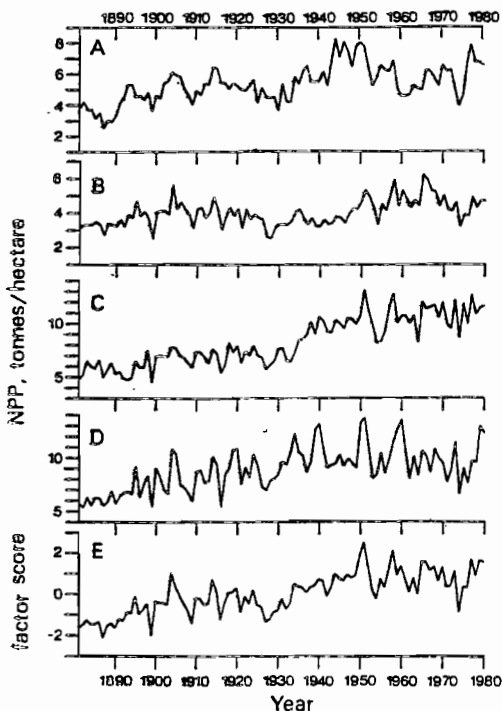
FIGURE 2   Annual estimates of NPP for forest stands on the upper slopes of the Cascade Range, Washington.   (A-D) NPP estimates for four individual sites (see Table 1).   (E) Factore scores obtained from the principal compenent analysis of the four series (A-D).

The time series of factor scores for the first component represents the common variation in NPP at the four sites. In subsequent analyses this series was considered to be a record of regional NPP, which represents diverse forest types in the west Cascade Mountains. The regional NPP record shows strong similarity to summer temperature trends ($r = .46$). The correlation of NPP with precipitaion, although significant, is less strong ($r = .21$).
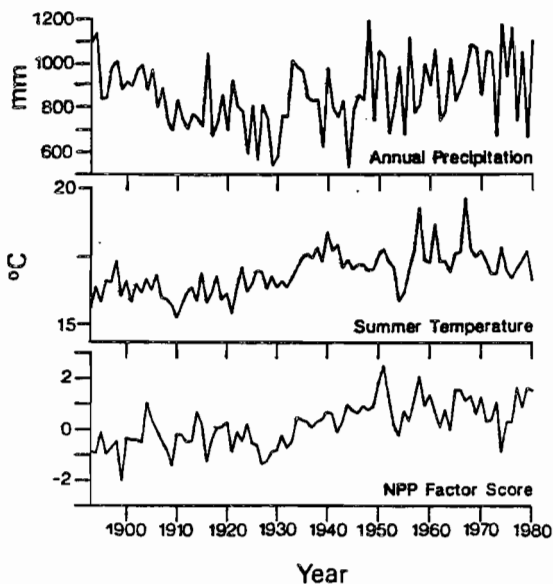
FIGURE 3   Annual precipitation and summer temperature, Seattle, Washington, (1893–1979) and time series of NPP factor scores, as in Figure 1 E.

The purpose of the cross spectral analysis was to identify over which temporal frequencies NPP is most closely associated with temperature and precipitation. The squared coherency, analogous to the square of the correlation coefficient between two time series calculated at different frequencies, revealed that NPP is associated with temperature over periods of 6 years and greater and with precipitation at periods of 3 years and less. In agreement with the results of the correlation analyses, the association of NPP with temperature is much stronger than that of NPP with precipitation.

5.   DISCUSSION

The net primary productivity of stands sampled in this study are similar to values reported elsewhere in the west Cascades (Lassoie et al. 1985). Thus, the current and, by implication, past productivity of our stands appears to be representative of forests in much of the western Cascade Mountains.

The similarity of NPP trends at the four sites is strong evidence that factors operating at a regional scale are important in determining the productivity of forests in these mountains. Although local disturbances and processes of stand dynamics may be important determinants of productivity in individual stands, these factors cannot explain the consistent productivity trends that we have observed in stands of different ages, species, and geographic locations. The significant statistical association of regional NPP records with temperature and precipitation records suggests that recent climatic variations, particulary variations in summer temperture, have been important factors controlling the productivity of western Cascade forests over the past century. Variations in global atmospheric carbon dioxide have apparently not directly affected forest productivity in this region (Graumlich et al. in review). Likewise, no evidence exists for a production decline due to air polution (Gaumlich et al. in review).

Temperature and precipitation can influence NPP through a variety of processes (Lassoie et al. 1985). Precipitation variations predominantly affect short-term processes regulating tree water balance, such as stomatal responses to xylem pressure potential and vapor pressure deficits. The effects of temperature are more complex, including short-term influences on photosynthesis, cell division, and water and nutrient uptake, as well as longer-term controls over leaf production, allocatio of carbon to above- and belowground parts, and rates of decomposition and mineralization. Differences in the way temperature and precipitation affect production-limiting processes may be responsible for the differences in the time scales over which NPP is correlated with these factors.

Our results also have implication for other studies of forest productivity in this region, and possibly in other regions where productivity responds strongly to temperature variations. Because the strongest relationship between temperature and productivity is over long time periods (greater than 6 years), short-term measurements of temperature and productivity may not adequately specify the nature of the relationship between these variables. In addition, since NPP at each site varies substantially over short time periods, conventional practices of estimating NPP based on 1-to-5 year records of biomass increment may not accurately reflect long term forest prduction rates.

7. CONCLUSIONS

The natural variability of productivity of upper elevation Cascade Mountain sites is great and controlled primarily by variations in summer temperature. NPP increased by 60% over the period 1880-1979. Thus, prior to 1980 these forests show no evidence of a substantial decline in productivity that could be attributed to atmospheric pollution.

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8.5 PROBLEMS IN ASSESSING BASE-LINE TRENDS FOR THE RADIAL GROWTH OF TREES IN FINLAND

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1. INTRODUCTION

Time series of radial tree increment are, in some cases, useful indicators of the adverse effects of environmental pollution (Eckstein et al. 1983, Schweingruber et al. 1985, Schweingruber 1985). It has been suggested that an international network of tree-ring data points could be used for monitoring the past and present development of forest ecosystems. This approach was discussed at the IIASA Workshop on "Regional Resource Management", held in Bulgaria, in 1985. In principle it should be possible to construct "base-line curves" for radial growth of trees by choosing sites which have experienced natural conditions over a long period of time. The effects of environmental pollution in time and space could be tested against this "base-line" data.

One would imagine that in Finland, which is a relatively sparcely settled country, it would be easy to find many suitable sites for the collection of such dendrochronological base-line data. History shows, however, that human impact on Finnish forests has been extremely strong during the past centuries. Forest cuttings for different purposes have been very common, while in the present century the natural growth of forests has been changed by effective forest management.

2. LONG-TERM BACKGROUND DATA

A forest vegetation spread over Finland after the end of the last ice age. The whole country was free of ice by around 9000 years ago, but even at that time large areas of southern and western Finland were still covered by water. Land uplift, which is still proceeding, raised those regions above sea level. Because of this development, the soils in eastern Finland can be over 10,000 years old, whereas the land surface near the present coast has emerged from the sea only recently. Rich clayey and silty soils deposited originally in deep water are common in the west and south, contrary to the poorer ground-moraine soils predominant in other parts of the country (Donner 1976, Eronen 1983).

Climatic variations during postglacial time affected the contemporary forest composition which, in turn, is a source of information of past climatic development. The warmest period of the postglacial was about 8000-5000 years ago. Since then climate has been slowly deteriorating, but there have probably been many fluctuations within that trend, each lasting decades or even centuries. Such fluctuations were experienced relatively recently during the "Little Ice Age" (cf. Eronen et al. 1985).

Pollen-analytical research has shown that different tree-species spread
to Finland at different times. Nevertheless, all tree species growing
naturally in Finnish forests arrived there several thousands of years ago
(see e.g. Donner et al. 1978).

The humid climate of the postglacial has favoured peat growth and
accumulation so that about a third of the land area is covered by peat. The
spread of mires has considerably changed forest composition and growth (Laine
1982).

If only those factors mentioned above had affected forest development
and growth in Finland, it would certainly be possible to determine base-line
trends for radial tree increment without any great difficulty. However, the
anthropogenic conversion of natural forests to different uses has changed the
picture radically.

3. SLASH-AND-BURN CULTIVATION AND ITS CONSEQUENCES

Although there are records of cultivation in prehistoric times in
southern Finland, the area of fields was relatively small until the past few
centuries, when a strong expansion of agriculture occurred. Most fields were
cleared during that period using the slash-and-burn technique; i. e. trees
and bushes were cut and the logs and brush piles were burned. The soil was
fertile for some years, after which time a new field had to be cleared in a
new place.

It can be seen from Fig. 1 that slash-and-burn cultivation was very
common practice in the southern half of Finland in 19th century and was still
carried on to a relatively large extent in the early part of this century.

Vast forest areas became subject to destruction in this way. Only
forests growing on peat bogs, very wet (paludifying) and very dry (consisting
of coarse sand and gravel) mineral soils and barren rocks were saved from the
cultivators. With increasing population numbers the same areas were cleared
at shorter and shorter time intervals. The proportion of coniferous trees in
the forests decreased in line with this development, because there was
insufficient time for the forest succession to reach the conifer-dominated
stage. The nutrient content of the soil decreased step by step because the
period of reforestation was too short to compensate for nutrient loss during
the cultivation phase.

This clearance of forest for shifting agriculture was especially
destructive to spruce, which in some regions disappeared almost totally from
the forest flora and there are still many forest areas in central and eastern
Finland which are dominated by deciduous trees, primarily by birch. Still
spruce forests have also recovered over large areas during this century
(Heikinheimo 1915, Alho 1968, Yli-Vakkuri 1980, Huttunen 1980).

4. THE EFFECTS OF TAR MAKING

Some commercial tar making was practised in southern Finland as early as
16th century. During 17th century Sweden became the center of the European
tar production and large amounts of tar were produced especially in the
eastern part of the kingdom of that time, that is in Finland. Over the
centuries tar formed one of the most important goods for export for the
Finns. The cessation of tar making came at about the same time as the end of
slash-and-burn cultivation, that is early in this century.

Tar making led to a devastating use of forests. Pine provided the raw
material for tar distillation and, in consequence, the area of pine forests
shrank and spruce was   to spread into the tar production areas even onto

relatively dry areas which were naturally occupied by pine.
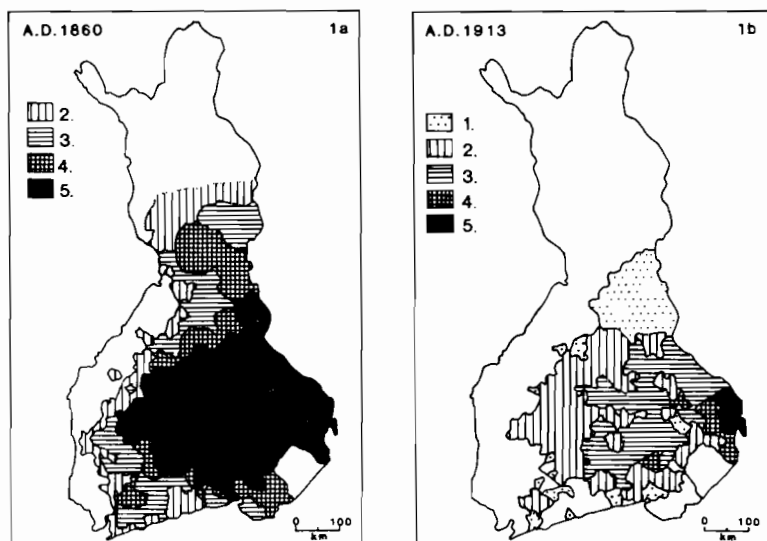
Fig. 1. The extent of slash-and-burn cultivation in Finland AD 1860 and AD 1913. Although wide reforestation has occurred the former use of land for shifting agriculture still affects the forest composition and growth over large areas. Redrawn after Heikinheimo (1915). 1. Ended in early 1900s, 2. Rare, 3. Moderately common, 4. Common, 5. Very common.

Tar making was concentrated in those areas which had good connections to the coast of the Baltic Sea (Fig. 2). From 18th century onwards the Ostrobothnia region (east of the Gulf of Bothnia) took a leading position in tar production, the peak of production being reached in mid-19th century. In 1863 227,000 barrels of tar were exported from Finland (Alho 1968).
    The wood for tar making was taken in the first place from forests growing on dry, relatively poor soils, which were usually not used for slash-and-burn cultivation. So these two modes of action together destroyed different forest communities.

5. FOREST FIRES

Both slash-and-burn cultivation and tar making involved the careless use of fire, which led to the frequent occurrence of forest fires during the summer. The number of fires has decreased in this century due to a radical change in forest use and effective fire-fighting (Heikinheimo 1915, Laitakari 1960, p. 89-91, Alho 1968).
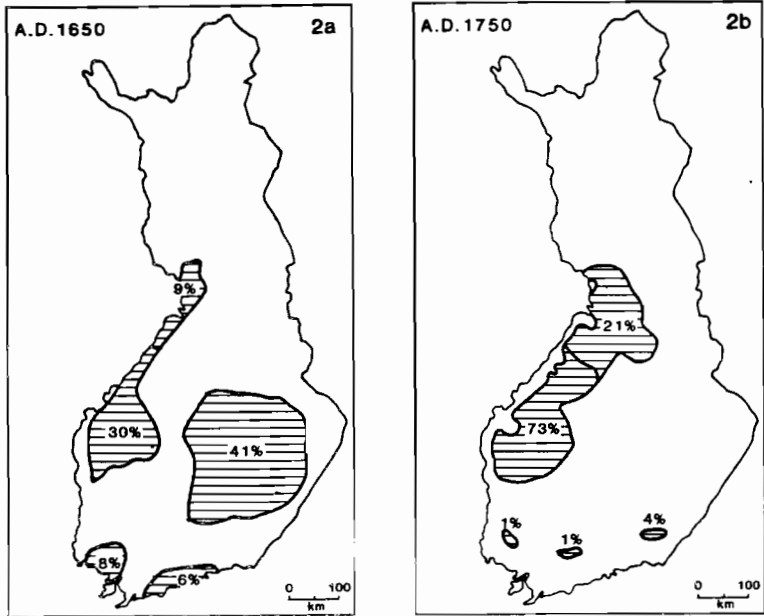
Fig. 2. The proportions of different regions of Finland contributing to tar production, AD 1650 and AD 1750. Fig. 2B shows, how the Ostrobothnia region took a leading position in tar making in 18th century. It was still the centre of tar production in 19th century. In many places in that region the forests have not yet fully recovered from the devastating effects of large-scale tar making. Redrawn after Alho (1968).

Charcoal layers found in lake sediments indicate that in southern Finland the average frequency of forest fires was one in every 80-160 years before the period of wide-spread slash-and-burn cultivation. The sedimentary record of one particular lake (Lammi, southern Finland) shows that in its surroundings the fire interval was, on average, 57 years between AD 1100 and 1600 while between AD 1600 and 1900, when slash-and-burn cultivation was very common, the time interval between fires was only 30 years (Huttunen 1980, Tolonen 1983).

Recurrent fires decreased soil acidity (as also did slash-and-burn cultivation), because organic acids were burned with other humus substances. On the other hand, the fires encouraged the spread of mires on wet mineral soils, because evapotranspiration was reduced after a fire. Spruce trees were often killed in fires but the more deep-rooted pines could even withstand many forest fires during their life time, the damage caused by fires being only visible in the shape of the trunk and in the ring patterns of old trees (e.g. Zackrisson 1977, Eronen and Zetterberg 1986).

6. SOME OTHER FORMER FOREST USE TRADITIONS

Houses were commonly built from logs in earlier times and wood was used to head the rooms during the cold season. During the briskest period of the tar trade ships were built in great numbers from heavy pine timber.

Traditionally the forest was used as a pasture ground, with a large number of cattle being grazed in the Finnish forests during the summers right up until the past few decades. Animals roaming in the forest destroyed the young tree shoots and pasturing also retarded the reforestation of fields cleared for slash-and-burn cultivation.

It is evident that all these activities described above must have had a very strong and profound effect to the condition of Finnish forests. Fig. 3 shows how wide-spread forest destruction was in 19th century. The shortage of wood, especially of heavy timber, was very common in the southern half of Finland. There were some larger untouched forest areas in the watershed regions, which were difficult to reach at that time (Alho 1968, Yli-Vakkuri 1980, Huttunen 1980).

7. MODERN METHODS OF FOREST MANAGEMENT

The wood processing industry began to expand vigorously in the latter part of 19th century and during the present century it has developed to become the backbone of the Finnish economy. The timber needed by the industry became extremely valuable, which swiftly changed attitudes with regard to forest treatment. It became profitable to take care of the forests and to grow them for timber cuttings. Reforestation occurred over wide areas. Nation-wide general forest surveys were organized to estimate the amounts of timber and to follow forest development (Ilvessalo 1927). These forest inventories have already been repeated seven times (Kuusela 1986).

Forest management for economical purposes has become particularly effective during the past decades and large areas of wet mineral ground and peatlands have been drained. About one half of the Finnish mires are now artificially drained and in southern Finland only a small minority of mires remain under natural conditions today (Laine 1982).

Fertilization of forests became common in 1970´s when the yearly fertilized area grew to over 200,000 hectars (Yearbook of Forest Statistics 1984). Modern forestry practise also involves the planting of saplings and thinning the young forests.

Effective forest management has increased forest growth to such a degree that, despite large clear-fellings, the volume of timber in Finnish forests has increased during this century. On the other hand, clear-felling has been extended far to the north and to other remote areas where some relatively large virgin forests still existed in 1950´s (Alho 1968, Heikurainen and Seppälä 1973, Kuusela 1976, Paavilainen and Tiihonen 1985).

8. POSSIBLE EFFECTS OF ATMOSPHERIC POLLUTION

Air pollutants, which have caused forest damage in many industrialized countries, present a serious problem in Finland, too. Conifers with reduced foliation can frequently be seen in southern Finland, especially in the surroundings of the major cities. According to a survey made in summer 1985 about 11 % of the coniferous trees in southern and central Finland had suffered such serious damage that they had lost over 20 % of their needles.
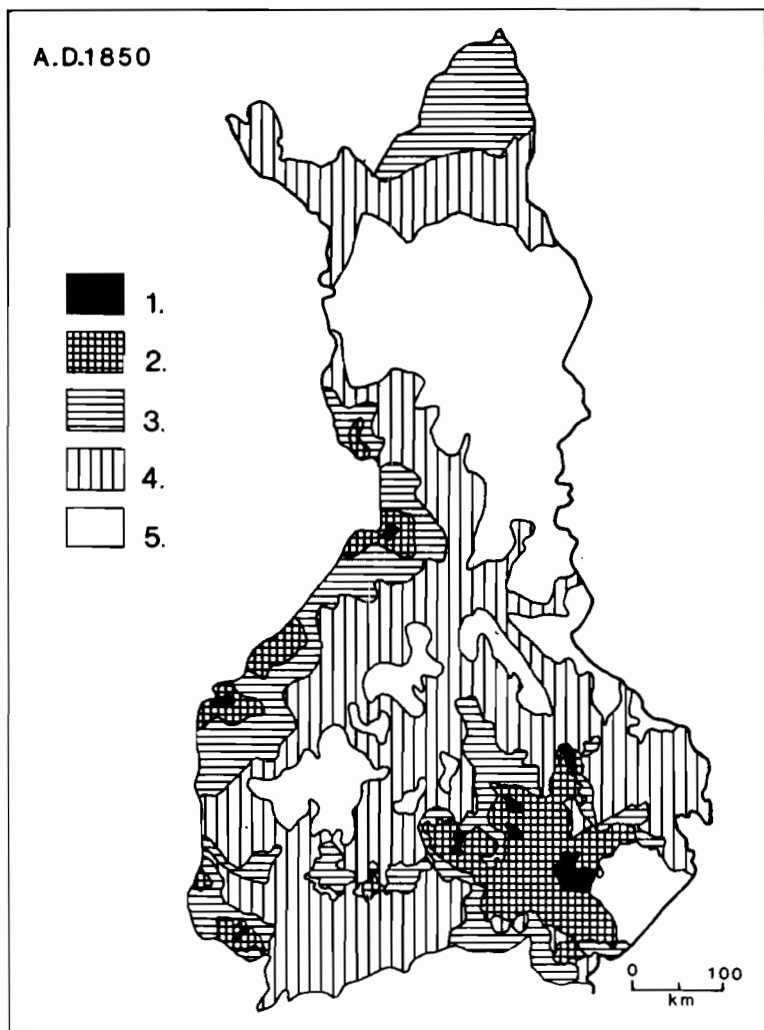
Fig. 3. The condition of Finnish forests around AD 1850. After C.W.
Gylden. Redrawn from Yli-Vakkuri (1980), slightly altered. 1. Common
shortage of all kinds of timber and fuel, 2. Shortage of fuel and timber,
3. Fuel for family use, shortage of heavy timber, 4. Mainly young or inferior
forests, 5. Mature forests.

However, the reasons for these injuries could not be determined and there are no accurate data of similar damage in earlier times to form a comparison. Therefore, the rate of spread of damage is not known (Jukola-Sulonen et al. 1986). Finland is one of those industrialized countries who agreed, in 1985, to reduce their sulphur emissions by at least 30 % by 1993. Reliable estimates of the future effects of air pollutants are impossible to make at present, when even the mechanisms of damage are largely unknown.

Of global concern is the increase in atmospheric CO_2 and its "greenhouse effect", a global warming attributable to that change in atmospheric chemistry (Manabe and Wetherald 1980, Rotty 1984). An increase in mean temperature of several degrees centigrade would certainly enhance forest growth in Finland. The shifting of natural vegetation zones and possible changes in seasonal wetness might, on the other hand, bring about many negative consequences. There is experimental evidence for an acceleration in plant growth following increased atmospheric carbon dioxide but there are still uncertainties as to its effect under ambient conditions (see LaMarche et al. 1984, Cooper et al. 1986).

9. DETERMINING A BASELINE TREND FOR RADIAL TREE INCREMENT

As is evident from the earlier chapters, virgin forests have disappeared almost entirely from Finland and present-day forests are mostly relatively young and managed for economic purposes. Pine is the most common tree species (approx. 55 % of forests are dominated by Scots pine, 32 % by Norway spruce, and 7 % by birch species, Kalliola 1973). Pine ought to be the most suitable tree species for establishing a base-line growth trend. Old pine stands are rare but some still exist (cf. Fig. 4). In northern Finland there are some protected areas with relatively large old forests (Mikola 1976).

In southern Finland pine forests growing on barren rocks have often remained undisturbed, partly because such places could not be used for agriculture and partly because the quality of timber of these somewhat stunted trees is not good. Trees growing in these poor habitats could be useful for monitoring the effects of air pollution, because they are likely to be very sensitive to that kind of environmental stress. Additional material for comparison could be obtained from conservation areas. That study remains to be done.

The curve in Fig. 4 serves as an example of a relatively long tree-ring record that theoretically could be useful for monitoring environmental changes. At the same time it elucidates the problems which will be raised in such studies. The curve, extending to AD 1450, is based on pine material collected from eastern Finland (see Eronen et al. 1985). Most of the material consists of living trees but tree-ring series from logs used as booms in timber floating and beams from old houses have also been utilized in the curve construction. The oldest living trees in the material are a little over 400 years old.

It can be seen that the biggest variations in ring width are in the early part of the curve. The reason for this is that ring series available for that period are very few. The average width of rings diminishes gradually towards the present time. The explanation for that trend is that the younger parts of the curve are based on material derived, on average, from older and older trees. That tendency in the curve, resulting from biological factors, makes it impossible to detect in this material centuries-long trends of climatic development or other correspondingly slow

shifts in environmental conditions. The scale of yearly variations in ring thickness also diminishes in pace with the ageing of the trees.
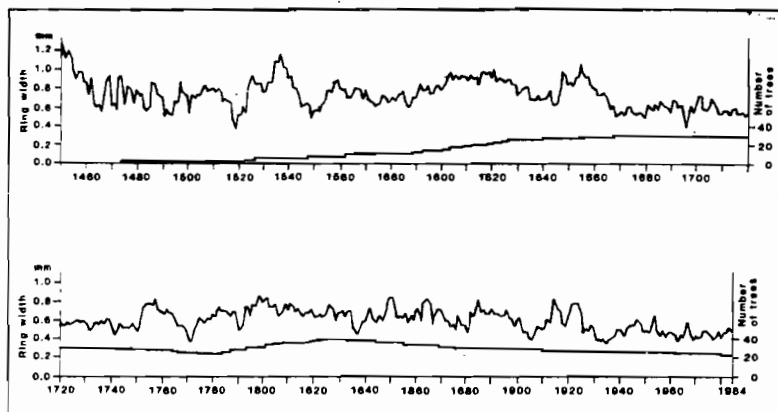
Fig. 4. Dendrochronological master curve for eastern Finland extending from the present time to AD 1450. The number of pines used in the tree-ring counts for each part of the curve is indicated. The initial rapid growth typical of young trees is omitted from each individual growth curve before the average ring widths have been calculated (cf. Eronen et al. 1985).

Thus the shape of this kind of tree-ring curve depends largely on the quality of the material used in constructing the curve. An indexing of the curves does not necessarily help, because some informative trends are easily removed by that procedure. Suitable series for certain kinds of environmental monitoring can be found by means of careful site selection. The curves from such sites can show the natural trends in radial growth and, in some places subject to recent pollution, even the effects of that environmental stress. The question remains, however, as to how representative such curves are. How can we compare the curves from specific ˈnaturalˈ sites to forest growth in general? The fact is that the overwhelming majority of forests in Finland are not under natural conditions. The growth of managed forests does not necessarily follow ˈnaturalˈ growth trends and the effects of environmental pollution can also be different. The specific tree-ring curves can provide some background data, but a lot of different kinds of data are needed for monitoring the productivity of forest ecosystems, which is determined by many, complex historical, cultural and natural factors.

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8.6 APPLICATION OF DENDROCHRONOLOGY FOR LONG-TERM POLICIES OF FOREST USE: ONE EXAMPLE IN THE LITHUANIAN SSR

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1. INTRODUCTION

The future development of the forest sector is very uncertain. This uncertainty is being increased due to increasing influence on the forest sector of economical, demographical, and social-genetic factors, being much exposed to the change themselves. But since the forest is a natural phenomenon, it has also a strong reaction to the influence of change of the climatic medium being determined by the inconstancy of the solarterrestrial connections. The ecological-climatic changes to a considerable extent influence the sustainability and efficiency of the forest ecosystems, sometimes strengthening, sometimes weakening them.

We are preparing [1] a simulation system to analyze different scenarios of the forest sector development taking into account the anthropogenic factors and long term ecolo-climatic environment changes. The long term changes of the forest systems productivity and sustainability can be estimated by dendro-climatic method [2]. In this paper, the impact of the climatic environmental changes on the long term forest use policy in the Lithuanian SSR is analyzed.

2. BLOCK SCHEME

The scenario scheme is presented in Figure 1. Input: areas of
the tree species and age classes, volumes of the stands to be cut,
and description of the dendroclimatic cycles. The indices of the
climatic cycles impact on forest growth is calculated by module
No. 1. In the module No. 2, those indices are used to estimate the
cyclic changes of the stands volume. Felling areas are determined
by the module No. 3. The volume is calculated by module No. 4.
Afterwards, the different forest cutting scenarios are analyzed.
The variant accepted is applied to an ecologo-economical model
for a region.
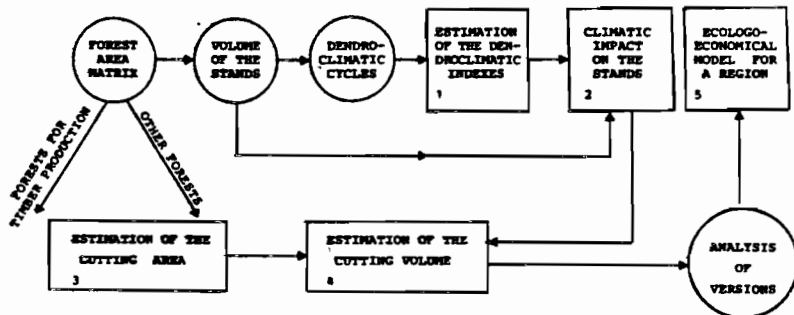
Figure 1. Scheme of the cutting volume estimation.

3. DENDROCLIMATIC INDICES

Long-term dendroclimatic cycles are used for simulation pur-
poses. They are described in Table 1; on the basis of data given
in this table, the results of all cycles' dendroclimatic indices
can be estimated by the following formula:

$$y(t) = \sum_{j=1}^{7} A_j \cos \left(\frac{2\pi(t-1940)}{T_j} - Y_j \right) \quad ,$$

Table 1. Description of the dendroclimatic cycles.

Number	Supplementary influence of cycles' indices (amplitude), %	Phase	Cycle duration (years)
1	0,76	-2,578	39
2	1,08	-2,054	52
3	1.18	-3,037	60
4	1,60	-3,625	78
5	1,82	-9,478	92
6	2,26	-2,1495	114
7	3,42	0,91859	171

where: $y(t)$ = dendroclimatic index in t years,

j = no. of climatic cycle,

A_j = supplementary influence of j cycles' indices (amplitude),

Y_j = cycle variation phase, and

T_j = j cycle duration.

The supplementary influence of the cycles' dendroclimatic indices are given in Table 2 and represented in Figure 2. During the period of stand growth, a change can be noted in the dendroclimatic indices. The timber volume increment is also not constant. That is why the average index for the cutting rate should be estimated. In order to achieve this goal, the dendroclimatic indices lines (a) must be formed:

$$A_{n,k}(t) = \{a_1, a_2, \ldots, a_{N_{n,k}}\} \quad ,$$

$$a_1 = y(t_1) \quad , \quad \text{where } t_1 = t - 10(N_{n,k} - 1) \quad ,$$

$$a_2 = y(t_2) \quad , \quad \text{where } t_2 = t - 10(N_{n,k} - 2) \quad ,$$

$$\vdots$$

$$a_N = y(t_N) \quad \text{where } t_N = t - 10(N_{n,k} - N_{n,k})$$

Table 2.   Indices of long-term dendroclimatic cycles, %.

Years	Summary index	Cycle index						
		1	2	3	4	5	6	7
1	2	3	4	5	6	7	8	9
1850	-2,8	0,6	-0,9	1,2	-1,4	1,5	-2,1	-1,6
1860	-4,6	-0,5	0,3	0,7	-1,5	0,5	-1,4	-2,6
1870	-4,9	-0,6	1,1	-0,5	-0,7	-0,7	-0,3	-3,2
1880	-3,7	0,5	0,5	-1,2	0,6	-1,6	0,9	-3,4
1890	-2,5	0,5	-0,7	-0,7	1,5	-1,8	1,9	-3,2
1900	-1,0	-0,6	-1,0	0,5	1,5	-1,1	2,3	-2,5
1910	1,8	-0,5	-0,0	1,2	0,6	-0,0	2,0	-1,5
1920	3,6	0,6	1,0	0,7	-0,7	1,1	1,1	-0,3
1930	1,8	0,4	0,7	-0,5	-1,5	1,8	-0,1	1,0
1940	-1,3	-0,6	-0,5	-1,2	-1,4	1,6	-1,2	2,1
1950	-1,0	-0,4	-1,1	-0,7	-0,4	0,7	-2,0	2,9
1960	2,3	0,7	-0,3	0,5	0,8	-0,5	-2,2	3,4
1970	4,0	0,3	0,9	1,2	1,6	-1,5	-1,9	3,4
1980	2,5	-0,7	0,9	0,7	1,4	-1,8	-0,8	2,9
1990	0,5	-0,3	-0,3	-0,5	0,3	-1,3	0,4	2,1
2000	-0,2	0,7	-1,1	-1,2	-0,9	-0,2	1,5	1,0
2010	0,3	0,2	-0,5	-0,7	-1,6	0,9	2,2	-0,3
2020	1,6	-0,7	0,7	0,5	-1,3	1,7	2,2	-1,5
2030	2,6	-0,2	1,0	1,2	-0,2	1,7	1,5	-2,5
2040	0,7	0,8	0,0	0,7	1,0	0,9	0,4	-3,2
2050	-4,3	0,1	-1,0	-0,5	1,6	-0,2	-0,8	-3,4
2060	-7,8	-0,8	-0,7	1,2	1,2	-1,3	-1,8	-3,2
2070	-6,8	-0,0	0,5	-0,7	0,1	-1,8	-2,2	-2,6
2080	-3,9	0,8	1,1	0,5	-1,1	-1,5	-2,0	-1,6
2090	-2,3	-0,0	0,3	1,2	-1,6	-0,5	-1,2	-0,4
2100	-0,6	-0,8	-0,9	0,7	-1,1	0,7	-0,1	0,8
2110	3,5	0,1	-0,9	-0,5	0,1	1,6	1,1	2,0
2120	7,7	0,8	0,3	-1,2	1,2	1,8	2,0	2,8
2130	8,6	-0,2	1,1	-0,7	1,6	1,1	2,3	3,3
2140	6,5	-0,7	0,5	0,5	1,0	0,0	1,9	3,4
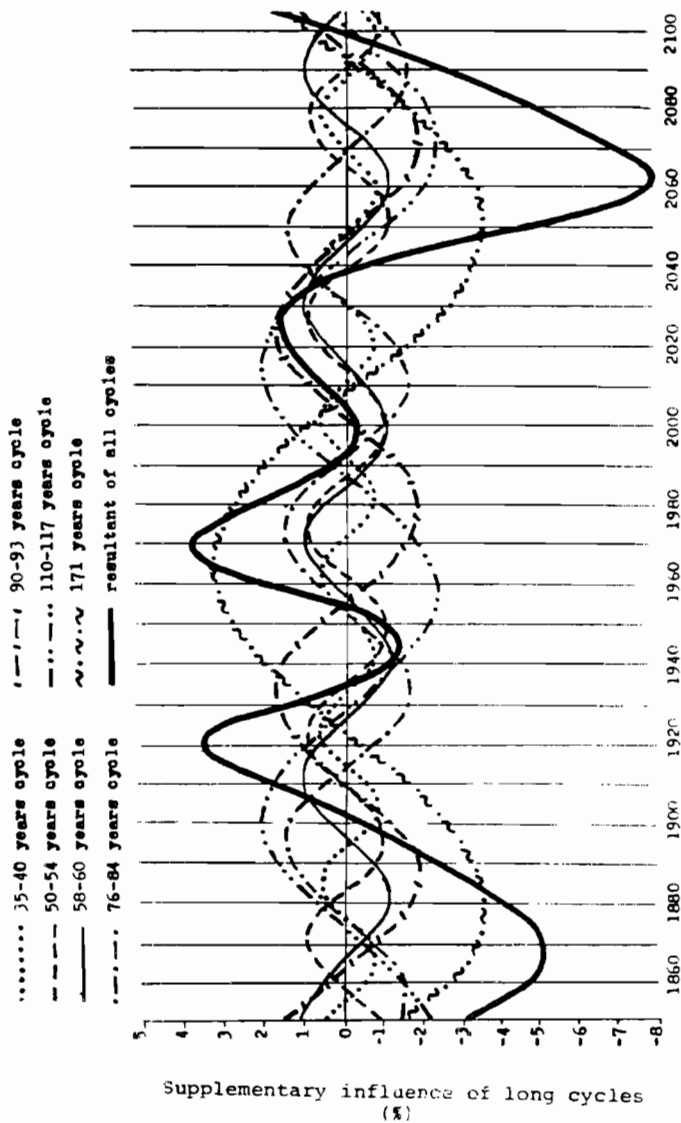
Figure 2. Super long-term dendroclimatic fluctuations.

where: k = specialized forest sector (exploitative and non-exploitative forests),

n = tree species,

$N_{n,K}$ = number of the age classes (10 years) in the rotation age.

The data of Table 3 serve as a basis for the volume increment intensity (b) lines:

$$B_{n,k} = \{b_1, b_2, \ldots, b_{N_{n,k}}\} \; .$$

The average index of the forest productivity change is calculated as follows:

$$\Delta_{n,k}(t) = \frac{\sum\limits_{i=1}^{N_{n,k}} a_{i,n,k}(t) \; b_{i,n,k}}{\sum\limits_{i=1}^{N_{n,k}} b_{i,n,k}} \; ,$$

where i = number of an age class.

The allowable cut is estimated using the average real volume of the mature stands (forest inventory 1980). It is impacted by the climatic fluctuations and that is why the cycle impact on the volume must be eliminated:

$$V^*_{n,k} = \frac{v_{n,k} \; (1980)}{1 + \dfrac{\Delta_{n,k} \; (1980)}{100}} \; ,$$

where $V^*_{n,k}$ = volume of mature stands,

$\Delta_{n,k}$ = productivity change as a result of the climatic impact on the stand volume, %.

The average volume to be cut in mature stands (m^3/ha) is estimated as follows:

$$V_{n,k}(t) = V_{n,k}^* \left(1 + \frac{k \cdot \Delta_{n,k}(t)}{100}\right) \quad ,$$

where k = coefficient; to estimate the exact value of k, a special study is necessary; we assume $k = 1$.

Table 3. Increment intensity (m^3/ha).

Age class	Tree species							
	Pine	Spruce	Oak	Ash	Birch	Alder black	Aspen	Alder grey
I	1,8	1,9	1,8	3,0	4,3	4,0	5,6	4,6
II	4,0	5,2	2,5	5,3	6,8	5,4	3,7	4,6
III	4,3	5,0	3,7	4,7	5,0	4,5	3,7	3,0
IV	4,1	4,2	3,7	3,6	4,0	3,4	3,8	1,8
V	3,7	3,8	3,8	2,8	3,1	3,0	3,3	1,1
VI	3,0	3,1	3,7	2,2	2,1	1,9	2,9	
VII	2,4	2,9	3,6	2,1	1,4	1,4	2,3	
VIII	2,1	2,6	3,4	1,8	0,9	1,1		
IX	1,8	2,2	3,4	1,7	0,5	1,0		
X	1,6	1,8	3,2	1,7		0,7		
XI	1,5	1,7	3,2	1,6				
XII	1,4	1,4	3,0	1,5				
XIII			2,8					
XIV			2,6					

4. DETERMINATION OF THE ALLOWABLE CUT

For the final yield regulation, an area method OPTINA (3) has been developed. It is based on a growth rotation and the age class distribution of the management classes. In the Soviet

Union, the management classes are combined on the level of a
forest enterprise after the stand inventory has been carried
out and they are characterized by the dominant tree specie, its
rotation and areas of age classes in ten-year intervals (there
are 8 main tree species in Lithuania). When estimating the
allowable cut for such a management class, we seek a normal
(regular) age-class area distribution in it in order to ensure
a sustained yield. The area yield for a ten-year period can be
calculated by the following formula:

$$L_r^k = \frac{1}{r} \left(\sum_{i=1}^{r} f_i^k + \alpha f_{i+1}^k \right) \quad , \quad r = 1 : T_k - 1 \quad ,$$

where L_r^k = possible area yield of k tree species management
       class for a ten-year planning period,
    f_i^k = area of i age class (beginning from the mature stand),
    T_k = number of ten-year age class in the k tree specie ro-
       tation, and
    α = coefficient, $\alpha < 0,9$. This coefficient is based on
       the theoretical presumption that the stands of every
       year in an age-class are occupying equal areas and
       gradually moving up to the next age class.

The volume cut would be the average volume per unit of the
area, multiplied by the area cut.

5. SCENARIOS

The following inputs have been used: age class table (Tables
4,5), rotation age (Table 6), average volumes of mature stands
(Table 7). Two scenarios of the allowable cut estimation have
been simulated: without and with climatic cycles' impact. The
forecast period is 1985 to 2135. The results of the first
scenario are given in Tables 8 and 9, and those of the second
scenario in Tables 10 and 11. The allowable cut amendments caused
by climatic fluctuations are depicted in Table 12.

Table 4. Exploitative forests, ha.

Tree species					Age	class,	10	years						Total
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	
Pine	7700	21800	45800	37600	31700	33000	30600	22700	15200	8000	7600			261700
Spruce	14500	13000	11400	12700	19700	27800	27400	16400	16000					158900
Oak	100	200	700	500	400	500	500	400	500	500	400	200	1900	6800
Ash	2200	2100	2500	2300	2100	1800	1700	1100	550	350	200			16900
Birch	5100	13200	36800	41600	36600	25200	21000							179500
Alder black	2000	3400	5300	8000	9100	6200	6300							40300
Aspen	700	2600	5100	8700	16800									33900
Alder grey	1300	6700	3900	6300										18200
Total	33600	63000	111500	117700	116400	94500	87500	40600	32250	8850	8200	200	1900	716200

Table 5. Nonexploitative forests, ha.

Tree species					Age	class,	10	years						Total
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	
Pine	4800	16300	33200	29900	27700	26000	22700	17500	12400	7500	8700			206700
Spruce	5200	3500	4500	6400	10000	12900	12600	9600	6300	3300	2800			77100
Oak	50	50	400	600	300	310	340	320	400	530	300	400	1100	5100
Ash	200	400	800	1000	800	800	700	700	200	300	200			6100
Birch	2200	3700	11800	15700	12600	9300	7000	4100						66400
Alder black	700	1000	2200	3500	3600	3100	2200	1500						17800
Aspen	100	200	1400	2800	2400	3100								10000
Alder grey	600	3200	1600	3000										8400
Total	13850	28350	55900	62900	57400	55510	45540	33720	19300	11630	12000	400	1100	397600

Table 6. Rotation age

Tree species	Exploitative forests	Nonexploitative forests
Pine	101	101
Spruce	81	101
Oak	121	121
Ash	101	101
Birch	61	71
Alder black	61	71
Aspen	41	51
Alder grey	31	31

Table 7. Average volume in the mature stands, m^3/ha

Tree species	Exploitative forests	Nonexploitative forests
Pine	224	252
Spruce	221	234
Oak	179	210
Ash	199	225
Birch	179	186
Alder black	210	229
Aspen	242	238
Alder grey	170	162

Table 8. Allowable cut for the exploitative forests
(Scenario No 1), 1000 m^3

Year	Tree species								Total
	Pine	Spruce	Oak	Ash	Birch	Alder black	Aspen	Alder grey	
1985	190,4	331,7	7,6	5,8	420,2	110,7	155,0	79,6	1300,8
1995	193,4	331,7	7,6	6,3	420,2	110,7	155,0	79,6	1304,5
2005	375,5	331,7	7,6	12,1	420,2	110,7	155,0	79,6	1492,2
2015	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2025	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2035	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2045	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2055	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2065	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2075	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2085	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2095	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2105	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2115	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2125	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6
2135	452,8	331,7	7,6	26,0	420,2	110,7	155,0	79,6	1583,6

Table 9. Allowable cut for the nonexploitative forests
(Scenario No 1), 1000 m^3

Year	Tree species								Total
	Pine	Spruce	Oak	Ash	Birch	Alder black	Aspen	Alder grey	
1985	226,6	75,4	6,1	3,8	109,1	43,3	33,7	30,6	528,6
1995	226,6	83,5	6,1	6,1	131,2	43,3	33,7	30,6	561,1
2005	309,3	127,8	6,1	6,1	131,2	43,3	33,7	30,6	688,1
2015	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2025	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2035	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2045	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2055	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2065	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2075	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2085	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2095	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2105	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2115	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2125	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5
2135	369,1	127,8	6,1	9,7	131,2	43,3	33,7	30,6	751,5

Table 10. Allowable cut for the exploitative forests
(Scenario No 2), 1000 m^3

Years	Tree species								Total
	Pine	Spruce	Oak	Ash	Birch	Alder black	Aspen	Alder grey	
1985	191,5	331,8	7,6	5,8	417,9	110,1	155,6	80,4	1300,7
1995	195,1	330,3	7,7	6,4	418,2	110,1	156,3	80,0	1304,1
2005	379,7	329,1	7,7	12,1	421,1	110,1	156,0	79,1	1494,2
2015	456,0	330,4	7,7	26,3	423,9	111,3	155,0	78,6	1588,2
2025	455,8	332,2	7,7	26,2	421,3	110,9	154,7	78,8	1587,6
2035	456,7	332,2	7,7	26,3	418,4	110,2	154,7	79,3	1585,5
2045	456,8	329,6	7,7	26,3	416,3	109,6	153,7	79,0	1579,0
2055	454,6	326,1	7,6	26,2	414,7	109,1	151,7	77,6	1567,6
2065	451,1	323,7	7,6	26,0	412,6	108,5	149,4	75,4	1554,3
2075	448,2	322,4	7,6	25,8	409,3	107,6	147,3	73,7	1541,9
2085	446,5	321,2	7,5	25,7	403,7	106,2	145,7	73,6	1530,1
2095	445,4	319,5	7,5	25,7	397,4	104,7	146,2	75,1	1521,5
2105	444,5	317,7	7,5	25,8	395,1	104,2	149,4	76,9	1521,1
2115	443,6	317,5	7,5	25,8	400,1	105,5	153,8	78,9	1532,7
2125	442,6	320,2	7,6	25,7	409,6	108,0	157,5	81,2	1552,4
2135	442,6	325,3	7,6	25,5	419,0	110,5	160,4	83,2	1574,1

Table 11 Allowable cut for the nonexploitative forests
(Scenario No 2), 1000 m³

Years	Tree species								Total
	Pine	Spruce	Oak	Ash	Birch	Alder black	Aspen	Alder grey	
1985	227,9	75,9	6,1	3,9	108,8	43,2	33,6	30,9	530,5
1995	228,5	84,4	6,2	6,2	130,1	43,0	33,7	30,9	562,9
2005	311,9	129,2	6,2	6,2	130,2	43,0	33,3	30,4	690,9
2015	371,4	128,3	6,2	9,9	131,2	43,3	33,8	30,2	754,7
2025	371,3	128,6	6,2	9,9	131,7	43,5	33,7	30,3	755,1
2035	372,0	128,9	6,2	9,8	131,2	43,3	33,5	30,5	755,4
2045	372,0	129,1	6,2	9,9	130,1	42,9	33,3	30,4	753,8
2055	370,2	128,5	6,1	9,9	129,3	42,6	33,0	29,9	749,5
2065	367,4	127,4	5,1	9,7	128,9	42,5	32,7	29,0	743,7
2075	365,1	126,5	5,1	9,7	128,4	42,3	32,4	28,3	733,3
2085	363,7	125,9	6,1	9,6	127,4	42,0	32,0	23,3	735,0
2095	352,3	125,7	6,0	9,6	125,9	41,5	31,9	23,9	732,1
2105	362,0	125,6	6,0	9,6	124,1	41,0	32,1	29,6	730,0
2115	361,3	125,6	6,1	9,6	123,6	40,9	32,8	30,4	730,3
2125	360,5	125,3	6,1	9,6	125,1	41,4	33,7	31,2	732,9
2135	360,5	125,1	6,1	9,5	127,9	42,3	34,3	32,0	737,7

Table 12   **Comparison of the two scenarios**

Years	Allowable cut		Difference	
	Scenario No 1	Scenario No 2	1000 m^3	%
1985	1829,5	1831,0	1,5	0,08
1995	1865,7	1867,0	1,3	0,07
2005	2180,4	2185,1	4,7	0,22
2015	2335,0	2342,9	7,9	0,33
2025	2335,0	2342,7	7,7	0,33
2035	2335,0	2340,9	5,9	0,25
2045	2335,0	2332,8	2,2	0,09
2055	2335,0	2317,2	-17,8	-0,76
2065	2335,0	2298,0	-37,0	-1,58
2075	2335,0	2280,7	-54,3	-2,33
2085	2335,0	2265,1	-69,9	-2,99
2095	2335,0	2253,6	-81,4	-3,49
2105	2335,0	2251,1	-83,9	-3,59
2115	2335,0	2263,0	-72,0	-3,08
2125	2335,0	2285,3	-49,7	-2,13
2135	2335,0	2311,8	-23,2	-0,99

In the forest sector of the Lithuanian SSR, the following situations are possible:

- significant increase in shortage of wood by the middle of the 21st century due to: unfavorable climatic changes, growth of forest which perform protective and social functions and of forests used for secondary products. This requires a percentage increase of wood covered area;

- in case of negative impacts of climate change on agriculture, an increase in forest areas is excluded. Tension in supplying the national economy with raw materials will be still more evident. To meet the demands for wood, intensive forest management is necessary;

- calculation of data on climate variations will essentially alter the national model of optimizing the exploitation of natural resources and environment formation. Territorial redistribution and investments in the economic sectors are necessary.

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9. CONCLUDING REMARKS

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The participants of this Workshop engaged in fruitful discussions at the conclusion of the meeting. **Professors H.C. Fritts, M. Hughes, M. Parker, J. Pilcher, and the author** took on the responsibility of drawing the following conclusions from the discussions:

A. The Kraków Workshop has made evident some recent trends in the development of dendrochronology:

1. Many new laboratories are being established throughout the world.

2. There is increased interest in international cooperation among the various laboratories. A Recommended Agreement was established to further cooperation between the International Tree Ring Data Bank (USA), the Commission on Dendroclimatology of the USSR Academy of Sciences (USSR) and the International Institute for Applied Systems Analysis (Austria); the Agreement was signed between Professor H.C. Fritts of the ITRDB (University of Arizona, Tucson, USA) and Academician L. Kairiukstis of the International Institute for Applied Systems Analysis (Laxenburg, Austria) during the Kraków meeting.

3. Technological advances have made possible improvements in data collecting, processing, storage, analysis and interpretation.

B. A list of the topics of the papers presented indicate that the main interest of dendrochronologists lies in the following:

1. Statistical methods of data processing and analysis.

2. Relatively new methods of data processing and analysis such as tracheidogram, X-ray densitometry and image analysis.

3. Methods of analysis of cycle components of tree-ring series to predict future growth trends.

4. Methods of detecting environmental influences, such as increased atmospheric CO_2 or air pollution, from tree rings.

5. Establishing guidelines for collecting tree-ring sites (site sampling and selection strategies).

6. Dating driftwood, archaeological and historical sites (including sunken ships).

7. Isotope and chemical ingredient studies using tree-rings.

8. Expanding regional networks of sites.

9. Description of the nature of tree-ring chronologies of different species from a number of sites and locations.

10. Dendroclimatic studies, including temporal and spatial comparisons of tree-ring and climatic data using maps.

11. Expanding tree-ring studies into new areas such as Tibet, Mongolia, etc.

12. Review and consideration of some of the basic principles of dendrochronology such as cross-dating and standardization.

13. Relating tree-ring analysis to other fields such as Quaternary geology.

14. Building of long tree-ring chronologies from ancient dead-wood samples.

15. Promotion of international and national cooperative organizations designed for the storage and exchange of data, such as the International Tree-Ring Data Bank (ITRDB) and the International Project in Dendrochronology (IPID).

C. Attention is still given to the important subjects of tree-ring dating and establishment of dendrochronology but increasing applications are being made to environmental studies, on regional and transregional levels (such as acid rain, CO_2 fertilization effects, forest decline due to anthropogenic pollutants, fire history, etc.) and wood quality and production. The field of dendroecology is growing rapidly and it will be necessary to establish sampling strategies and specialized networks.

D. The list of relatively new applications of tree-ring analysis, listed above, is indicative of the growing importance of the field for understanding some of the environmental crises facing the world today. It does not take a very astute observer to recognize that we are facing a number of global crises in terms of population explosion, man-caused climatic change, destruction of the world's virgin forests, inadequate food production and enviornmental pollution. Trees tell us about time, about change, about climate and about environment. They tell us that *Homo Sapiens* stands alone among the other animal species in its ability to drastically alter the earth's environment, even to the point of causing climatic change.

Science can be used to evaluate aspects of time, place and number in order to understand the very recent (in terms of total human history) marked changes in human culture and the natural environment. Dendrochronology can contribute to research dealing with each of these problems.

E. Common experience with dendrochronological methodology has shown that there are a number of broad areas in which there was agreement. For other areas, there are a variety of approaches and some kind of disagreement, especially where there are rapid methodological changes:

1) *Sampling*

There was general agreement on the topic of site and sample selection. The problems being studied in different centers are different, thus we must select our trees appropriately for the problem being studied. It is important, however, that the details of selection criteria, particularly concerning the representativity of trees to site stand and former treatment conditions) are stated in full. We must not assume that others are familiar with our methods and consideration must be given in our sampling strategies to other uses of the chronologies than those for which the sampling is primarily designed. The International Tree-Ring Data Bank entrance criteria may provide a guideline to minimum sampling requirements.

2) *Dating and Measurement*

There was general agreement on the principles of cross-dating and on the

necessity of this in all chronology construction. New techniques and new measurement parameters of wood density variations, isotope composition of wood, cell structure characteristics, etc., are coming and will need to be readily adopted in this field.

3) *Standardization*

The objectives of standardization were the same in all laboratories represented at the Task Force Meeting. These objectives may be summarized as the elimination of aspects of the data that may be considered as noise for the problem under study. Simple techniques of standardization are frequently appropriate, but the new technology should be evaluated in a wide variety of situations. The Task Force stressed the importance of achieving the raw ring-width data so that new standardization methods can be tested on old data sets. It would also be desirable to make standardization methods widely available in a form that could be applied using personal computers.

4) *Reconstruction*

Reconstruction can be made on a range of spatial scale from local to regional to transregional to hemisphere. The regional reconstruction can best be accomplished by the use of an *array* of site chronologies other than by the production of *average* regional chronologies. Whatever reconstructions are being attempted, verification is essential to show that the calibration relationship has not occurred by chance.

5) *Temporal and Spatial Coverage*

To make an efficient selection of trees and sites for a particular dendrochronological project it is desirable to have information on the range of local environmental conditions such as soil type, vegetation type, slope, aspect, altitude, etc. However, site and sample selection often fa.. . ... o: ine idea. Future sampling effort should concentrate on filling the gaps in global coverage in particular in the sub-tropics and also along the northern and southern Hemisphere..

Composite chronologies offer the only possibility of extending chronologies back in time for more than a few centuries in most areas. Efforts must be made at a national level to preserve old wood of natural and archaeological origin than may one day be of value for composite chronologies. The Task Force recognized the importance of the many medium length archaeological chronologies as well as for the few very long sub-fossil chronologies. It is possible that national site protection legislation such as that used to preserve geological type sites could be extended to the sites of major living and dead tree chronologies. Attention must also be paid to the preservation of timber in small laboratories that may close when the investigators leave.

6) *Prognosis*

In a number of reports ecological prognoses were stated to be a useful dendrochronological tool. However, in this field there is a need for a high degree of vigorous testing and verification. Accuracy of prognosis is no less important than apparent precision.

We can be encouraged by the observed improvements in methodology and by the international cooperation expressed at the Krakow meeting. Although dendrochronology has something to contribute to the solution of not only ecological but also regional socio-economic problems, there are few dendrochronologists in the world and relatively few are being trained. Very limited funds are being spent on tree-ring research, but the Kraków Workshop was a positive step forward and the organizing groups both in Poland and at IIASA deserve credit for a job well done.

E. As a further step in the international activities on the methodology of dendrochronology, it was recommended at the Kraków meeting that IIASA:

-- initiate the third phase of investigations into *Dendrochronology and its Application* with the aim to produce an international, multi-author book on *Methodology of Dendrochronology: An International Review and Rationalization of Dendrochronological Sampling and Analysis Methodologies*;

-- suggest user-friendly methods for the application of dendrochronology, particularly in order to estimate the base line of eco-climatic backgrounds, early indications of forest decline, and broad-scale ecological forecats; and

-- encourage and facilitate activities of national and international tree-ring data banks and laboratories in international cooperation such as data exchange, organization of meetings (Irkutsk, USSR, 1987; Seattle, USA, 1987), etc.

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METHODS OF DENDROCHRONOLOGY - II

TREE RINGS AND CLIMATE
Volume One

by H.C. Fritts

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Background document of the Task Force Meeting on
Methodology of Dendrochronology: East/West Approaches
2-6 June, 1986 ∗ Kraków, Poland

Warsaw, 1987

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Tree Rings and Climate

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1976

ACADEMIC PRESS
LONDON   NEW YORK   SAN FRANCISCO

A Subsidiary of Harcourt Brace Jovanovich, Publishers

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Contents

Chapter 1. Dendrochronology and Dendroclimatology

Chapter 2. Growth and Structure

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Chapter 6. The Statistics of Ring-Width and Climatic Data

Chapter 7. Calibration

Preface

The organization, information, and principles in this volume represent my views on the current status of the interdisciplinary field of dendroclimatology. This science is broadly defined to include tree-ring studies involving climate-related problems which touch on such diverse fields as archaeology, hydrology, oceanography, biology, forestry, and geophysics. Subject matter is presented in a set of graded chapters, starting with the basic biological facts and principles of tree growth, developing important quantitative methods, and ending with examples of reconstructing past climate.

Chapter 1 introduces and defines the most important terms, principles, and concepts of the science; chapters 2 through 4 cover the basic biology governing the response of ring width to variation in climate; and chapter 5 describes details of the climatic and environmental system and presents models of the growth–climatic relationships. Chapters 6 and 7 treat basic statistics and methods of analysis of these relationships; and chapters 8 and 9 describe various examples and applications using the methods described earlier in the text.

The reader is assumed to be at least a third-year college student with some experience and background in at least one science. However, most technical terms are described when they are first mentioned, and for purposes of review, definitions are provided in the Glossary at the end of the text. Because of the international interest, scientific names of tree species are used throughout, although they are listed with the common names in the Appendix, for which the following are among the references consulted: Bailey (1970); Kelsey and Dayton (1942); Little (1953); and Willis (1973).

The origins of this book can be traced to my graduate studies on forest tree growth. They began with the development of a dendrograph which was used to record reversible variations in stem size as well as the cumulative variations representing radial growth. At that time I was skeptical of tree-ring dating and of the possibility for climatic inference because I had read criticisms of the science by Waldo Glock (1955), Sampson (1940), and Sampson and Glock (1942).

Therefore, after joining the staff at the Laboratory of Tree-Ring Research in 1960, I embarked on an extensive program to examine and test the fundamental basis of such work. As it turned out, all major principles and concepts originally formulated by the founders of the discipline proved correct. Results of my tests and the botanical basis for them are treated in this book.

During the first years at the Laboratory of Tree-Ring Research, David G. Smith, Marvin A. Stokes, and a number of students worked with me on various aspects of these tests. Studies were conducted in the San Francisco Mountains of Arizona on the effects of moisture stress on ring width, and at Mesa Verde, Colorado, on the biological basis and climatological relationships governing the ring-width response. Subsequent investigations, which involved other students and associates, focused on *Pinus longaeva* (bristlecone pine) in the White Mountains of California and *Pinus ponderosa* (ponderosa pine) in the Santa Catalina Mountains north of Tucson, Arizona.

As the principles of dendrochronology became more firmly established, attention was increasingly directed to the utilization of climatic information in tree-ring widths. A resultant paper (Fritts, 1965) is the first major effort to analyze both the spatial and temporal variations in growth and to use them to infer variations in climate. Increased experience with statistics lead to the most important single discovery of my work which was made while on sabbatical leave at the University of Wisconsin in the spring of 1969. It involved the use of eigenvectors along with multiple regression and canonical analysis to calibrate climate and ring widths for objectively reconstructing past climate. At the same time Webb and Bryson (1972) were applying the technique to pollen analysis; Imbrie, several years earlier (Imbrie and Kipp, 1971), had applied similar methods of factor analysis to calibrate marine fossil data with sea-surface temperatures and to reconstruct past climate. T. J. Blasing, Bruce P. Hayden, and John E. Kutzbach joined me in the formal development and documentation of the method, and they are responsible for the precision and clarity of the mathematical descriptions in the paper that resulted from this work (see Fritts *et al.*, 1971).

There are physiological and ecological details of tree growth which, according to our present knowledge, appear to have little bearing on the year-to-year variations in ring width, and are therefore outside the scope of this book. These include some factors that *could* have an important influence on growth, but which have not as yet been proven to exert a significant effect. Other factors which are highly influential receive more attention than is usually given to them in standard texts. For example, genetic variation, soil factors, and many forest influences are considered

only briefly because these particular factors are more or less constant for a particular tree and site, and they do not contribute markedly to the year-to-year variations in ring width. On the other hand, factors affecting diurnal, seasonal, and yearly variations in stem growth receive more than the usual attention because the net effect of these variations can obviously contribute markedly to the variations in the resultant ring width. In short, the emphasis in the biological discussion is upon those factors and conditions that appear most relevant to tree-ring research.

It is recognized, however, that future studies of the growth–climate system will undoubtedly lead to new possibilities and refinements in which factors originally thought to be irrelevant will turn out to have a measurable effect. When this occurs, the newly discovered factors must be added to the list of others already considered important.

In addition, I would like to emphasize that this particular text is essentially a progress report on a rapidly developing subject. I hope no reader will consider these pages as unquestionable statements of fact. Rather, they should be viewed as a treatment of best inferences of dendroclimatology as we know it, including applications, conclusions, and principles that are *reasonable deductions from the accumulated facts.*

The treatment of statistics is equally pragmatic in that only the most pertinent techniques are included in this text. The juxtaposition of the biological and statistical discussions is a result of my firm belief that biological insight is essential for obtaining the most meaningful statistics, and that statistical methods are similarly important for the accurate quantifying and testing of the biological results.

Since this volume does not attempt to give a comprehensive review of all tree-growth research, the bibliography is designed to direct the reader to the most recent data sources and to provide more in-depth reading for the interested scientist. Because a large part of the text represents my own experience, the reference choices are heavily weighted towards my own work and the work of my close colleagues and students. I am well aware of the fact that important work has been accomplished elsewhere, both inside and outside the United States, and I regret that the focus on my own views and experiences excluded valuable studies from being individually cited in the book. I hope the texts and review articles that are included will assist the reader in finding some of the omitted works.

I am indebted to colleagues, friends, and students who have played a very important role in the development of this discipline as described in the text. The present and past staff of the Laboratory of Tree-Ring Research should be mentioned at the outset, as well as the many colleagues in botany and dendrochronology scattered throughout the world who have participated, either directly or indirectly, in this work.

Some of the most important contributors appear as authors and co-authors of papers cited in the text.

The following people deserve special mention for their important contributions to the development, preparation, and critical review of this book. First and foremost are Karen Babcock McDougall and Judith A. Sherwood, who most ably carried out many editorial responsibilities during the three most important years of the preparation of this work. Others who shared this responsibility are Nelle W. Noble, Marna C. Ares, and Emily De Witt. Marilyn J. Huggins is responsible for most of the scientific drawings and figures in the text.

A number of scientists made specific contributions in addition to their publications listed in the references. The most important of these are T. J. Blasing, Charles W. Stockton, and Valmore C. LaMarche, Jr. Prodyot K. Bhattacharya and James R. Gebart advised me on various statistical problems; William D. Sellers made constructive suggestions regarding the energy and water balance, and Fiorenzo C. Ugolini assisted with the section on soils development. Others, among them Martha A. Wiseman, G. Robert Lofgren, C. Larrabee Winter, and Linda G. Drew, also contributed to the scientific content.

Many of the above, as well as others, have read at least portions of the manuscript and have made numerous helpful suggestions and comments. Special thanks are expressed to Linda G. Brubaker, David J. Shatz, T. J. Blasing, G. Robert Lofgren, Martha A. Wiseman, Thomas Nash III, and Miriam Colson, whose reviews were most helpful in the editing of the text.

HAROLD C. FRITTS

September, 1975

DEDICATED TO

Colleagues and students throughout the world
who share with me the excitement and challenges
of this new scientific field.

Chapter 1

Dendrochronology and Dendroclimatology

I. Introduction

It is well known that the approximate age of a temperate forest tree can be established by counting the growth rings in the lower part of the stem. It is less well known that the patterns of wide and narrow rings can be compared among trees to establish the exact year in which the rings were formed. The same sort of comparison can be made among wood fragments of unknown age and the rings in living trees in order to

establish the date when the fragment was part of a living, growing tree. Thus, tree rings can be used to establish the year in which an event took place, as long as the event involved the maiming or killing of a tree. Precise dates can be established for the building of a medieval cathedral or American Indian pueblo; the occurrence of an earthquake, landslide, volcanic eruption, or fire; and even the date when a panel of wood was cut for a Dutch painting.

Such precise dating is possible from ring widths for a very simple reason: tree growth is frequently affected by variations in climates, and the yearly sequence of favorable and unfavorable climate (wet and dry or warm and cold years) is faithfully recorded by the sequence of wide and narrow rings in large numbers of trees. These patterns of wide and narrow rings are observable not only in living trees in an area, but also in stumps and the wood of trees that have grown in nearby areas. The procedure of matching ring patterns among trees and wood fragments in a given area is referred to as *crossdating* (Fig. 1.1). The procedure is used to identify the year in which each ring was formed and to assign exact calendar dates to the rings. The matching is necessary to identify special cases where rings may be absent or where two or more apparent rings have been formed during one year. When the ring patterns are matched carefully enough to identify the problem rings, the date of the outermost ring of a tree indicates exactly when it died or was sampled and the innermost one when the tree was a seedling. In addition, an old tree used as a construction timber can be crossdated with the early record in a living tree of the same area, as long as their life spans overlap. The rings of the construction timber in turn can be crossdated with a beam from an older structure to extend the ring-width sequences back in time (Fig. 1.1).

In dating of past historical and natural events, the climatically induced sequences of wide and narrow rings are used only to identify the year in which each ring was formed. The climatic information in the rings can, however, be analyzed in its own right to give a view of what the climate has been in the past and what it is most likely to be in the future. The science of reconstructing past climate by use of tree rings is known as *dendroclimatology*, which is a branch of the more general discipline of *dendrochronology*. The prefix *dendro* is from the Greek word for tree, *dendron*, and the word *chronology* is the name of the science that deals with time and the assignment of dates to particular events.

Such reconstruction of past climate is accomplished by taking the following steps: (1) Comparing modern meteorological records with the widths of tree rings produced during the same period of time; (2) establishing a statistical equation for the relationship between the two; and (3) substituting the widths of the dated rings in the equation to obtain
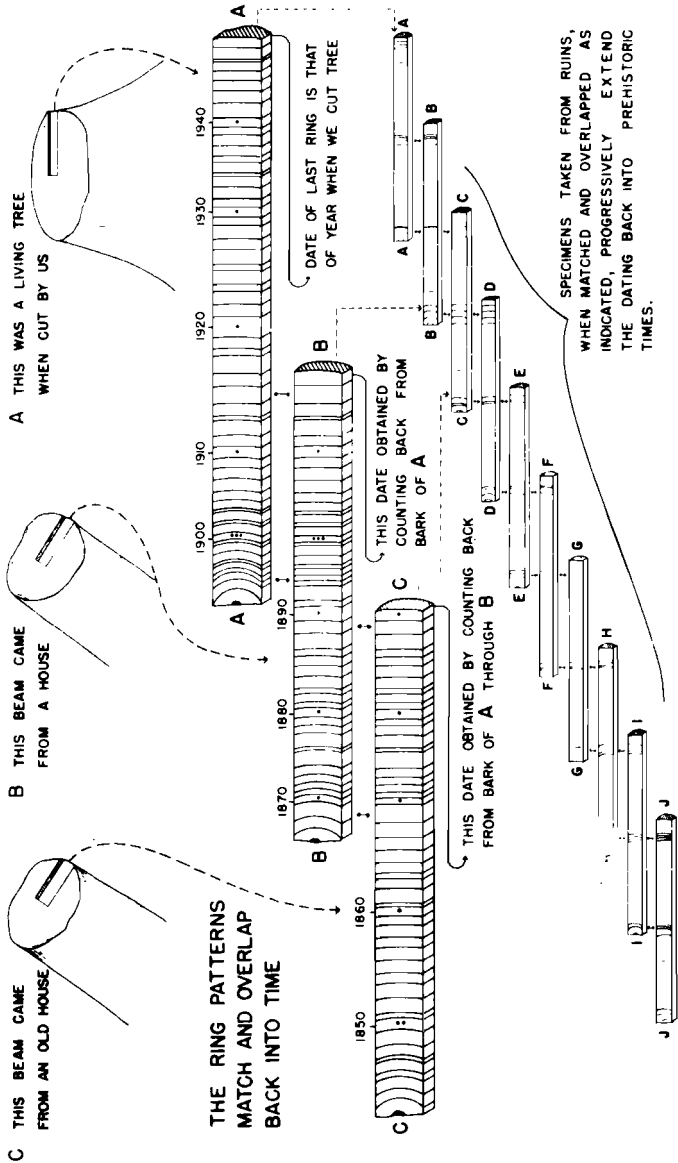
FIG. 1.1. A diagram illustrating crossdating and the extension of a dated ring-width chronology backward in time. (After Stallings, 1949)

a statistical estimate of the climate for previous years. Thus, the estimates of climate from tree rings can substitute for meteorological records and provide valuable information for periods and areas where no meteorological information exists.

However, as simple as the principle of reconstruction sounds, a variety of biological and statistical variables and many complicated relationships must be understood to make accurate reconstructions. When the principles and techniques are applied properly, dendroclimatic analysis can resolve a surprising variety of problems encountered in many fields of research. This volume will deal with both the basic knowledge and the specific techniques, necessary for making many types of climatic reconstructions and for testing the validity of the results.

II. Historical Background

Andrew E. Douglass (Fig. 1.2) is the acknowledged father of dendrochronology. He started his career as an affiliate of Harvard College Observatory and in 1894 traveled to Flagstaff, Arizona, where he became the "First Assistant" to the director of the Lowell Astronomical Observatory.

One of Douglass's research interests was sunspots. He thought sunspot activity might influence the weather on earth and was looking for a relationship between the cyclic activity of sunspots and the behavior of climate, particularly precipitation (Dean, in press). The records of weather available at that time were too scanty and discontinuous to establish a clear relationship between the two.

In 1901, while Douglass was on a long buckboard trip through the forest of northern Arizona, he hit upon an idea which allowed him to test the weather–sunspot relationship. He noticed that the rings exposed on a log cut from a pine at Flagstaff exhibited variations in width. He had already been struck by the differences between the forests in Arizona and those he had known in New England (Dean, in press). The trees in Arizona forests were widely spaced, while in New England the forests were dense with much undergrowth. He knew that the growth of New England trees was influenced mostly by shading and competition within the forest. Douglass wondered if trees in Arizona were influenced more by available moisture than by competition within the stand and if moisture stress had a corresponding effect on the width of the rings. He reasoned further that if this were so, the dry years might be recorded as narrow rings, and he could use the tree-ring widths as a proxy for a long record of weather and climate.

FIG. 1.2. A. E. Douglass, the founder of dendrochronology, holds a corer (borer) which is used to extract a sample of wood 4 mm in diameter. (Courtesy of Charles W. Hubert, Western Ways Photo, Tucson)

Douglass began to examine stumps in the vicinity of Flagstaff. In 1904 he acquired six log sections from a local sawmill and noticed that the 1st, 3rd, 6th, 9th, 11th, and 14th rings in from the bark were considerably smaller than their neighbors. He was particularly impressed by a group of small rings that occurred 21 rings inside the bark. Later he examined an old stump in a rancher's field and observed the same pattern, but there were 11 rather than 21 rings between the group of small rings and the bark (Douglass, 1914). Douglass reasoned that the tree must have been cut in 1894. He surprised the owner as he correctly identified the year the tree had been felled.

It was not until 1911 that Douglass recognized the real significance of his observations. He identified a pattern of wide and narrow rings in trees from Prescott, Arizona, some 50 miles (81 km) southwest of Flagstaff which was similar to those he had noted in the Flagstaff trees. In this manner Douglass established crossdating, a procedure which he

recognized could be applied in areas where ring growth is frequently limited by climate.

Dean (in press) in describing Douglass's contribution points out

> Douglass was not the first to discover crossdating (Heizer, 1956; Studhalter, 1955). That honor goes to the French naturalists Duhamel and Buffon, who in 1737 discovered that a conspicuous frost-damaged ring occurred 29 rings in from the bark on each of several newly felled trees. Other investigators confirmed their observation, and this feature was subsequently used as a marker for the 1709 ring. Crossdating based on relative ring widths was independently recognized in 1827 by A. C. Twining in Connecticut, in 1838 by the mathematician Charles Babbage in England, in 1859 by Jacob Kuechler in Texas, and in 1904 by Douglass. Although Twining was the first to grasp the full significance and potential of crossdating, it was Douglass who utilized the principle as the basis for the development of the science of dendrochronology.

Douglass noted two major implications of his discovery (Dean, in press). The first was that crossdating could be used as a chronological tool to identify the exact calendar year in which rings were produced by studying the pattern of wide and narrow rings. All that was required was that the year for the outermost ring of the stem be known, and that the same relative variations in ring structure be observable in many trees. Wood samples of unknown age could be dated to the year by matching their ring-width patterns with that of a previously dated ring-width chronology.

The second implication of Douglass's finding was that the ring-width patterns themselves represent a record of environmental conditions over a region. While some of the ring-width variation was attributable to local conditions within and surrounding the habitats of the trees, a large portion of the variation was observable in all trees and thus could only reflect factors occurring over the entire region, such as the yearly variations in climate. Douglass hoped that this surrogate of climate would allow him to test for a causal link between sunspot variations and climatic conditions, as well as to extend the record of sunspots several centuries back into the past.

He proceeded to derive this record of climate by comparing and combining the ring records of many trees, a procedure now called *chronology building*. After studying hundreds of trees from the Flagstaff–Prescott area, Douglass noted that the most reliable patterns for crossdating were found in the narrow rings. He also observed that the trees at the lower elevational boundary of the species exhibited the most variability in ring width.

By 1914, Douglass had succeeded in building a composite chronology

of nearly 500 years from the rings of *Pinus ponderosa*.* He demonstrated from the available weather records that ring width was directly related to precipitation of the preceding winter. From these observations he hypothesized that precipitation replenished soil moisture which in turn affected the amount of growth in the spring. He also noted that trees exhibited "a reserve power or vitality which may run low or be built up by varying environment". He called this the conservation term and adjusted a chronology for it by obtaining a running mean or by applying a numerical coefficient which was thought to adjust the ring widths for the effects of prior conditions (Douglass, 1919). Modern statistical techniques have now replaced many of Douglass's early quantitative procedures.

Douglass traveled to the eastern United States in 1914, where he presented a talk on his research at the Carnegie Institution of Washington, D.C. Among the dignitaries in the audience was Clark Wissler, an anthropologist at the American Museum of Natural History, New York, who was attempting to date the prehistoric and historic pueblo sites of arid southwestern North America and was intrigued by the chronological implications of Douglass's method. Would it not be possible to date the rings from logs in the pueblos as Douglass had dated the old stumps? Wissler discussed the possibility with Douglass and sent him specimens of the prehistoric wood (Douglass, 1921, 1929, 1935).

After studying several specimens, Douglass was able to crossdate six that had been collected from a huge ruin at Aztec, New Mexico, and he used them to establish a composite chronological sequence of 139 years (Dean, in press). He could not match this Aztec chronology with the living trees from Flagstaff so calendar dates could not be applied to it, and it remained for several years as a chronology "floating" in time. In 1920 Douglass received nine sections from the large ruin of Pueblo Bonito located in Chaco Canyon 50 miles (81 km) south of the Aztec ruin. Douglass found that seven of these specimens crossdated, yielding a 100-year-long chronology, and the series crossdated with the Aztec chronology. The Pueblo Bonito series ended 39 years earlier than the Aztec rings from which he concluded that the Pueblo Bonito was under construction 40 years before parts of the Aztec ruin were built. Thus, the first precise time-relationship among the prehistoric pueblos was established, although the absolute dates of the chronologies were still "floating" in time.

According to Dean (in press), Neil M. Judd, who was excavating Pueblo Bonito, was one of the first archaeologists to realize the dating

* A full list of species referred to in this text is given in the Appendix, together with the common names of each.

potential of tree rings. He envisioned extending the prehistoric floating chronology forward in time toward the present by crossdating ring series from sites known to postdate Aztec. At the same time the Flagstaff chronology could be pushed backward in time by selecting materials from early historic structures, such as Hopi Indian pueblos, and from late prehistoric sites. He realized that when the Flagstaff and Aztec chronologies overlapped sufficiently in time to establish the dating, it would be possible to assign calendar dates to all prehistoric sites linked to the floating chronology. In 1922 Judd proposed his scheme to Douglass and helped him obtain funding from the National Geographic Society, with the result that three expeditions to archaeological sites were arranged. The first and second, in 1923 and 1928, resulted in a 585-year floating chronology for the prehistoric sites, and an extension of the Flagstaff chronology back to A.D. 1260. No overlap appeared to exist between the two sets, however.

The third expedition focused on sites that appeared to occupy the temporal gap between the two tree-ring chronologies. On June 22, 1929, a charred beam marked as HH-39 was excavated which extended the Flagstaff record back to A.D. 1237. Work that evening revealed that the inner rings of HH-39 crossdated with the outer part of the floating sequence. Absolute dates could now be assigned to all the prehistoric sites that had been crossdated with the floating chronology (Douglass, 1929; Haury, 1962). The spectacular cliff dwellings of Mesa Verde, Canyon de Chelly, and Tsegi Canyon were dated in the A.D. 1200's, Aztec was built between 1111 and 1120, and Pueblo Bonito was constructed in the late 11th century. The ring chronology through the former gap period was confirmed by many additional materials. Douglass had made a significant contribution to archaeology and he had obtained for himself a tree-ring record of climatic variations that extended from A.D. 700 to 1929.

Today the southwestern archaeological tree-ring chronology has been extended back to 322 B.C. and more than 20,000 dates have been derived from nearly 1000 sites (Dean, in press). Tree-ring dating has also been extended to many other regions of the world, including nonarid sites, and it has been applied to many different kinds of phenomena.

In 1906 Douglass moved to the University of Arizona in Tucson and in 1937 he established the Laboratory of Tree-Ring Research, which became the first institution devoted exclusively to tree-ring studies. Two students were especially helpful to Douglass in developing and extending tree-ring analysis to other problems, new species, and a wide range of sites. Waldo S. Glock, a geologist, was instrumental in developing qualitative analytical techniques while Edmund Schulman (Fig. 1.3), an

astronomer and climatologist, leaned more toward statistical analysis and dendroclimatic techniques.

FIG. 1.3 Edmund Schulman was a student of Douglass who pioneered dendroclimatic studies and, in a search for old trees, discovered the ancient high-elevation *Pinus longaeva* of California. Schulman is surfacing a mounted tree core with a razor blade. (Courtesy of Laboratory of Tree-Ring Research, Tucson)

Glock left the Laboratory of Tree-Ring Research and wrote several extensive reviews of tree growth and climatic relationships (Glock, 1955; Agerter and Glock, 1965). Maintaining contact with the developing science in Europe, he championed detailed anatomical and other botanical investigations on the subject.

Schulman continued his work in southwestern North America at the University of Arizona, where he obtained the title of dendrochronologist in 1941. His two best known contributions are a monographic study on dendroclimatology (Schulman, 1956) and his discovery of 4500-year-old *Pinus longaeva* (Bailey, 1970), the ancient bristlecone pine (Schulman, 1958).

Bruno Huber at the Forest-Botany Institute in Munich, Germany, was the first to initiate tree-ring dating studies in Europe (Huber, 1941). He was followed by Karol Ermich in Poland, O. A. Hoeg in Norway, Bo

Eklund in Sweden, Peitsa Mikola and Ilmani Hustich in Finland, and Erik Holmsgaard in Denmark, to mention only a few.

III. The Scope of Dendrochronology

A. Subfields of Dendrochronology

Some authors have restricted the term *dendrochronology* to the use of tree rings to date events (de Martin, 1970; Bitvinskas, 1974). However, the techniques of dendrochronology are applied to a variety of problems of environment and climate. In this volume the term is defined broadly to include all tree-ring studies where the annual growth layers have been assigned to or are assumed to be associated with specific calendar years.

Dendrochronology may be divided into a number of subfields, several of which focus on its application to problems of environment and climate. The prefix *dendro* is used in conjunction with the name of the particular scientific discipline, so that just as the term *dendroclimatology* refers to dendrochronological investigations of past and present climates, the term *dendroclimatography* refers to the application of tree-ring analysis to the mapping of past and present climates. Similarly, *dendroecology*, *dendrohydrology*, and *dendrogeomorphology* (Alestalo, 1971) refer to the application of dendrochronology to the study of, respectively, the ecology of past biotic communities, river flow and flooding history, and geomorphic processes. The choice of the indentifying term is arbitary and many dendrochronological studies may fall legitimately into more than one of these subfields. In this volume examples are drawn from many subfields.

B. Value of Dendroclimatology

Tree rings have characteristics which make them an exceptionally valuable source of paleoclimatic information. Among such attributes are the facts that (1) the width of rings is easily measured for a continuous sequence of years, and these measurements may be calibrated with climatic data, and (2) the rings can be dated to the specific years in which they were formed, so that the climatic information is precisely placed in time. Few other sources of paleoclimatic information can provide both continuity and precise datability (Gates and Mintz, 1975), and few can be replicated and quantified as easily as tree rings.

Tree-ring data can be used to reconstruct the yearly variations in climate that occurred prior to the interval covered by direct climatic measurements. These reconstructions can extend the climatic record

backwards in time and increase its length sufficiently to improve the existing statistics on climatic variability. Such improvements could help man to better anticipate possible future climatic changes as well as to better understand those of the past (Gates and Mintz, 1975). For example, the works of Lamb (1963, 1969a, 1972), Lamb *et al.* (1966), and Ladurie (1971) have served to establish estimates of the characteristics of natural climatic variability for the past thousand years. These data, however, are largely restricted to the North American and North Atlantic–European sectors of the world, and climatic variability elsewhere in the Western Hemisphere is not well known.

It will be shown in Chapters 8 and 9 that tree rings of North America do provide significant information on past variations in climate over eastern Asia and the North Pacific Ocean as well as over the North American continent. In addition, as tree-ring analysis is applied to new areas and species, it is reasonable to expect that information will become available on past variations in climate for additional large sectors of both the Northern and Southern Hemispheres (Fritts *et al.*, 1971; LaMarche, 1974a).

Although the actual prediction of future climatic change is a task for the atmospheric scientist, the detailed reconstructions of past climatic variability obtained from tree rings should give these scientists an improved base from which to estimate the possible climatic modes, their frequencies, and geographic extent. Such knowledge also can help to improve the modeling of atmospheric circulation (Sheppard, 1966), allow man to discriminate between natural climatic variability and unnatural changes accentuated by him, and help to estimate probable future occurrences of devastating climates, such as prolonged drought.

C. Biological Constraints on Dendroclimatology

The link between past climate and ring width occurs because plant growth is affected by certain conditions in the forest environment. A large number of these environmental conditions vary throughout the life of a plant, and at times they may limit growth and affect the form of many plant structures.

The specific limiting conditions which can affect plant growth may be classed as either external or internal factors. Some of the most important external limiting factors are water, temperature, light, carbon dioxide, oxygen, and soil minerals. Some of the most common internal limiting conditions are the amounts of available food, minerals, growth regulators, enzymes, and water. In reality the level of the internal factors is often a result of external factors that were limiting at some prior time in

the life of the plant. Complex interactions can occur between external factors, internal conditions, physiological processes, and growth, but few of these interactions have been studied adequately.

There is a considerable lack of understanding, especially of the relationship between large trees and their environment. Most of our knowledge has been obtained by laboratory experimentation on seedlings or relatively small plants grown in controlled environmental chambers, green houses, tree nurseries, or plantations, and measurements may not accurately reflect the same processes as they occur in mature trees in the complex natural environment. In spite of the limits of our knowledge and the obvious complexities in biological systems, however, there are many valid inferences that can be made using existing information about environmental factors, internal conditions, and structures in plants.

In recent years the growth layers, or rings, in woody plants have been studied in this light and used to make many inferences about conditions within plants and their surrounding environments. These growth layers are, in reality, sheaths of cells that appear as concentric rings in a cross section of the stem. Each ring is usually the result of a single yearly flush of growth which begins in the spring and ceases in the summer or in early autumn, so that one layer is produced every year. A sharp boundary occurs between rings (Fig. 1.4) because cells along the inner boundaries of rings are larger and have thinner walls than those along the outer boundaries.

Not all rings are distinct annual increments of growth, however. Sometimes when factors are highly limiting, growth cannot begin and no ring is produced. At other times, a stress period occurring in the middle of the growing season may cause two or more growth layers to form within a particular year. When there is a possibility that no ring has been formed in some years and more than one ring may have been produced in other years, a simple count from the outside to the center of the stem obviously cannot be used to determine the year in which each ring was formed, so crossdating with other specimens is necessary.

There are many species, geographic areas, and instances where dendrochronology and its related subdisciplines cannot and should not be applied because tree-ring patterns cannot be or have not been dated. For instance, many woody species, such as those growing in the tropics or semitropics, can produce several growth layers per year, and the number and features of the growth layers are often not coincident from tree to tree or on opposite sides of the stem from the same tree (Alvim, 1964). Similarly, *Cupressus arizonica*, several species of *Juniperus*, and other troublesome species have traditionally been avoided by dendro-

chronologists, because several rings can be produced during a single growing season and crossdating cannot be obtained (Glock, 1951; Schulman, 1951; Glock *et al.*, 1960).
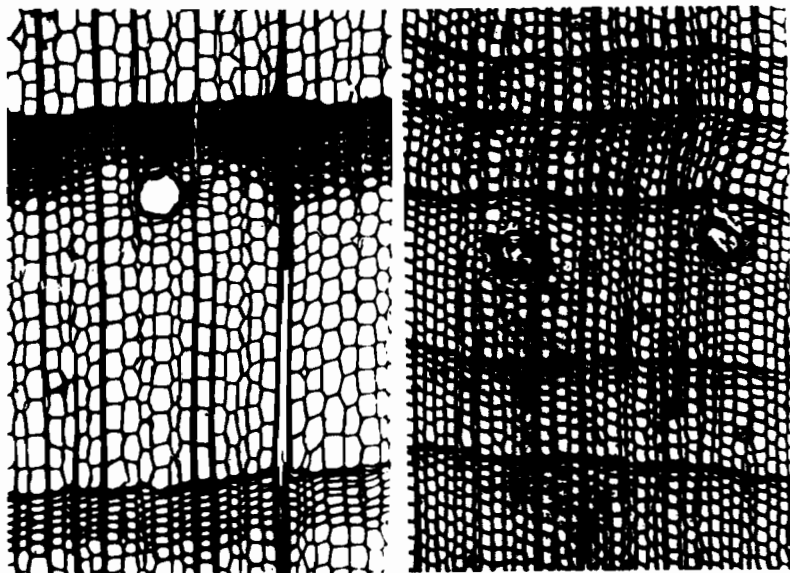
FIG. 1.4. Annual rings result from varying physiological conditions that affect the cells formed throughout the growing season. At the beginning of growth in the spring, large thin-walled cells are produced. As the end of the season nears, smaller cells with thicker walls are formed. The ring boundary is the abrupt change in cell size between the small cells formed at the end of one growing season and the large cells formed at the beginning of the next. The large openings are resin ducts. *Pinus sylvestris* is on the left and *Pinus cembra* on the right. (Photo courtesy of Fritz H. Schweingruber, Eidgenössiche Anstalt für das forstliche Versuchswesen.)

Other species may exhibit anatomical features that provide little contrast in the cell structure throughout the ring, so that the boundary of an annual growth layer is not visible except when thin cross sections of the stem are made (Fahn, *et al.*, 1963).

In still other cases the woody plants may produce an annual growth layer, but there may be little difference in structure or appearance from one ring to the next. This can arise because climatic factors do not vary sufficiently to limit processes affecting growth. In such cases, factors

arising from local site conditions and internal conditions of the plant override the climatic factors of the forest environment. Effects of climate on ring growth are not apparent when the rings are wide, when their structure is the same from year to year, or when the structural variations are unique for each individual tree and therefore cannot be associated with any particular condition of climate. A wood specimen is considered undated if there is *any* doubt about the synchrony of the growth rings. Table 1.I lists those genera known by the author to have been utilized successfully for dendrochronological work.

TABLE 1.I Genera with at least one species that is known to crossdate

Abies	*Cupressus*	*Populus*
Agathis	*Ephedra*	*Pseudotsuga*
Alnus	*Fagus*	*Purshia*
Amelanchier	*Fitzroya*	*Quercus*
Araucaria	*Fraxinus*	*Sequoia*
Artemisia	*Juniperus*	*Sequoiadendron*
Austrocedrus	*Larix*	*Taxodium*
Betula	*Libocedrus*	*Thuja*
Carya	*Picea*	*Tsuga*
Cedrus	*Pinus*	*Ulmus*
Celtis	*Pistacia*	*Zygophyllum*
Cercocarpus	*Podocarpus*	

IV. Some Basic Principles and Concepts of Dendrochronology

Every science accumulates a body of knowledge from which generalizations can be made. These generalizations, based upon repeated observations and experience, may be described as *principles* or concepts which embody the fundamental truths of the science. The following pages will describe the most widely used and basic principles and concepts in the field of dendrochronology, with primary focus on the subfield dendroclimatology. Some principles and concepts may be familiar, as they often represent modifications borrowed from other sciences. The actual biological and physical bases for these principles and concepts will be described in subsequent chapters.

A. *The Uniformitarian Principle*

A principle basic to any study of the past is the principle of "uniformity in the order of nature," originally proposed by James Hutton in 1785. It is commonly stated as:

The present is the key to the past.

Applied to dendrochronology, the uniformitarian principle implies that the physical and biological processes which link today's environment with today's variations in tree growth must have been in operation in the past. Likewise, the types of weather variations and climatic patterns observed today also must have occurred in the past. This does not imply that the paleoclimate was the same as the climate at the present. However, it does imply that the same *kinds* of limiting conditions affected the same *kinds* of processes in the same ways in the past as in the present; only the frequencies, intensities, and localities of the limiting conditions affecting growth may have changed. Therefore, one can establish the relationship between variations of tree growth and variations in present-day climate and infer from past rings the nature of past climate.

In order to make this kind of inference, however, it is important that the entire range of variability in climate that occurred in the past is included in the present-day sampling of environment. For example, at least one year's climate should be as dry and one as wet in the modern period of calibration as was the extreme climate of the past. If this is not the case and the past conditions lie outside the domain of modern climate, then the inferences from tree rings may be inappropriate and inaccurate. The uniformitarian principle is assumed in all dendrochronological inferences, and, as in all sciences of the past, if this principle does not hold, no conclusions regarding the past can be made. Checks of actual past climatic conditions, using data and evidence independent of tree rings (examples given in Chapters 8 and 9), support the validity of the uniformitarian principle to dendroclimatological research. Thus, it is reasonable to conclude that inferences may safely be made about climates of the recent past by applying dendroclimatological techniques.

B. The Principle of Limiting Factors

The well-known biological law or principle of limiting factors may be simply stated: a biological process, such as growth, cannot proceed faster than is allowed by the most limiting factor. The same factors may be limiting to some extent in all years, but the degree and duration of their limiting effects vary from one year to the next. If a factor changes so that it is no longer limiting, the rate of plant processes will increase until some other factor becomes limiting. For example, during periods of ample but not excessive moisture, growth will increase until it is limited by some other condition. This principle is important to dendrochronology because ring widths can be crossdated only if one or more environmental factor becomes critically limiting, persists sufficiently long, and acts over a

wide enough geographic area to cause ring widths or other features to vary the same way in many trees.

The principle implies that the narrower rings provide more precise information on limiting climatic conditions than do the wider rings. During years when rings are generally wide, factors may become limiting to different degrees in each tree, depending on its locale, ecological position in the site, and a great variety of nonclimatic factors. As a result considerable variation in growth patterns may occur from tree to tree. If the growth of a tree is never limited by some climatic or environmental condition, there will be no information on climate in the widths of rings and they will not crossdate. No amount of study of ring widths from such trees can be expected to reveal information on past climates. The principle of limiting factors including nonlinear complications is described more fully later in Chapter 3 and in other sections of this book.

C. The Concept of Ecological Amplitude

Each species, depending upon hereditary factors which determine its phenotype, may grow and reproduce over a certain range of habitats. This range is referred to as its *ecological amplitude*. Some species grow on a wide range of habitats because their heredity allows a large ecological amplitude. Other species are limited to a small number of specific sites because their heredity allows a small ecological amplitude, and still other species such as *Pinus radiata* and *Sequoiadendron giganteum*, which appear to have large ecological amplitudes, have become restricted to certain natural localities because of isolation resulting from geographic factors.

Near the center of its geographical distribution, a species is often found on the widest varieties of sites, and climatic factors may rarely be limiting to growth except in years of most extreme climate and in the most limiting local situations. Near the margin of its natural range, a species may occur on a relatively small variety of sites, and climate frequently becomes highly limiting to physiological processes, including growth.

Often the growth of trees near arid forest limits is most affected by drought, while the growth of trees near the upper elevational or high latitudinal forest limits is most affected by low temperatures. Species differing in ecological amplitude may be limited by the same climatic factor if the individual trees are growing in comparable habitats within their own ecological amplitudes. For example, a high elevation or northern species and a low elevation or southern species which are both near their arid limits can respond similarly to a year of drought, even though they may be responding to different moisture amounts.

In many situations such factors as length of the daylight period, shade,

and low amounts of soil minerals, which do not vary significantly from one year to the next and do not involve variations in climate, can limit plant distribution but have little influence on the variability in ring width. Other nonclimatic factors such as fire, insect attack, or disease can affect both plant distribution and ring width, and the latter cannot be used to infer climatic variation except in cases where these factors may themselves be affected by variations in climate.

D. Site Selection

Critics in the past have questioned the validity of selecting the most drought-sensitive trees for sampling rather than selecting trees randomly (Glock, 1955). Such judgment fails to recognize that the
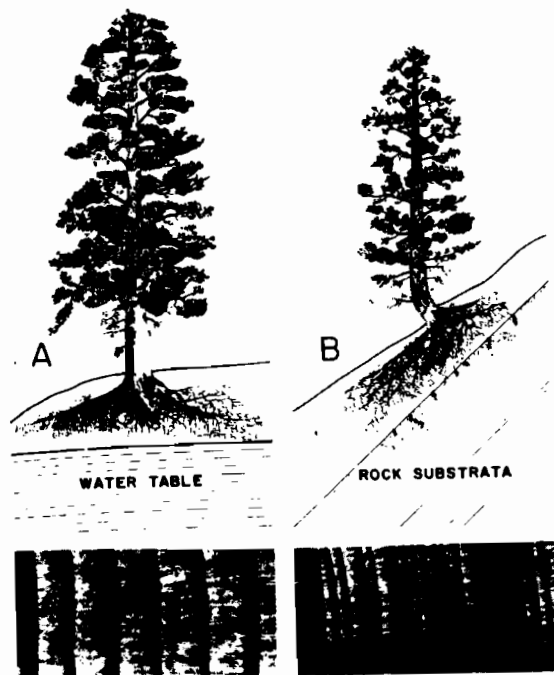
FIG. 1.5. Trees growing on sites where climate seldom limits growth processes produce rings that are uniformly wide (A). The ring widths provide little or no record of variations in climate and are termed *complacent*. Trees growing on sites where climatic factors are frequently limiting produce rings that vary in width from year to year depending upon how severely limiting climate has been to growth (B). These are termed *sensitive*.

dendrochronologist has a particular strategy in mind which requires that his samples be affected similarly by a given set of growth-limiting factors. The sampling is deliberately stratified to draw observations from that population of ring widths which contains the desired information, and it is further restricted to a particular species to keep genetic response more or less constant. Within these restrictions the sampling may be drawn by
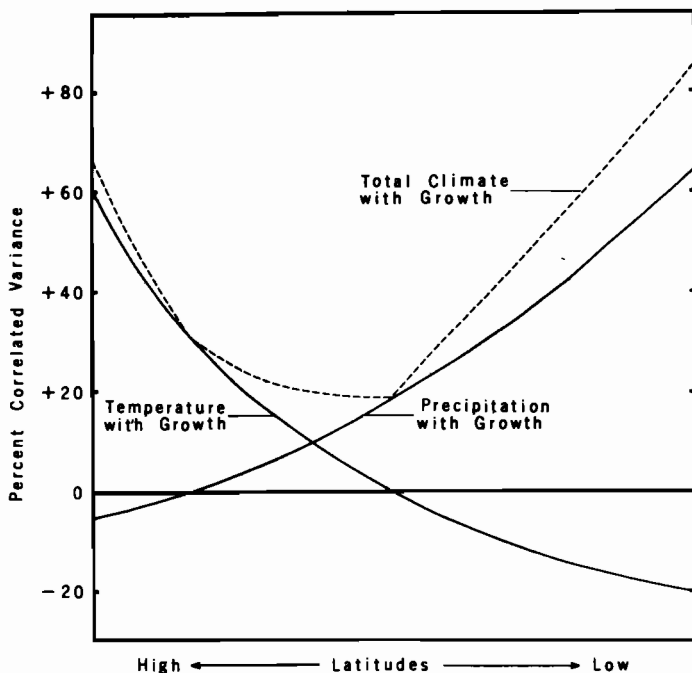
FIG. 1.6. A diagram modeling the changes in the amount of correlation expected between variations in ring width and variations in precipitation and temperature plotted as a function of latitude of the tree site. Solid lines represent the percentage correlation and the sign of the relationships, and the dashed lines express the total amount of variation accounted for by both climatic variables neglecting the sign of the relationship. At low latitudes, as well as at low elevations, variations in ring width often are highly and positively correlated with variations in precipitation and negatively correlated with variations in temperature. These values diminish in magnitude toward midlatitudes because the two climatic factors are less often limiting to growth. At high latitudes, as well as at high elevations, the correlation with temperature is likely to reverse in sign and to increase as temperature becomes directly correlated with growth. There is little correlation of growth with precipitation in many high latitude and high elevation sites, though sometimes the correlation becomes inverse and has a negative sign.

some random design. The selection of drought-sensitive arid-site trees is no different than a forester's selection of a homogeneous stand to test a particular management practice. Selection involves limiting the sampling space to a small number of variables, thus eliminating a variety of possible circumstances not relevant to the question at hand.

Dendrochronologists must apply the law of limiting factors and the concept of ecological amplitude when they obtain their research materials in order to assure selection of trees which will give them the information they desire. This selction is referred to as *site selection*. Thus, in studies of ring widths and drought, it is important to rely upon trees growing in the driest sites, for those are the individuals in which ring width is most likely to have been limited by drought (Fig. 1.5b). In studies of temperature, the ring widths of trees near the species' upper elevational or latitudinal limits will yield the most reliable information on temperature. In regions of temperate and moist climates, only the ring widths of trees in the most extreme environments are sufficiently limited by climatic factors to allow easy crossdating and dendroclimatic analysis of the tree rings (Fig. 1.6). Certain techniques that are described elsewhere in the book can be applied to facilitate analysis of materials from temperate and moist climates.

E. Sensitivity

An inspection of rings under a magnifying glass can provide a clue as to how often climate becomes limiting to growth. The more the tree has been limited by environmental factors, the more the tree will exhibit variation in width from ring to ring (Fig. 1.5a). The dendrochronologist refers to this variability in ring width as *sensitivity* and to the lack of width variability as *complacency*. Such fluctuations in ring width can be estimated qualitatively by visual inspection of the rings; or it can be calculated from measurements of width and expressed as a statistic called *mean sensitivity*, which is a measure of the relative differences in width between adjacent rings. The details of this statistic are described in Chapter 6.

Douglass (1937) likened the contrast between sensitive and complacent ring series to the difference between the Morse telegraph code of dots and dashes and an undifferentiated continuum of sound. By breaking the sound continuum into discrete contrasting units, the dots and dashes, we can produce coherent messages. In much the same way, the sequence of narrow (dots) and wide (dashes) rings in a sensitive ring series conveys messages about the life of the tree (Dean, in press).

F. Crossdating

Crossdating is the most important principle of dendrochronology. Its application provides a type of "experimental" control because it assures the proper placement in time of each growth layer. The yearly ring widths must be crossdated among all radii within a stem and among different trees in a given stand, as well as among ring-width patterns of neighboring stands. The variations in ring characteristics, especially ring widths, are examined and synchronously matched among all samples from a given region. If there is sufficient covariation among rings in
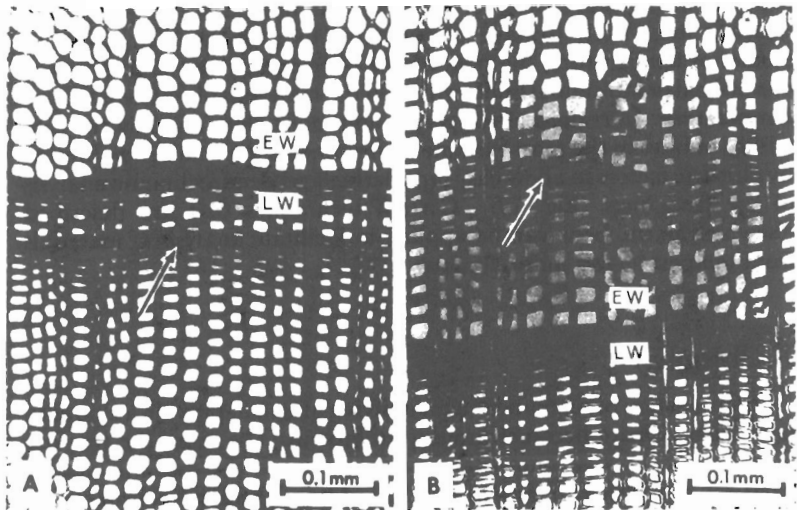
FIG. 1.7. Annual growth layers or rings are formed because the wood cells produced early in the growing season (EW) are large, thin-walled, and less dense, while the cells formed at the end of the season (LW) are smaller, thick-walled, and more dense. An abrupt change in cell size between the last-formed cells of one ring (LW) and the first-formed cells of the next (EW) marks the boundary between annual rings. Sometimes growing conditions temporarily become severe before the end of the season and cause subsequently formed cells to be smaller with thicker walls (arrows). When more favorable conditions return, the subsequently formed cells are larger and have thinner walls. The resulting dark bands within the growth layer are called *intra-annual growth bands* or *false rings* and are usually easily identified by the gradual transition in cell size on both margins of the band. Occasionally, these intra-annual bands are indistinguishable from the true annual ring and the problem must be resolved by crossdating. In A the false ring is within the latewood formed near the end of the growing season. In B it is within the earlywood formed near the beginning of the growing season. Growth is in the upward direction. (Adapted from Kuo and McGinnes, Jr., 1973)

different trees and the sample is large enough, the year in which each ring was formed can be correctly ascertained.

Crossdating is possible because the same or similar environmental conditions have limited the ring widths in large numbers of trees, and the year-to-year fluctuations in limiting environmental factors that are similar throughout a region produce synchronous variations in ring structure. The fact that crossdating can be obtained itself is evidence that there is some climatic or environmental information common to the sampled trees.

To continue Douglass's Morse code analogy, crossdating involves the recognition of identical "messages" in the "dot–dash" sequence of ring-width variability in the sensitive ring series of different trees (Dean, in press).

Sometimes during a year of extreme climate a tree may not form a ring on all portions of the stem. The ring is then said to be *partial, locally absent*, or *missing* along certain stem segments or radii. At other times a change in cell structure will occur within an annual growth increment so that the layer resembles the boundary of a true annual ring. Such features are called *intra-annual growth bands* or *false rings* (Fig. 1.7).

When rings are absent from a sampled radius or if an intra-annual growth band appears to be an annual layer, the variations in ring widths for that particular specimen do not crossdate exactly with variations in widths seen in samples from other trees or from other portions of the stem (Fig. 1.8). The problem rings can be spotted because, if the rings are properly matched on one side of the problem area, they will appear not to match on the other side. When the discrepancy is recognized (see arrows in Fig. 1.8) and the ring-width sequence is corrected for the absence of certain annual growth layers or for the presence of false layers, the patterns of widths throughout the entire length of a specimens are observed to be consistent with respect to variations in other specimens from nearby sites. If, however, there is little sensitivity and low correlation of ring-width variation among trees, or if there are large numbers of locally absent or false rings, the dating may be uncertain, and the samples must be laid aside as unsuitable for dendrochronological work.

Thus, crossdating includes matching of ring-width patterns among specimens; examining the synchrony; recognizing any lack of coincidences; inferring where rings may be absent, false, or improperly observed; testing the inference by examining carefully the ring structure in other specimens; and finally arriving at the correct regional chronology with agreement among the growth sequences of trees in neighboring stands.
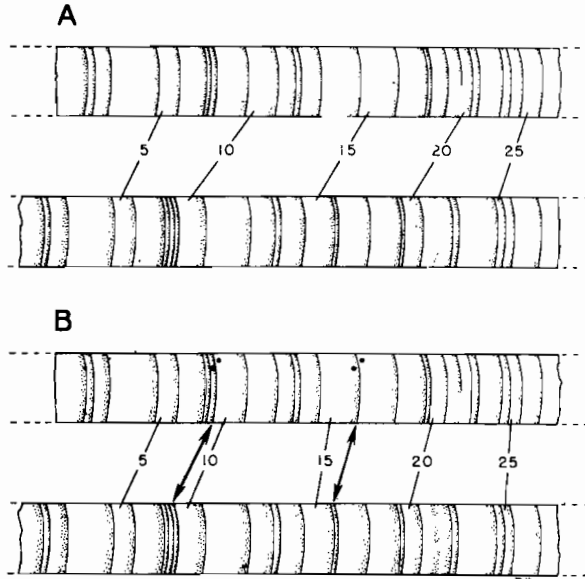
FIG. 1.8. Crossdating makes it possible to recognize areas where rings are locally absent or where an intra-annual growth band appears like a true annual ring. The patterns of wide and narrow rings are compared among specimens. Every fifth ring is numbered in the diagram and in A the patterns of wide and narrow rings match until ring number nine, after which a lack of synchrony in pattern occurs. In the lower specimen of A, rings 9 and 16 can be seen as very narrow, and they do not appear at all in the upper specimen; while rings 21 (in the lower) and 20 (in the upper) show intra-annual growth bands. In the upper specimen of B, the positions of inferred absence are designated by two dots, the intra-annual band in ring 20 is recognized, and the patterns in all ring widths are synchronously matched. (Drawing by M. Huggins)

It was shown in Figure 1.1 how ring-width chronologies are constructed and lengthened beyond the age covered by living trees by crossdating their ring-width patterns with those of older pieces of wood which have inner portions that extend the chronology back in time (Stokes and Smiley, 1968; Bannister, 1969; Dean, in press).

Remnants of dead bristlecone pine *Pinus longaeva* (recently *P. aristata*; renamed by Bailey, 1970) from southern California have been crossdated with living trees and with each other to develop an especially long chronology. The arid-site chronology developed from the ancient bristlecone pines is now more than 8,200 years in length, which is

considerably beyond the maximum age of 4,600 years for the oldest living tree (Ferguson, 1970b). Also, a 5405-year-long chronology has been developed for the same species at the upper tree line (LaMarche and Harlan, 1973). In other areas wood and charcoal from archaeological and historical sites have been used to extend the chronologies backward in time (Dean, in press).

G. Repetition

A number of specimens must be examined and crossdated from any given site to avoid the possibility that all collected specimens could be missing a ring for any one year or could have an intra-annual growth band appearing like a true annual ring. Further verification is obtained when several independently dated samples are compared and no inconsistency appears.

In addition, the *average* of replicated measurements from a large number of trees provides the best estimate of climate, because the growth variation that is associated with climatic variation, which is common to all trees, is retained when such averages are made. A large portion of the effects of nonclimatic factors which differ among individuals and from site to site is minimized by the averaging process.

Repetition or replication in sampling of more than one stem radius per tree, as well as from more than one tree, allows statistical comparisons of variability within the same tree as compared with variability between trees and between groups of trees. Measurements of this variability provide valuable information on how factors of the site and climate control tree growth. If climate is highly limiting to growth, all replicated samples within and among trees will show approximately the same ring-width variation and the rings will be easy to crossdate. In such cases, a reliable ring-width chronology may be developed from a relatively small number of radii and trees. If climate is not highly limiting, variations in factors of the site may cause marked differences in ring sizes between trees, and differences in growth on opposite sides of the same trees may result from variations in the structure of the forest stand, lean of the stem, and competition from neighboring trees. A greater amount of replication may be necessary to achieve a reliable chronology from such a site.

Statistical techniques described in Chapter 6 can be used to ascertain the amount of replication needed to obtain the desired reliability. These techniques utilize the amounts of ring-width variability in a particular sample to estimate what is referred to as *variance*, including not only the average variability in the chronology of a site but also the differences within trees, among trees, and among sites.
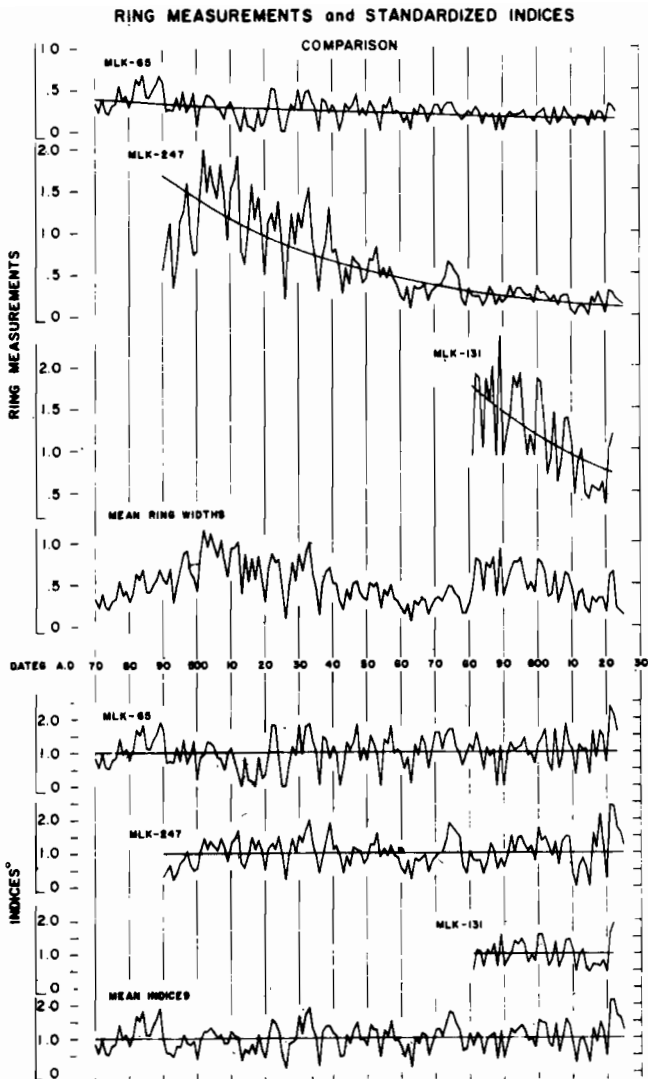
FIG. 1.9. Standardization of ring-width measurements is necessary to remove the decrease in size associated with increasing age of the tree. If the ring widths for the three specimens shown in the figure are averaged by year without removing the effect of the tree's age, the mean ring-width chronology shown immediately below them exhibits intervals of high and low growth associated with the varying age of the samples. This age variability can be removed by fitting a curve to each measured series, and dividing each ring width by the corresponding value of the curve. The resulting values shown in the lower half of the figure are referred to as indices and may be averaged among specimens differing in age to produce a mean chronology for a site.

H. Standardization

Standardization is such a basic procedure in dendrochronology that it is considered by some to be a principle. It will be shown in Chapter 2 that ring widths can vary not only with fluctuations in environmental conditions, but also with systematic changes in tree age, height within the stem, and conditions and productivity of the site. In studies of ring-width variability associated with climate, it is usually most convenient to estimate the systematic changes in ring width associated with age and to remove them from the measurements (Fig. 1.9). This correction of ring width for the changing age and geometry of the tree is known as *standardization* and the transformed values are called *ring-width indices*. The indices generally have no linear trend; their mean value is one; and the larger variability in ring width of the younger, fast-growing portions of a tree is made comparable to the lesser variability in the ring width of the older, slower-growing portions of the tree. The standardized indices of individual trees are averaged to obtain the mean chronology (*mean standardized indices*) for a sampled site (see lowest plot, Fig. 1.9). The terms *chronology* or *ring-width chronology* as used in this text, refer to the averaged yearly standardized indices for a number of trees sampled from a particular site. Details of the standardizing procedure are described more fully in Chapter 6.

I. Modeling Growth—Environmental Relationships

Inferences about past environments and climates are based upon some idea or model of how the environment affects growth. A *model* may be a statement, equation, or diagram which represents a basic set of facts and their interrelationships. They can range from extremely simple preconceived notions to highly complex equations derived from literature reviews, field observations, and extensive experimental research. Models may be used in many different ways.

Models presented as diagrams or equations may be used to illustrate particular phenomena, such as the model in Fig. 1.6 which illustrates the association of ring-width variations with variations in two climatic factors.

Models of various types may serve as *hypotheses* which are checked by comparison with information derived from observation. Such models are often revised repeatedly when inconsistent situations appear or as contradicting data dictate. When models closely resemble actual relationships, the model may be accepted as the best available inference, though it is subject to further testing and revision as more knowledge is obtained or as new ideas suggest improvements.

A model in the form of a mathematical or statistically derived equation can serve as an objective and precise description of the linkages between the inputs and outputs of a particular system. In such models numbers can be assigned to the variables and the equations can be solved to obtain statistical or mathematical estimates of the effect of changes in inputs on the system outputs. Observations of the modeled phenomena can then be compared with the estimates, and equations adjusted to improve the estimates.
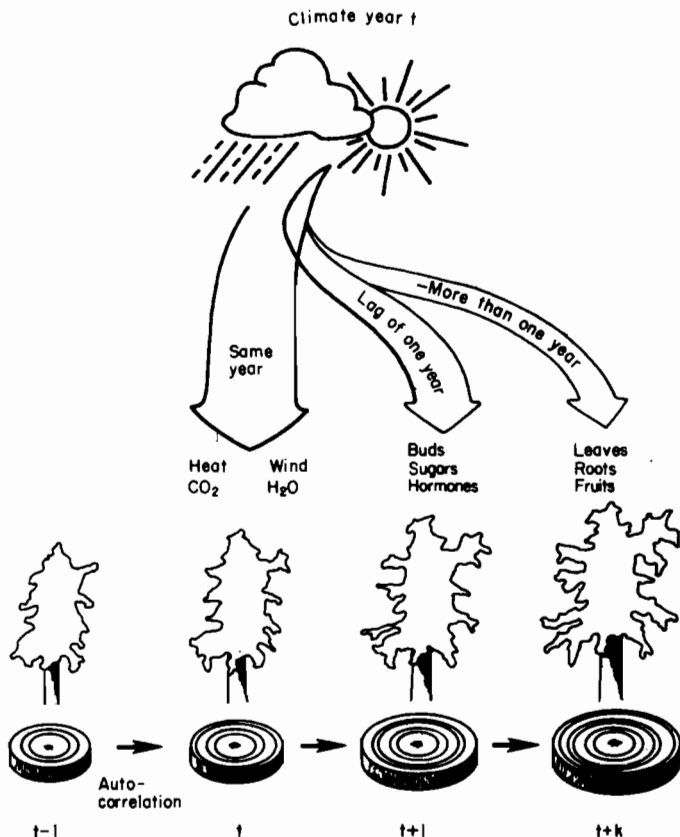
FIG. 1.10. Climate of a given year t is modeled to have a large effect on ring width for the same year through the heat, wind, carbon dioxide, and water that impinges on the tree. However, it can also affect ring width in the following years, $t + 1$ up to $t + k$, through effects on buds, sugar, hormones, and the growth of leaves, roots, and fruits. Because of these linkages the width of the ring in year $t - 1$ is statistically related to the ring width in year t. This effect is modeled as autocorrelation in ring width. (Drawing by M. Huggins)

The diagram in Fig. 1.10 is a pictorial representation which models the way climate of a given year (*t*) affects ring widths in a tree not only for the same year *t* but in subsequent years so that the response lags 1 to *k* years behind the occurrence of climate. The diagram also portrays the lagging effect of autocorrelation, an association between ring width of year *t − 1* and the widths of the subsequently formed rings for years *t*, *t + 1* up to *t + k*, which can perturb the causal relationships.

Some early workers thought that ring growth of trees on dry sites was influenced only by soil moisture available during the period of growth. Others working on trees near their polar limits or at high elevations modeled growth as a simple and direct function of temperatures during the period of growth (see Fig. 1.6). Both models, especially the one for arid sites, have been shown to be overly simplified. They were good first approximations for the relationships known at that time, but as knowledge has increased and better statistical techniques have become available, new and more complex models have been developed. The most recent ones, which describe the important biological relationships between climate and ring widths are presented in Chapters 5 and 8, and details on development of statistical models are described in Chapters 6 through 9.

J. Calibration and Verification

The units of ring widths, like those of a thermometer, can be calibrated with units of environmental variables. This can be accomplished by constructing a statistical model (Fig. 1.11) resembling the actual relationships (Fig. 1.10), establishing the values for the statistical coefficients of the model, and then applying the coefficients to tree-ring indices to reconstruct climate for early time periods where ring-width indices are available but where no record of past environments exists. The statistical association giving rise to the calibration may result from a cause-and-effect relationship between tree growth and climate, or it may represent purely correlated effects. Such correlated relationships are useful for reconstructing past climatic variations even though it may be impossible to determine the actual chain of cause and effect.

It is desirable, especially when dealing with correlated relationships, to hold back some of the environmental data for use as an independent check. The *reconstructions* derived from tree rings are compared to actual environmental data to verify the accuracy of the estimate. Such verification is the proof necessary to demonstrate that the reconstructed variations did in fact exist. Historical records, qualitative paleoclimatic information, and other data about past environments can also serve as
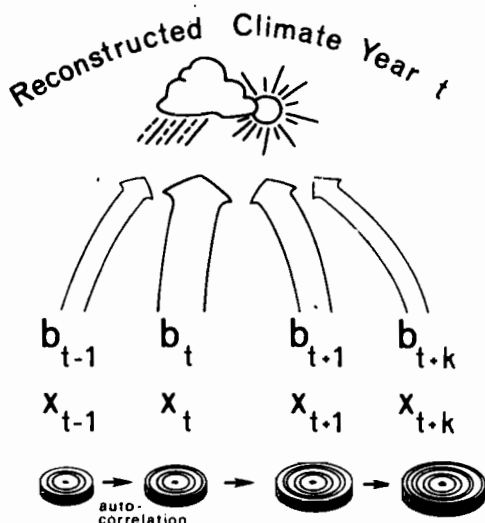
FIG. 1.11. A model for the statistical calibration of the system portrayed in **Fig.** 1.10, which is achieved by obtaining coefficients or scaling factors, b_{t-1}, b_t, b_{t+1}, and b_{t+k}, which can be multiplied by the corresponding ring widths and indices, x_{t-1}, x_t, x_{t+1}, and x_{t+k}, and the results added to obtain an estimate or reconstruction of the climate in year t. The scaling factors are then applied to ring-width indices for early time periods to reconstruct past climate. The scaling factor b_{t-1} is included in the model to correct the causal linkages for any statistical autocorrelation effects. (Drawing by M. Huggins)

additional checks. A variety of approaches to calibration and reconstruction have been used. Those which have proven most useful are described in Chapters 7, 8, and 9.

V. Dendroclimatic Procedures and Analysis

Now that the terms *dendrochronology* and *dendroclimatology* have been defined and the major principles of the field have been described, one might ask a number of questions: Just what is dendroclimatic analysis? How are the principles to be applied? What kinds of problems can it solve? How are the appropriate trees found and sampled? What are the actual laboratory procedures that are employed? How are the data processed and analyzed? What kinds of analyses can be made regarding past climates? This section includes a step-by-step description of how a hypothetical problem might be approached and how the principles are employed. The details and the scientific basis for these procedures are described throughout the remaining pages of this book.

For purposes of illustration, let us follow a present-day study through the basic steps of dendroclimatic analysis. Let us assume that a climatologist is working in a semiarid area for which there exists only a 20- or 30-year climatic record. By using the extended record provided by tree rings, he hopes to answer several questions: Are the mean and the variations expressed in the climatic records representative of the long-term mean and variations as reflected by the rings of 200- to 300-year-old trees? Is the recorded climate wetter or drier than that of the past? What is the time structure of recurring climatic extremes, such as drought? He may wish also to model the atmospheric circulation in hopes of evaluating possible climatic changes in the future and in the more distant past. For such an endeavor he could use available meterological records, plus the extended record from tree rings as a *proxy* of climate, to ascertain variability of past climate and to guide him in deciding whether his estimates of future changes are within the ranges of past climatic variations.

How could this scientist proceed to collect materials, process data, and exploit information in tree rings? He would first collect data from a selected site, perhaps a relatively undisturbed and open forest where the climatic factor of interest (in this example, drought) is most limiting to tree growth. If he wishes to calibrate his collections with a particular weather record, he would choose an area where a weather station has been maintained for a number of years. He need not be overly concerned about the precise location, as trees may be sampled at distances of 20 or more miles (32 km) from a weather station without substantially reducing the correlation between ring width and climate at the recording station (Julian and Fritts, 1968). It will be shown in Chapter 9 that not every tree-ring sample need be associated with a nearby weather station when large-scale variations in climates are to be reconstructed from tree growth.

The sampled trees would need to be of the sensitive type and located at the lower elevational or drier limits for the particular species. The form and structure of the tree often provide clues as to its age and the quality of the ring-width record (Fig. 1.12). Within these restrictions of site, the researchers could select trees randomly, though most workers search for the oldest trees with the most ring-width variability to maximize the amount of information on climate that can be obtained.

The samples are usually collected with an *increment corer* (or borer) (see Fig. 1.2), which is used to extract a thin cylinder of wood from the stem. The corer usually does not harm the tree and exuded resin from conifers soon seals the wound. The core holes have, however, been shown to be penetration points for certain diseases (Hart and Wargo, 1965), and in

FIG. 1.12. Tree form provides valuable clues as to the tree age and degree of stress on the site. Characteristics of old age exhibited by this *Austrocedrus chilensis* from Aconcagua Province, Chile, are (1) gnarled snag top from which all small branches have disappeared, (2) the narrow strip of living bark, shown on the left, which formed an asymmetrical buttressed trunk, and (3) the small cluster of dense foliage on the living branch, intermixed with dead and dying twigs. Some or all of these characteristics are exhibited by many different species of old-age conifers (Schulman, 1956). The tree is on a typical barren, rocky slope, is over 1000 years old, and has a sensitive and datable ring-width pattern reflecting moisture stress. (Courtesy of V. C. LaMarche, Jr.)

such cases simple precautions such as sealing the hole, using a disinfectant, or not sampling during times of infection may be advisable.

It is generally more expedient to locate the best sites by first coring a few trees and immediately examining their rings to check for width variability and crossdating. If the rings are generally wide and exhibit

little width variation, then the researcher can conclude that climatic factors have not been very limiting to tree growth in the site, and he can move to drier, more exposed, or rockier sites where climate is likely to be more limiting. If the second choice of sites is too extreme, the worker will find that the samples exhibit many *partial* (locally absent) rings, so that the accuracy of crossdating is questionable. He would then move to slightly less extreme sites or sample a different species. A knowledge of nearby chronologies and a brief visual examination of the specimens for synchronization during the critical growth years can be a great help in selecting the optimum sample.

Once the general ecological niche and appropriate species for good crossdating and high sensitivity are located, at least two radii from 20 or 30 trees of the same general age in a given site are sampled. Replication by sampling two radii per tree is sufficient to allow analysis of the variations within and among trees. If one is interested in evaluating the chronologies and the site factors of specific trees, he may choose to replicate with a large number of cores per tree, although collection of more than two radii per tree is usually not worth the effort for many dendroclimatic analyses.

After returning to the laboratory, the scientist will dry, mount, and surface the cores for purposes of examination. Crossdating, as practiced in North America, is a time-consuming process (Table 1.II) in that it

TABLE 1.II Average work time required to collect and process a 200-400 year ring-width chronology

	Time (in person-hours)[a]			
Task	Mean minimum	Mean	Mean maximum	Mean %
1. Collection[b]	11	15	23	7
2. Specimen preparation	7	12	17	6
3. Dating	51	72	120	33
4. Dating check	10	17	28	8
5. Measuring	30	39	53	18
6. Measuring check	20	22	27	10
7. Keypunching	6	6	7	3
8. Computer set-up	4	6	8	3
9. Output check	5	15	19	7
10. Project supervision	8	11	15	5
TOTALS	152	215	317	100%

[a]Based upon estimates for each category made by 8 persons, figures rounded to nearest hour. [b]Assuming collection of 50 cores from 25 trees by 2 persons. Figures include field documentation but not travel time.

requires both tedious examination of the specimens by eye, an operation ·that can be facilitated by certain graphical techniques (Stokes and Smiley, 1968; Ferguson, 1970a; Bitvinskas, 1974), and computer analysis. It may be helpful to start with a small number of the most easily dated or oldest specimens and to gradually incorporate the more difficult specimens in this group.

In areas of mild and moist climate, such as western Europe, the variations in ring width may be too small to permit easy dating by eye. In such cases all specimens may be measured before dating, and certain computations can be made to help identify the correct yearly sequence (Eckstein and Bauch, 1969; Baillie and Pilcher, 1973; Bitvinskas, 1974). However, if some rings are missing from any portion of the samples, it is difficult to use these particular computer methods and dating may be best accomplished by eye first. Even when a computer program is used, the worker must reexamine the various matches made by the computer and make a final judgement based upon his knowledge of the sample and visual inspection of the wood. Only after exact dating is obtained for each ring can the data from many trees be pooled and the attempt be made to reconstruct variations in past climate from the mean ring-width variations in the trees.

At the Laboratory of Tree-Ring Research, Tucson, as each core is dated the specimen is marked to facilitate the process of measurement. The rings identified with the end of each decade, each half century, and each century are marked differently with a needle prick, as are difficult areas where rings may be partial, absent, or hard to see (Stokes and Smiley, 1968). In the case of extremely arid sites, 10 or more trees are selected which have the longest, most sensitive, and most complete ring-width records, as shown by the two most complete radii sampled from each tree. If the sites are less extreme, if the rings do not vary greatly in width, or if crossdating between trees is poor, a sample of 20, 30, 40, or more trees may be an appropriate sample size. Sometimes samples of 60 or more trees have been obtained.

After the width of each dated ring is measured, the values are coded on computer cards or written on magnetic computer tape. All of the coded data are computer-processed through a preliminary cleanup routine; the data are listed to assist checking for tabulation and coding errors; and certain calculations are made to facilitate selection of materials for subsequent analysis. The mean ring widths for 20-year intervals, overlapping by 10 years, are plotted to assist in choosing the appropriate standardizing curve. After the output from this cleanup routine has been checked, errors corrected, and obvious anomalies of growth deleted, the data are resubmitted for final processing and analysis. Table 1.II

includes estimates of the time involved in collecting and processing a typical dendroclimatic sample.

With field work and laboratory work done, the researcher is ready to analyze his data. Analysis usually proceeds in four basic phases:

(1) A growth function of some form is fitted to each measured radius by means of a curve-fitting computer technique (see Chapter 6). Different curves for different specimens may be specified by using appropriate computer control cards. Standardization is accomplished by dividing the ring width by the value of the fitted curve for the particular year, which removes the systematic changes in ring-width values associated with increasing tree age. The resulting indices from all rings formed in each year are averaged to obtain a mean index chronology for individual trees, subgroups, and sites, depending on the sampling design (Fig. 1.9).

(2) Certain statistical characteristics are calculated from the indices of each measured series. Additional statistics are obtained from all chronologies representing the merger of two or more sets of ring-width measurements. Finally, if a worker desires more extensive statistical measurements, the necessary computations are made. A variety of statistics described in Chapter 6 can be used to characterize a sample, which in turn can guide further collection or subsequent analysis.

(3) The relationships between ring-width indices and climate are modeled, and the degree and character of the relationships are assessed. A variety of statistical tools is described in this text which can assist in this part of the analysis.

(4) The relationships between ring width and climatic variation established in phase 3 are then used to reconstruct past climate, and these reconstructions are verified by independent data. After verification is obtained, the reconstructions may be compared directly with meteorological records to test the proposed climatological question.

The most rapid dendroclimatological advances in recent years have been made because new statistical techniques have greatly increased our capabilities in the last two phases of analysis. Models in the past were developed in a rather rigid *a priori* fashion, often using preconceived notions about growth processes. Meteorological data were transformed by the model to a single synthesized variable which supposedly resembled the way the trees responded to climate, and the growth data were used only for comparison with the synthesized variable to see whether a relationship existed. If the results were judged to be unsatisfactory, the model was abandoned and a new *a priori* model developed.

For example, precipitation sometimes was summed over an interval of several months to a year, because the sum was thought to represent the moisture available for tree growth. In more sophisticated studies precipitation and temperature were combined in a way to simulate conditions of water stress (Palmer, 1965; Zahner and Stage, 1966). In studies at high latitudes temperature was averaged for several-month intervals or transformed in a fashion to resemble the energy available to growth (Dahl and Mork, 1959).

However, the growth itself provides valuable information which can be used in model development. This is accomplished by starting with a general and flexible *a priori* model and applying statistics in *a posteriori* fashion to shape the general model to the specific yearly tree-ring responses.

For example, variables of climate derived from monthly meteorological records, such as precipitation, temperature, or evaporation, can be compiled for a number of intervals corresponding to different seasons (Fritts *et al.,* 1965c; Fritts 1969). Several of these variables are used to estimate ring-width indices statistically, using multiple regression techniques to obtain the optimum relationship. The resulting statistical equation is an *a posteriori* model in which coefficients are the statistical expression of the way the trees are responding to variations in climate. A number of statistical equations may be developed using different types of measurements and applying more and more complex models in a stepwise fashion, adding one variable at a time, and testing for improvements. The gradual increase in complexity of the general model allows assessment of the relative importance of each variable at each stage of complexity. The final models are derived in *a posteriori* fashion by selecting those that appeared physiologically most reasonable, as well as those that provided the most significant statistics.

The final models may become so complex that the individual coefficients of the equations cannot be interpreted directly. In such cases the statistical equations can be solved by substituting values for one climatic variable at a time. Calculated changes in growth associated with specified changes in each climatic variable are used to estimate the relative importance to growth of each climatic variable. Now, however, through the use of principal component analysis it is possible to utilize the characteristics of the meteorological data in compiling the variables for regression analysis. Fewer *a priori* decisions are required, the statistical problems are simplified, and more precision is obtained in the final analysis. Details on this new approach to statistical modeling are described in Chapters 7 and 8.

Once the tree-growth responses to climatic variables have been

suitably tested, past variations in tree growth can be used to deduce climate. The simplest approach is to plot the variations in past growth, observe the intervals of unusually high and low growth, and to use the best tree-growth response model to deduce past climate.

A more elaborate approach is to select ring-width chronologies which respond to the same climatic factors and to use the spatial variations in growth to infer spatial variations in climate. The growth values can be scaled for purposes of comparison; the data are then averaged by decade, these values plotted on maps and isograms drawn to facilitate analysis (Fig. 1.13) (Fritts, 1965). The areas of higher than average and lower than average growth are inferred to be areas dominated by the appropriate anomalies in climate. Hence, the extremely high growth at the beginning of the 20th century followed by low growth in the 1930's (Fig. 1.13b) is one of many lines of evidence suggesting that the climate changed around the turn of the century.

The anomalies in growth for a particular period of time may be compared to the anomalies in another period of time to deduce the extent of a change. For example, the mean ring width and its variability as measured by the standard deviation for western North American chronologies from 1901 to 1960 were compared to the same variables for the longer period from 1631 to 1932 (Fig. 1.14). Large positive anomalies in growth and, by inference, high moisture supply can be inferred for many areas in the West. High variability in moisture may also be inferred especially for the Pacific Northwest. As in the previous example, the particular climatic anomaly is inferred from a knowledge of the growth response to climate.

However, the same multiple regression and principal component techniques used for *a posteriori* modeling of the tree growth response may be applied to the calibration of the tree-ring data and the statistical reconstruction of past climate. For example, it will be shown in Chapter 7 that spatial patterns in tree growth throughout western North America can be calibrated with spatial patterns of surface air pressure during 1900-1962 for half of the Northern Hemisphere. A series of equations is derived which transfers variations of ring-width indices into estimates of variations in pressure. Ring-width indices are then applied to these transfer functions to reconstruct the associated patterns of surface pressure as well as other variables of climate. Maps are constructed of the estimated anomalies in pressure for past periods and areas where few measurements of pressure are available.

Such statistical methods are significantly more powerful than the simple mapping and inference techniques, because a large number of tree-ring chronologies can be handled simultaneously and their
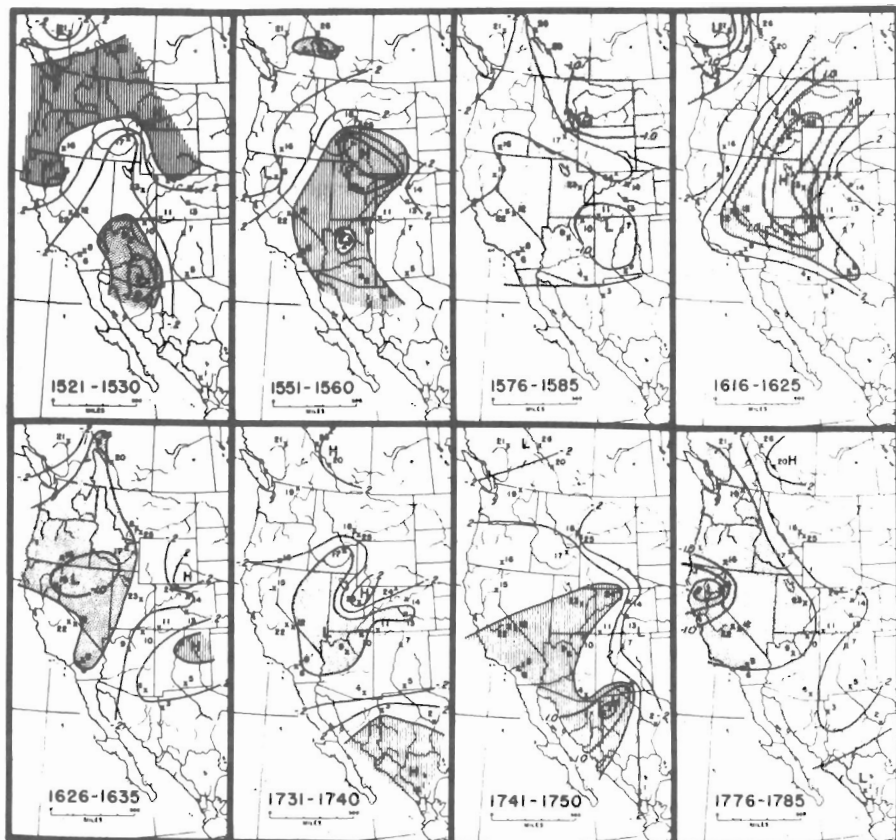
FIG. 1.13a

differences as well as their similarities utilized to estimate anomalies in a much larger spatial grid of climate. Other statistical techniques of importance to dendroclimatic reconstruction include analysis of variance, conditional probability, power and cross-power spectral analysis, and digital filtering. The details of these and other techniques are described in subsequent chapters.
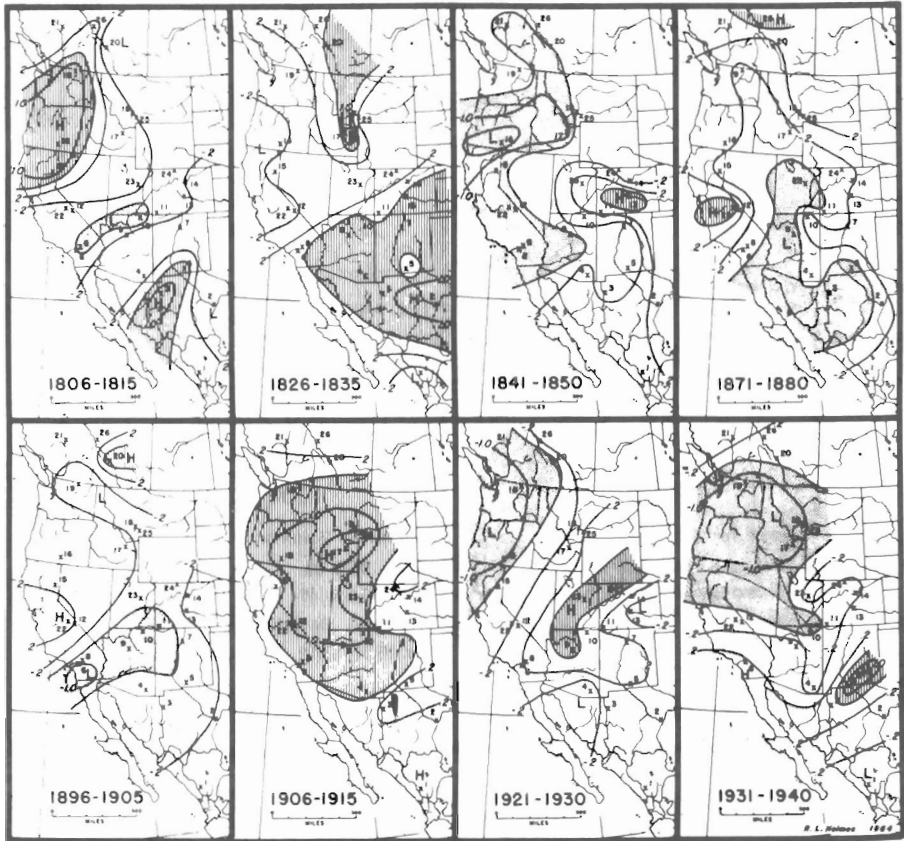
Fig. 1.13b

FIG. 1.13a and b. Decades since A.D. 1500 for which there are large departures from average in ring width over western North America. Data are from arid-site trees and are scaled to standard units by subtracting the means and dividing by the standard deviations for the period A.D. 1651–1920. Isograms join values of equal growth departure and the shaded areas of high growth (H) and low growth (L) designate those departure values equal to or exceeding values of 0·6. There are some similarities between the growth patterns prior to 1900 and after 1900, but marked differences occur. These differences indicate that the climate of the present is somewhat different from the climate of the past. (From Fritts, 1965
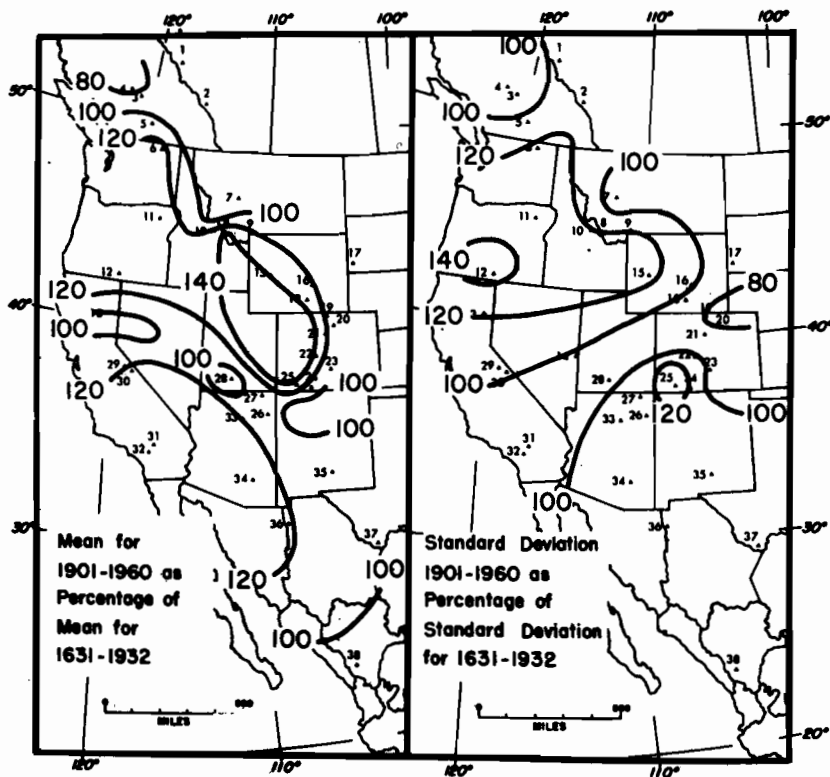
FIG. 1.14. Ring-width data for different time periods can be compared to reveal particular anomalies in climate. The means and standard deviations of 38 tree-ring chronologies for A.D. 1901–1960 are expressed as a percentage of the means and standard deviations for the longer period, A.D. 1631–1932. The mean growth and, by inference, the moisture supply have been anomalously high in the extreme Southwest, along the western slope of the central Rocky Mountains, and in the Pacific Northwest during recent times. The variability of moisture as revealed by the standard deviation of ring width has been high in the Northwest and locally in the Southwest. (From Fritts, 1971)

VI. Examples of Analysis

While the sequence of steps and the data used are similar for many kinds of dendroclimatological analyses, there are alternative procedures and innovations that have been applied. The following paragraphs describe some of the most interesting examples.

LaMarche and Harlan (1973) sampled and built a ring-width chronology for *Pinus longaeva* at the upper elevation limits for the species. The chronology in these trees was statistically modeled with temperature and precipitation, and narrow rings were found to be correlated with low temperatures (LaMarche, 1974a). Also it was noted that the tree-growth response lagged behind and averaged the effects of climate for periods as long as 15 or more years. LaMarche recognized that if he used the standard indexing procedures, a large portion of the averaged and lagged response would be removed. There were portions in the early part of the trees' ring records, however, that reflect the vigorous growth of youth. Therefore, he discarded those portions of his ring-width record and then averaged the actual ring-width measurements occurring in the remaining record. In order to bring out the long-term changes in growth, he averaged the ring widths for 100-year intervals (Fig. 1.15).
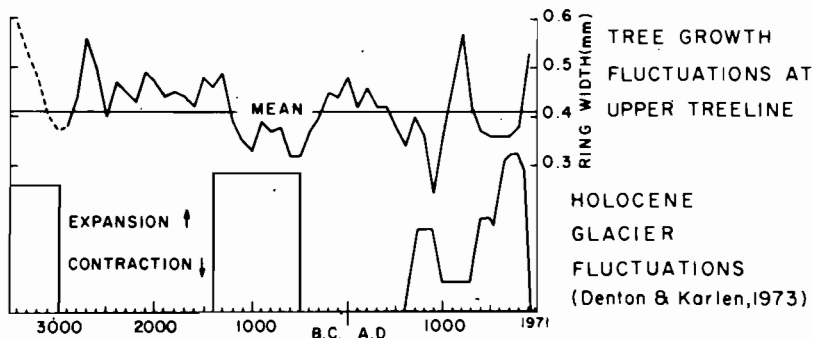
FIG. 1.15. Upper plot shows the average ring-width in temperature-sensitive *Pinus longaeva* in the White Mountains of California taken for successive 100-year periods centered on the first year of each century during the past 5300 years. Lower plot shows the periods of expanding and contracting mountain glaciers. Good comparison is seen between periods of inferred low summer temperature and periods of growth and advance of glaciers. (Courtesy of V.C. LaMarche, Jr.)

Since LaMarche lacked sufficient climatic data to verify his results by 100-year intervals, he examined the glacial record in the nearby Sierra Nevada of California and in other regions of the Northern Hemisphere and found good agreement between periods of inferred low temperature in summer and periods of growth and advance of mountain glaciers (Fig. 1.15).

Another study by LaMarche and Fritts (1971b) involved two
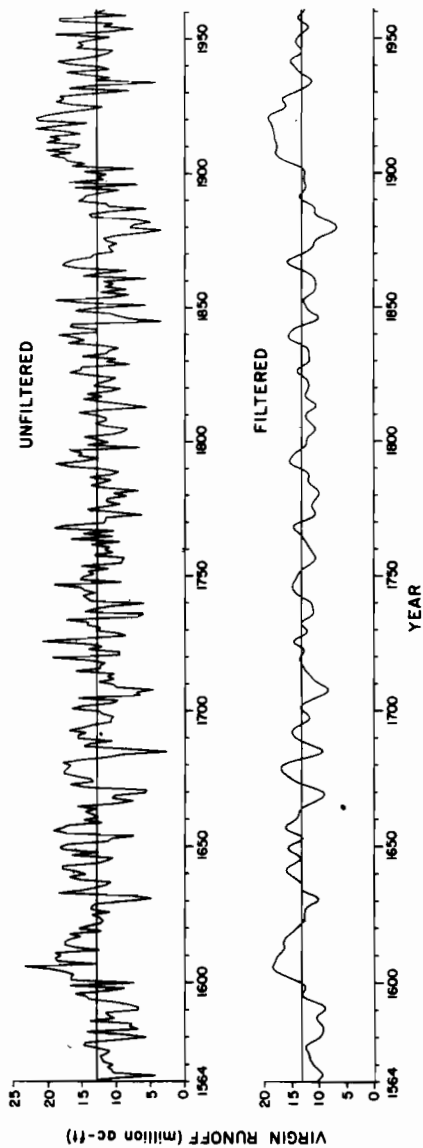
FIG. 1.16. The annual virgin streamflow of the Colorado River at Lee Ferry as reconstructed by using ring-width index variation in trees on 17 sites in the Colorado River Basin. The calibration period was 1896–1961, and growth for each year and the three following years was used to statistically estimate streamflow. The smoothed curve shown below the reconstruction represents essentially a running 10-year mean (see Chapter 8). (Reprinted by permission from "Long-term Streamflow Records Reconstructed from Tree Rings", Paper of the Laboratory of Tree-ring Research at the University of Arizona, No. 5, by C. W. Stockton, Tucson: University of Arizona Press, © 1975.)

replicated samples from high elevation *Pinus cembra* in the Alps for which ring-width variations were associated with the percentage of glaciers that were advancing in the Alps. The relationship between the two variables turned out to be linear, so that plots of the tree-ring chronologies were used to identify times in the past marked by glacial advance and retreat.

LaMarche and Fritts (1972) utilized a variety of tree-ring chronologies from arid southwestern North America in making statistical tests for possible linkages between ring width and sunspot numbers. They were unable to establish the existence of any significant relationship and concluded that 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 2 years and 22 through 29 years.

Stockton (1971, 1975), and Stockton and Fritts (1971a) describe a study which utilized ring-width chronologies from sites throughout river basins to extend the relatively short streamflow records backward in time. Replicated tree-ring samples were obtained from 3 different river basins of varying size and the several chronologies calibrated with the sequence of streamflow, precipitation, and temperature data for the area. Equations were derived which were applied to the variations in past ring widths to reconstruct streamflow in past years for which no hydrologic record exists (Fig. 1.16).

Stockton and Fritts (1973) studied an environmental problem in Canada created by the construction of a dam. Closure of the dam gates had reduced the normal high flow in the Peace River during the spring and early summer. Before closure of the gates, the high water impounded the water in Lake Athabasca and caused flooding in the waterways forming the Peace–Athabasca delta system. The record of water levels began in 1935, and it was thought the characteristics of flooding for the 1935-1966 period might not be a proper representation of the long-term features of the ecological system in which the plant and animal communities of the area developed. An estimate of the character of flooding for a longer period of time was needed to make decisions for the proper management of the delta area and the releasing of water from the dam.

The nearest trees with a record of climate were at the Arctic tree line some 300 miles (483 km) to the north. However, stands of *Picea glauca* growing along the channels, sloughs, and minor depressions within the Peace–Athabasca delta were found to crossdate and certain differences in the ring-width chronologies were apparent from site to site. It was inferred that soil moisture regimes associated with the water levels in the
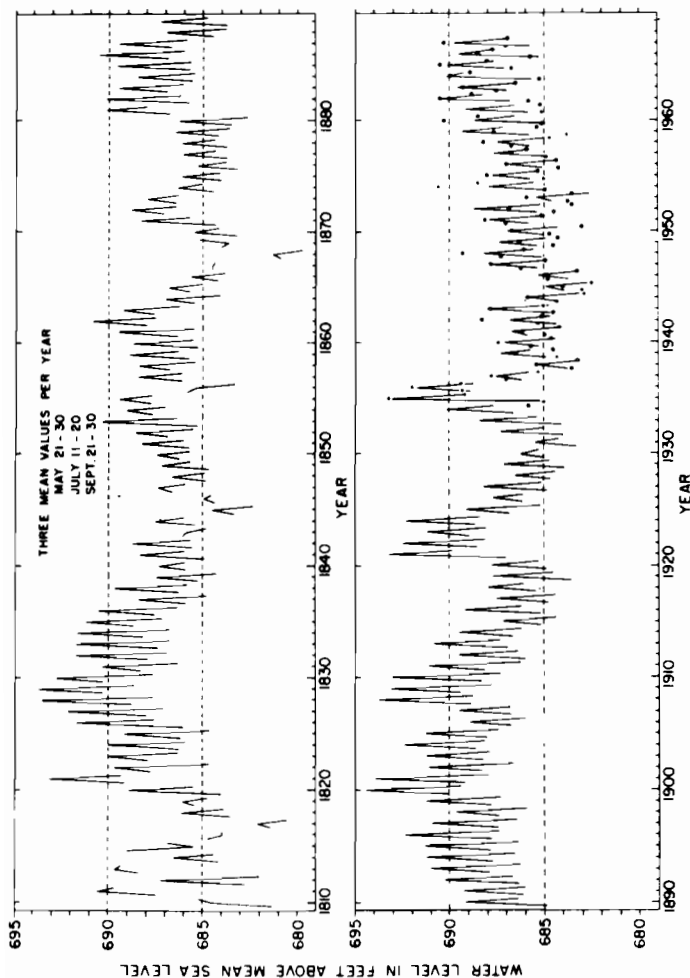
FIG. 1.17. Levels for Lake Athabasca, Alberta, Canada, as reconstructed from tree-ring data. Tree rings indicate that prior to 1935 there was greater variability in lake levels during May and July, but there was less variability in lake levels for September than during the recent calibration period. Points indicate actual lake levels used for calibration and the crosses indicate estimated data. The lines connect the three estimates from tree rings representing mean lake level for May 21–30, July 11–20, and September 21–30. Points are not connected over the winter season, as calibrations of levels for the frozen lake could not be made. (From Stockton and Fritts, 1973, courtesy of the American Water Resources Association)

channels had influenced tree growth. These relationships were statistically modeled, and the water level records for the lake observed for May 21–30, July 11–20, and September 21–30 were calibrated with the ring-width variation for each year as well as for the following year. Calibration accounted for 57% to 80% of the lake level variation. The calibration equation was utilized to reconstruct the water levels from 1810 through 1934 (Fig. 1.17). The variations in water levels, especially those early in the season, were found to be considerably greater in the longer reconstructed record than in the 33-year calibration period. That is, if the variations in water levels had been estimated from the short, 33-year period, those for the early spring would have been only one-third the amplitude observed for the longer period of 1810–1967. The extended record of lake levels obtained from the trees helped the Canadians to decide on an appropriate management system for the delta area to counter the deleterious effects of the dam.

Dendrochronological studies may be used to solve many environmental problems. There is considerable interest in air pollution damage and its effect upon the growth of trees (Vinš and Tesař, 1969). Trees in the San Bernadino Forest in Southern California that were supposedly killed by the Los Angeles smog (Taylor, 1973) show reduction in the width of the outermost growth rings (Fig. 1.18).

Another study (Ashby and Fritts, 1972) represents an attempt to use tree rings to measure possible inadvertent climatic changes at LaPorte, Indiana. An increase of rainfall had been attributed to increased industrialization and subsequent air pollution. Growth at first increased with the supposed increase of rainfall; but, as the amounts of pollution and rainfall reached their apparent maximum extent, growth became markedly reduced. It was thought that deleterious effects on the trees due to the increase in pollution may have countered the more favorable effects of increased precipitation, and it was concluded that the ring record in oak neither supported nor refuted the anomaly in precipitation. The studies of tree rings and air pollution suggest that tree-ring analysis can be used in a variety of ways to diagnose pollution effects in their early stages before death begins to take its toll on the trees.

New techniques have been pioneered by H. Polge (1966, 1970) in France and developed by M. L. Parker (M. Parker, 1971, Parker and Meleskie, 1970; Jones and Parker, 1970; Parker and Kennedy, 1973) in the use of X-rays and densitometry to obtain measurements of wood density within the ring (Fig. 1.19). The X-ray film negative is scanned with a beam of light, and a photocell measures the intensity transmitted by the film. The resulting electrical signal can be plotted or converted to units of wood density by comparison with a standard. Measurements at

selected distances across the ring can be fed directly into a computer and
a program used to calculate ring width, density, and cell structure
variation making up the earlywood and the latewood. Densitometry
could provide a means of gathering much more information on past
environmental conditions than is available from only ring width. Parker
and Henoch (1971), Heger *et al.* (1974), and Cleaveland (1975) present
evidence that X-ray analysis will be especially meaningful for studies in
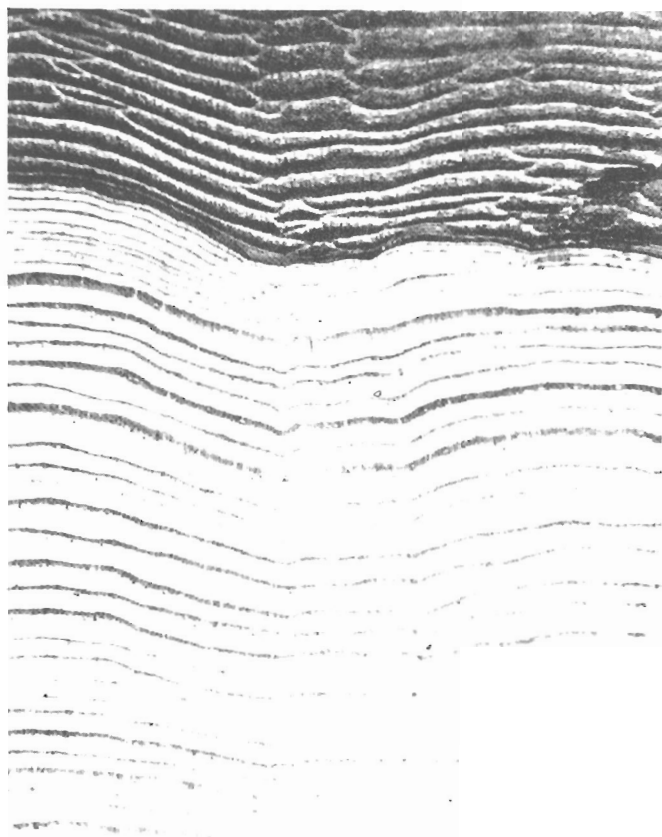
FIG. 3.18. A section from a Jeffrey pine (*Pinus jeffreyi*) in the San Bernardino National
Forest which showed apparent damage from the Los Angeles smog. Note that near the
bark (dark area at the top) there is a reduction in the amount of latewood and in ring
width that occurred about nine years before damaged foliage was noted and the tree was
cut. (Photograph by James Husha)
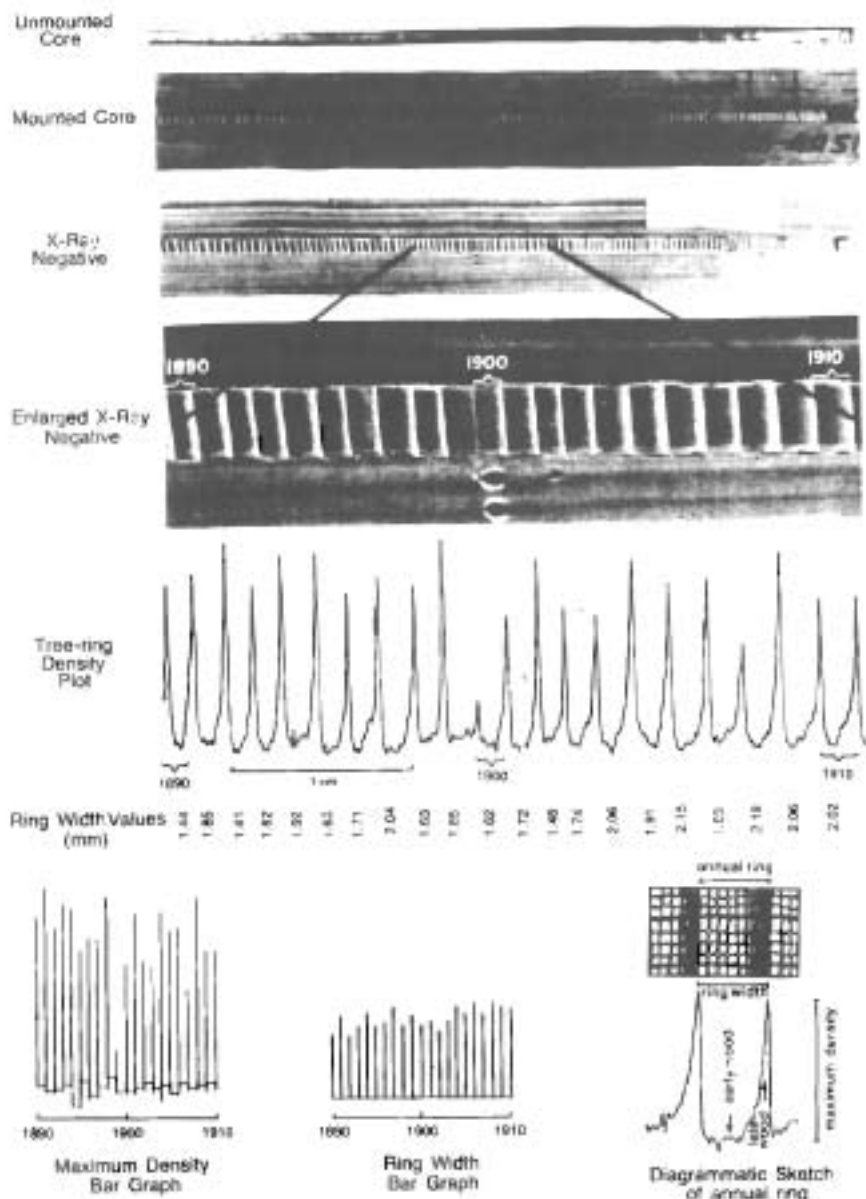
Fig. 1.19. A core extracted from a tree can be mounted and X-rayed to measure changes in wood density. The X-ray negative is then scanned with a beam of light and photocell. The electrical output can be calibrated in terms of wood density. Ring widths can also be measured as the distances between peaks in maximum density. This allows measurement of several features in ring structure which can result from different environmental factors and can provide a variety of information on past environments. (From Jones and Parker, 1970)

temperate regions and on mesic sites, where variations in the environment of the growing season are often more highly correlated with changes in cell structure and wood density than with variations in ring width.

The X-ray method is now included as an important part of certain new dendroclimatic and dendroecological work. The applied aspects of the field are changing very rapidly as new improvements are made. This volume calls attention to some of the possibilities, but does not attempt to cover systematically all the important developments, nor does it do justice to the new innovations and applications. The interested reader should watch the forestry, wood technology, and dendrochronology literature for current developments.

VII. Further Definitions and Concepts

This chapter has reviewed some of the historical roots of dendrochronology as practiced in western North America. The field and its various subfields have been defined, and some of the basic principles and concepts have been described. A few selected applications have been mentioned, and the value of dendroclimatology has been stressed. This chapter will conclude with discussion of a few additional terms and concepts which apply to the phenomena which actually link variations in ring width with variations in climate.

A. *The Domain of Climate*

Climate may be defined simply as an expression of meteorological phenomena representing weather occurring over a long period of time. It includes processes of exchange of energy and mass between the earth and the atmosphere. Energy may be represented by temperature, by radiant energy, and by the movement and condition of the earth's fluids, including both the liquids and gases. The aggregate of climatic conditions expressed as means, variance, and extremes for a region over a period of many years is referred to as the *macroclimate*. The data used to describe the macroclimate are often based either upon 30 or more years of observation from a single station or upon the average of several measurements from stations at diverse locations within a particular region.

According to Gates and Mintz (1975) the climate may be regarded as a system with certain properties and processes that produce the climate including its variations:

> The properties of the *climate system* may be broadly classified as thermal properties, which include the temperature of the air, water, ice, and land; kinetic

properties, .which include the wind and ocean currents, together with the associated vertical motions, and the motion of ice masses; aqueous properties, which include the air's moisture or humidity, the cloudiness and cloud water content, groundwater, lake levels, and the water content of snow and of land and sea ice; and static properties, which include the pressure and density of the atmosphere and ocean, the composition of the (dry) air, the oceanic salinity, and the geometric boundaries and physical constants of the system. These variables are interconnected by the various physical processes occurring in the system, such as precipitation and evaporation, radiation, and the transfer of heat and momentum by advection, convection, and turbulence.

The term *macroclimate* implies that climate is the expression of a steadystate or a more or less constant system when, in fact, macroclimate may be more appropriately portrayed as an average frequency of occurrence of different *climatic states* which may persist for periods of a month to many years (Table 1.III). Changes in the frequency of these climatic states may be attributed to slowly varying characteristics of the climate system, such as variations in temperatures of the ocean and its circulation, changes in the coverage by permanent ice and snow, changes in the transparency of the atmosphere, or possibly changes in radiation output from the sun. Sometimes climatic states in the past have persisted long enough to be considered climatic change (Gates and Mintz, 1975). There is no general agreement, however, among scientists as to how long a climatic state must persist or how large the variation must be to be designated a climatic change.

TABLE 1.III Components of the climate–tree system involved in dendroclimatology and their spatial and temporal domains

Level	Component	Spatial Domain	Temporal Domain
1	Macroclimate	Regional	Many years
2	Climatic state	Regional	One month to a number of years
3	Weather	Regional and local	Minutes to days
4	Microclimate	Local	Minutes to years
5	Operational environment	Plant surface	Instantaneous to years
6	Plant process	Molecular	Instantaneous to hours

Estimates of the earth's actual macroclimates from station records can be in error if the number of meteorological stations for a given region is small, if station locations are not representative of the area, if observations are poorly made, if the instruments are unreliable, or if the records are

short. For example, the averages of climate for the first 30 years of the current century as reported by many stations in western North America can be shown to be biased by anomalously high precipitation and high tree growth (Figs. 1.13, 1.14).

The term *climate* includes a seasonal component representing variations throughout the annual cycle. The term *weather* refers to short-term variations in the climate system, including all observable meteorological phenomena which can change abruptly within a few minutes and vary from day to day. Such phenomena include the precipitation, heat, light, wind, and related factors that affect the day-to-day conditions of the biosphere.

A particular organism experiences only that portion of the weather that occurs within its particular site. A tree, for example, is affected by the moisture conditions of the soil around its roots, the radiant energy on its leaves, and the temperature and movement of gases surrounding its leaves, stems, and roots. The aggregate of meteorological elements occurring within a localized site may be defined as a *microclimate*.

The term *microclimate*, like macroclimate, may refer to the aggregate of local weather for many years. However, in practice, the word *microclimate* often includes relatively short-term measurements in a specific locale which just as easily could be considered the weather or *micrometeorology* of the local site. In this text the term *microclimate* will be used for both short-lived micrometeorological conditions and the longer-term aggregates of measurements for a local site (Table 1.III).

The microclimate varies markedly for different organisms and different parts of the same organism. For example, the top of a forest canopy on a clear day may be exposed to relatively intense light, heating of the leaf surface, and wind, which can dissipate energy and remove moist air that surrounds the leaves. Simultaneously, near the forest floor there may be little light and air movement, high humidity, and leaf temperatures near those of the surrounding air. The microclimate of a hill crest may differ from that of a valley because of marked differences in exposure to wind or because of cold air drainage at night.

B. The Domain of Environment

Not all elements of the microclimate influence plants; only those that limit some physiological process will exert an effect on growth. Mason and Langenheim (1957) propose that the term *operational environment* be used for all relationships occurring between micrometeorological elements and the physiological processes which produce such an effect. They propose further that only the specific phenomena which enter such

operational relationships at a given time should be considered to be *environmental factors* (Fig. 1.20). Thus the specific factors of the operational environment may change markedly throughout the day, season, and year as well as throughout the life history of the organism (Table 1.III). For example, temperature and moisture may be the most important factors of the operational environment to the germinating seed, while light and minerals in the soil become more important as the seedling grows older, and the operational environment may become increasingly complex as a seedling grows into a mature forest tree.
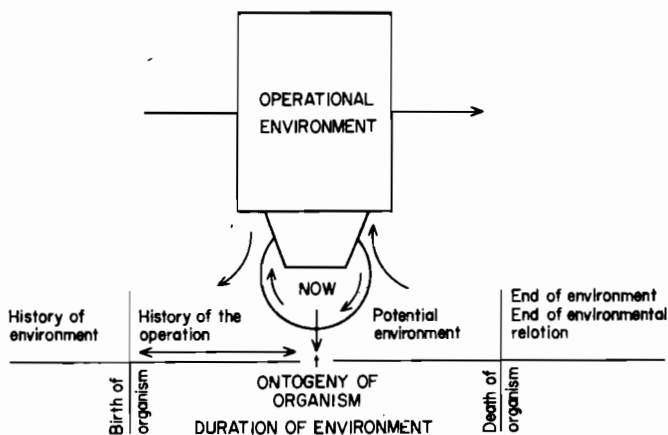
FIG. 1.20. A diagrammatic representation of the concept environment as described by Mason and Langenheim (1957). The environment is an organism-related concept and exists only when it has an operational relationship with the organism at time *t*, shown in the diagram as NOW. The components of the operational environment vary with the life history of the organism. The environment begins with the birth of the organism and ends with its death. Portions of the potential environment become used in the operation. Old relationships become history of the operation. The operational environment may be influenced by the history of the environment as it is evolved through geological time and successional changes in the biotic community on the site. (Redrawn from Mason and Langenheim, 1957)

Each environmental factor can enter into numerous interacting relationships in different parts of the plant, at different times throughout the year, and at different times throughout the life of the tree. For purposes of growth analysis it may be practical to consider an environmental factor as detrimental or beneficial only if its net effect is to decrease or increase growth. For example, an increase in solar radiation may increase light intensity and raise leaf temperatures. With more light

there is an increase in photosynthesis and the making of foods, but with the increase in temperature there is also increased respiration and increased consumption of food. The higher temperatures can enhance the potential for loss of water from the tree, and the increase in solar radiation may influence processes in other parts of the plant. It may heat the soil surface, increase the evaporation of water from the soil, and reduce soil moisture. If the reduction of moisture in the soil impinges upon water absorption, growth can be severely curtailed. The net effect of increased solar radiation, then, is favorable only if the beneficial effects of increased photosynthesis are not offset by the detrimental effects of increased respiration and reduction in available water.

There are many phenomena that we have traditionally regarded as environmental factors which are not a part of the operational environment as defined above. Some of these factors such as the presence of a disease or insect pest in the area, the potential for fire, or the absence of an important insect pollinator are capable of entering into a reaction with an organism but may not yet have done so. Mason and Langenheim (1957) class such factors as the *potential environment* (Fig. 1.20). As the environmental relationship between the microclimate and plant processes proceeds through time, the potential environment may be portrayed as being used in the operation, and a history of the operation is generated. The variations in ring width and cell structure are in one sense a recorded history of the past variations in the tree's operational environment.

Any phenomena not directly affecting the organism should be excluded from the concept of *environment* (Mason and Langenheim, 1957). Factors excluded are indirect factors and interactions that ultimately result in a phenomenon to which an organism later reacts directly, and factors to which the organism is indifferent. Such phenomena are a part of the history of the environment as depicted in Fig. 1.20, but they are not a part of the operational environment. The history itself can be important, however, because of its place in a sequence of events which leads to the final conditions that become part of the operational environment.

The difference between the history of the environment and history of the operation is also illustrated in Fig. 1.20. The latter, which is most important to tree-ring analysis, starts with the birth of the organism and extends through the development of the organism which can be viewed from any given point in the plant's development shown in the figure as time, t, or NOW. The operational environment ends at death of the organism because death marks the termination of the environmental relationship.

C. The Domain of Physiological Processes

The physiological processes are the physical and biochemical changes (such as diffusion phenomena and chemical reactions) which occur along plant surfaces, throughout all living structures of the organism, and sometimes in structures that are dead. All reactions, developments, and structures of an organism are the cumulative effects of the environment acting on growth processes. However, all processes also depend upon the genetic constitution of the individual organism. The relationships between heredity and environment as they affect processes and plant structures, such as ring width, may be diagrammed as follows:

hereditary
potential

processes and → growth → structural
internal conditions   characteristics
                             such as ring width
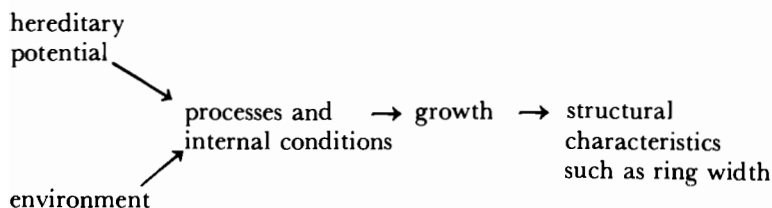
environment

Heredity determines what processes can occur, what environmental factors can affect them, and what range of each environmental factor will have a limiting effect. As mentioned earlier, internal conditions can also occur which modify the effects of the external environment.

Some factors of the operational environment, such as frost or extreme summer drought, may have immediate effects on ring growth and structure. They influence plant processes and can produce a chain of reactions in the tree which, over a period of minutes or hours, affects processes that modify or limit growth. Other factors of the operational environment, such as wintertime drought, may have no immediate effect on growth, since the growing tissue is dormant. They may, however, influence plant processes or change conditions within the plant so that at some later time they become limiting to growth. Factors such as competition for moisture, shading, and soil development also produce systematic changes in the operational environment. The effect of these factors is seen as variation in ring structure and size, which change systematically or vary slowly throughout the life history of the plant. Other factors such as death of a neighbor, fire, pollution, and defoliation by insects can result in sudden changes in the environment and in the structure of the tree. An abrupt increase or decrease in growth is usually followed by a systematic readjustment while the tree and its neighbors gradually attain a new equilibrium with the imposed change.

VIII. The Climate-Growth System and
Its Dendroclimatological Significance

For purposes of this book the components listed in Table 1.III are considered parts of a system in which the elements of weather and climate affect the tree microclimates, the operational environments, and the physiological processes which in turn control growth. Chapters 2 through 5 deal with the variety of physical and biological processes that are involved in the environment–growth linkages, and models described in Chapter 5 illustrate the many interactions and interlocking relationships. However, in spite of many interactions and complicating feedback relationships the primary flow of the system is unidirectional, starting with the climatic input and resulting in the ring-width output.

The degree of cause-and-effect linkage, that is, the influence which one phenomenon has upon another, is referred to as *coupling*; while the association between variations in two phenomena without regard to cause and effect is referred to as *correlation*. Phenomena that are directly coupled are generally correlated, but there are many phenomena which are correlated but not directly coupled. Usually, however, correlation between two phenomena is due to at least indirect coupling. Long chains of interacting cause-and-effect linkages can be involved.

For example, variations from day to day in the microclimates of a forest are more or less coupled with variations in the regional weather, because the weather systems control the inflow and outflow of energy and moisture available in the microclimates. The temperature of a single leaf is tightly coupled to the temperature of the surrounding air, the energy that is absorbed and lost by the leaf, and the disposition of the energy within the leaf. A number of physiological processes in the leaf can be affected by temperatures, which in turn can be coupled with conditions affecting growth. However, if growth is limited by other conditions or processes at the particular time, there can be no immediate and direct coupling between leaf temperatures and growth.

Since there are many leaves in the crown of a tree, the activities of growing tissues at the base of the stem are loosely coupled with the conditions in any particular leaf, but they can be more tightly coupled to the mean condition of all the leaves. In addition, the width of the ring is the average of growth processes throughout the entire growing season; so the width is very loosely coupled to conditions within the tree at any particular time. Thus, ring width is not correlated with specific conditions within the tree but with conditions averaged through both space (the tree tissues) and time (a number of months throughout the year).

In the discussion that follows concerning the many processes occurring throughout a tree, there are so many alternatives for cause-and-effect relationships and there is such a variety of microclimates from the top of the crown to the deeply buried roots, that possibilities for significant correlations between growth and climate appear exceedingly remote. However, the practice of site selection assures that only those trees are sampled in which growth-controlling processes are correlated with variables of climate; and the procedure of replication assures that a large number of rings are sampled so that much of the variation within and between trees is averaged for each site.

Thus the variations from one year to the next in the ring-width chronology are correlated with the variations in macroclimate not only because plant processes are coupled with environment, but also because the diversity in the microclimates and the physiological relationships have been averaged by the growing tree as well as averaged in the procedures of chronology development. The correlation between ring widths of many trees and regional climate makes it possible to statistically calibrate ring widths with certain variations in regional climate and thereby to reconstruct past climatic variations from past variations in ring widths.

If trees are in environments altered by nonclimatic factors such as fire, disease, or logging, changes in growth may occur which are not correlated with variations in the macroclimate. The ring record from such trees will show anomalies in growth which are not the same in other trees of the region. In such instances ring-width variation should not be used to represent variations in macroclimate. However, an investigator who is more interested in nonclimatic factors may seek out such trees, because the anomalies can be used to date and measure the magnitude of a nonclimatic change. Intensive sampling of rings from trees throughout a disturbed site can document the extent of the disturbance. Affected trees may be limited to some extent by both climatic and nonclimatic factors, however, and when this is the case it is possible to estimate the variations in past climatic factors while documenting site disturbance. Climatically related patterns are subtracted from those of the affected trees, and the remaining variance is attributed to the nonclimatic effects (Jonsson, 1969; Alestalo, 1971; Nash et al., 1975).

The sampling, evaluating, and ultimate use of ring-width data can vary depending upon the problem under investigation. In most cases, the success of a study depends upon the investigator's ability to decipher the anatomical evidence in the tree ring, to relate this evidence to the processes of the tree that affect growth, to model appropriately the relationships between variations in environmental factors and growth,

and to infer or estimate statistically the reconstructed environment or associated anomaly in climate.

The following four chapters describe the features of growth and discuss the physiological processes that contribute most to yearly variations in ring width. The important environmental variables that may limit each process are described, and these are related to the meteorological factors and energy and water budgets in the site. Biological models are then presented which relate climatic factors of precipitation and air temperature to variations in ring width. Chapters 5 through 9 deal with statistical characteristics and statistical analyses of tree rings and describe ways of calibrating variations in ring width with variations in climate. Various approaches to reconstructing climate using tree-ring data are presented, along with illustrations drawn from published as well as some unpublished works including current efforts.

Growth and Structure

I. Introduction

A knowledge of tree growth and wood structure is necessary for constructing realistic models relating environmental factors to ring widths or other anatomical features of the ring. For example, it would be difficult to specify in what ways variations in climate affect the width of rings without knowing where and when a tree grows, how growth can vary during each season and throughout the life of a tree, and how climatic factors affect the various chemical and physical processes that influence growth. An understanding of the manner in which seasonal growth begins and ends is also essential to explaining how two rings can form in one growing season or how a ring can be absent in certain parts of a stem. This chapter will describe the variety of ways in which the growing processes and woody structures can vary throughout the stems and roots of a tree. It also will set forth other relevant facts about growth and structure necessary to the application of dendroclimatic techniques dealt with in subsequent chapters of the book.

II. Gross Structure

In order to establish a working vocabulary for dendroclimatology, it is necessary to review some basic botany and to define several of the important terms and processes related to tree growth, beginning with tree structure. There are six principal organs of a tree: the roots, stems, and leaves, which are *vegetative organs*, and the flowers, fruits, and seeds, which are *reproductive organs*. Each of these organs is made of cells organized into various tissues, which are identified on the basis of appearance, structure, location, or function.

For example, a tissue named on the basis of appearance, its green color, is *chlorenchyma*, which includes all cells colored by the green pigment, *chlorophyll*. A tissue named on the basis of appearance and structure is *parenchyma*, relatively large cells with thin walls. Both *epidermis* and *mesophyll* are tissues identified on the basis of location, the former being
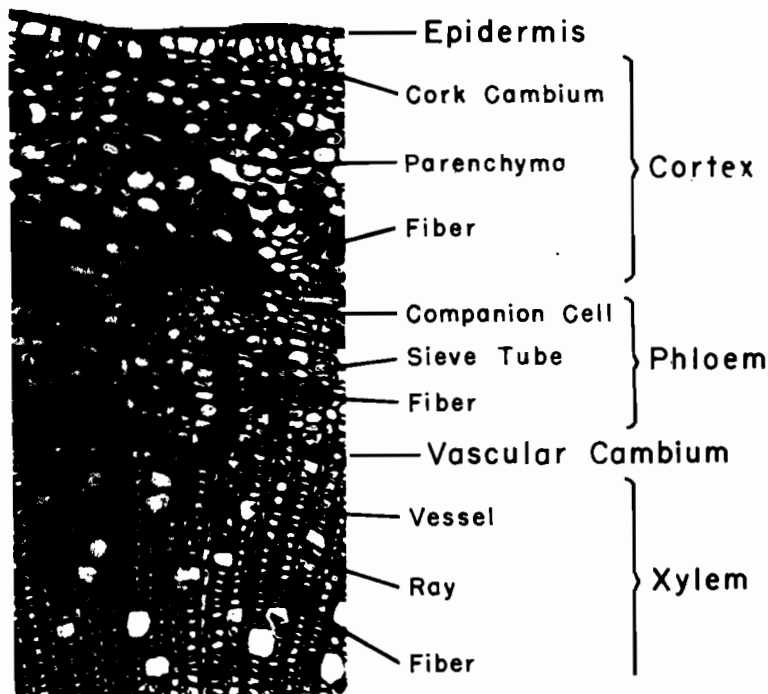
FIG. 2.1. A cross section of a young stem of *Populus deltoides* showing various tissues. (Courtesy of Tillman Johnson, Ohio State University)

one cell in thickness and located on the outside of leaves, young stems, and young roots, and the latter including all cells located between the upper and lower epidermis of a leaf. Two tissues named on the basis of their function in the vascular system are *xylem*, the water-conducting tissue which makes up the woody cylinder of a tree, and *phloem*, the food-conducting tissue in the bark (Fig. 2.1).

All tissues which contain cells that are capable of dividing and producing new cells make up a functional class of tissues called *meristems*. The thin layer of meristematic tissue joining the wood and the bark produces most of the vascular system and is referred to as the *vascular cambium*, while the cork-producing meristem (if present) in the outer bark is referred to as *cork cambium* (Fig. 2.1). Whenever the word *cambium* is used without its modifier, it refers to the vascular cambium. The *apical meristem* is the tissue capable of dividing at the tips of roots and stems (Fig.
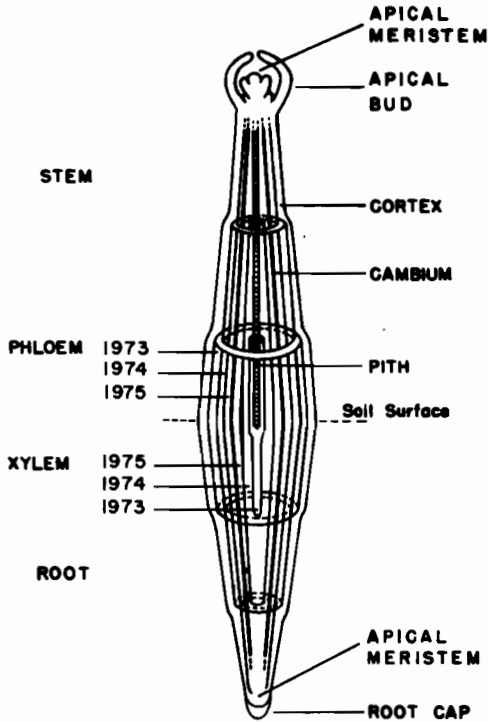
FIG. 2.2. A diagrammatic sketch of a three-year-old seedling showing the relationships of the various tissues to the growth layers in the phloem and xylem.

2.2). Meristematic tissue, which is found in all buds, is capable of producing new stems and leaves (*vegetative buds*) or flowers, fruits, and seeds (*reproductive buds*).

All organs and structures, except for certain parts of seedlings, originate either directly or indirectly from the meristems. A longitudinal section through a vegetative apical bud (Fig. 2.2) would show a meristem at the stem tip to be made up of tightly-packed, small cells with thin cell walls and dense protoplasm. The short appendages surrounding the stem tip in the drawing (Fig. 2.2) are embryonic leaves. Cells produced in the lower and central portion of the meristem enlarge and become the soft parenchyma tissue at the center of the stem called the *pith* (Figs. 2.2 and 2.3). A sheath of cells surrounding the pith becomes the first xylem and phloem. Other cells between the xylem and phloem continue to divide and this tissue becomes the vascular cambium. Parenchyma tissue, which lies outside the phloem in young stems, becomes *cortex* and epidermis (Fig. 2.1). Eventually, the cortex and epidermis are ruptured and are replaced by the corky tissue which develops from the cork cambium formed first within the cortex and later within the phloem (Fig 2.1). Although the first-formed xylem and phloem originate from the apical meristem, all subsequent xylem and phloem cells formed in the stem are generated from vascular cambium. Cells that are produced on the outside of the cambial layer become phloem, and cells that are produced on the inside become xylem (Figs. 2.1 and 2.2). The tissues outside the vascular cambium are referred to collectively as the bark.

Apical buds at the tips of dormant branches contain a meristem that can grow into a shoot if dormancy is broken. There are also lateral buds at the base of leaves and below the apical bud that contain similar meristems which can develop into lateral branches or shoots. As the bud grows throughout the season, new embryonic leaves or flowers are produced. The lower and older appendages expand and grow into well-defined leaves. The entire bud expands and grows into the one-year-old stem.

The root differs from the stem in that no buds are formed, the meristem is under a structure called a *root cap*, no pith is present, and the lateral roots originate from internal meristems within young roots, rather than from buds. For a more detailed treatment of meristems in woody plants, see Romberger (1963) and Kozlowski (1971a and b).

Figure 2.2 is a diagrammatic sketch of a three-year-old seedling showing the relative positions of the layers of xylem and phloem in the successive segments of growth. At the end of the third year, the stem segment formed during the first year includes three layers of xylem surrounding the pith which are in turn surrounded by the vascular cambium, three layers of phloem, cortex, and an epidermis. The most

recently formed xylem and phloem lie next to the cambium. These layers are continuous with the outermost xylem and innermost phloem layers of the two-year-old stems as well as the xylem and phloem of the one-year-old twig, leaves, branches, and secondary roots.

The cambium of the stem and root may be visualized as two paraboloids, joined at their widest circumferences at the soil surface and terminating in the apical meristems in the bud and under the root cap. As the stem grows in length and width, new layers of xylem and phloem are
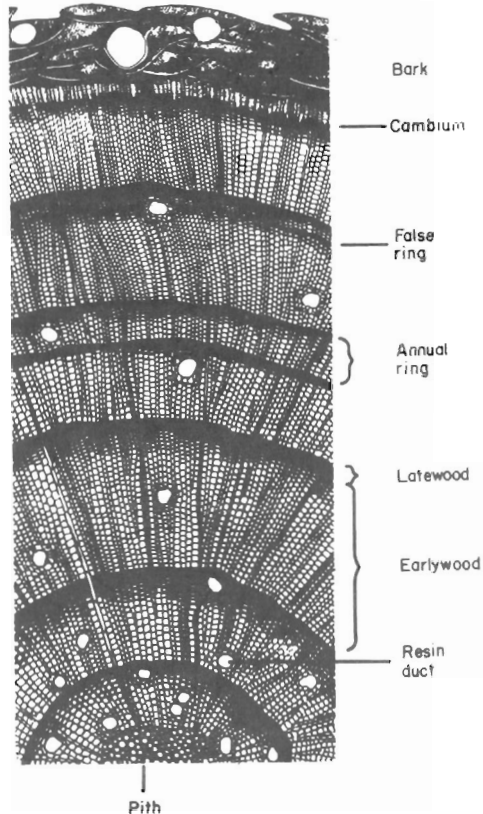
FIG. 2.3. Drawing of cell structure along a cross section of a young stem of a conifer. Tracheids are the predominant cells in the xylem. The earlywood is made up of large and relatively thin-walled tracheids, and the latewood is composed of small, thick-walled tracheids. Variations in tracheid thickness produce false rings in either earlywood or latewood. The large circular openings are resin ducts, which form a complex system of tubes throughout a coniferous tree.

produced along the paraboloid surface. The oldest phloem which lies nearest the epidermis or bark is crushed and becomes part of the bark, but the xylem, which is more rigid, maintains its shape.

A transverse or cross section through the stem of a tree (Fig. 2.4) will expose the growth layers as concentric rings. *Tracheids* are the predominant elements in the rings of *gymnosperms,* the nonflowering seed plants (Fig. 2.5a). These are vertically oriented cells with relatively thick lignified walls which die when they become functional as compared to parenchyma which have thin walls and can function as living cells. The tracheids may range from 0·5 to 15·0 mm in length (Kramer and Kozlowski, 1960), and their breadth (in a circumferential direction, see Fig. 2.4) can vary from 15 to 80 microns (Brown and Panshin, 1940). However, the tracheid width and wall thickness in a radial direction, that is, from the center to the outside of the stem (Fig. 2.4), can vary markedly within any one annual ring. Tracheids along the inner portions of a ring are wide and have the thinnest walls. These wide cells form the *earlywood,* sometimes called *springwood,* which is a porous tissue, low in density, and light in color (Fig. 2.3). Somewhere in the midportion of the ring the tracheids become markedly flattened along the radial dimension, and toward the outside of the ring the walls of the tracheids appear noticeably thicker. These narrow and flattened cells with thick walls form the *latewood* or *summerwood,* which is less porous, more dense, and darker in color than the earlywood portion of the ring (Figs. 2.5a and b).

PLANES

ABC   Transverse
ABED   Radial
BCFE   Tangential

DIRECTIONS

AB or AC   Radial
Within ABC plane   Transverse (horizontal)
BE, CF, or AD   Longitudinal (vertical)
EGF   Circumferential
C_1 Basipetal (within stem only)
C_2 Acropetal (within stem only)
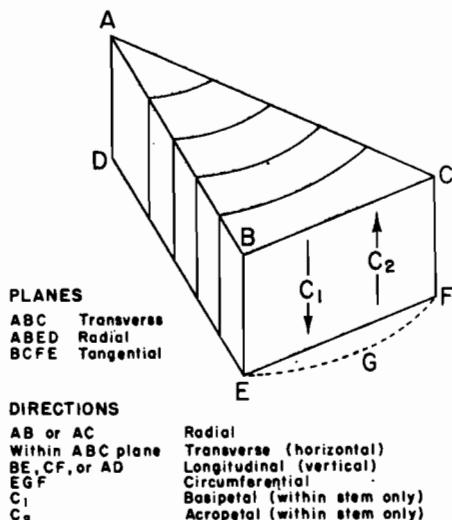
FIG. 2.4. Terminology used to describe directions and surfaces in a stem.
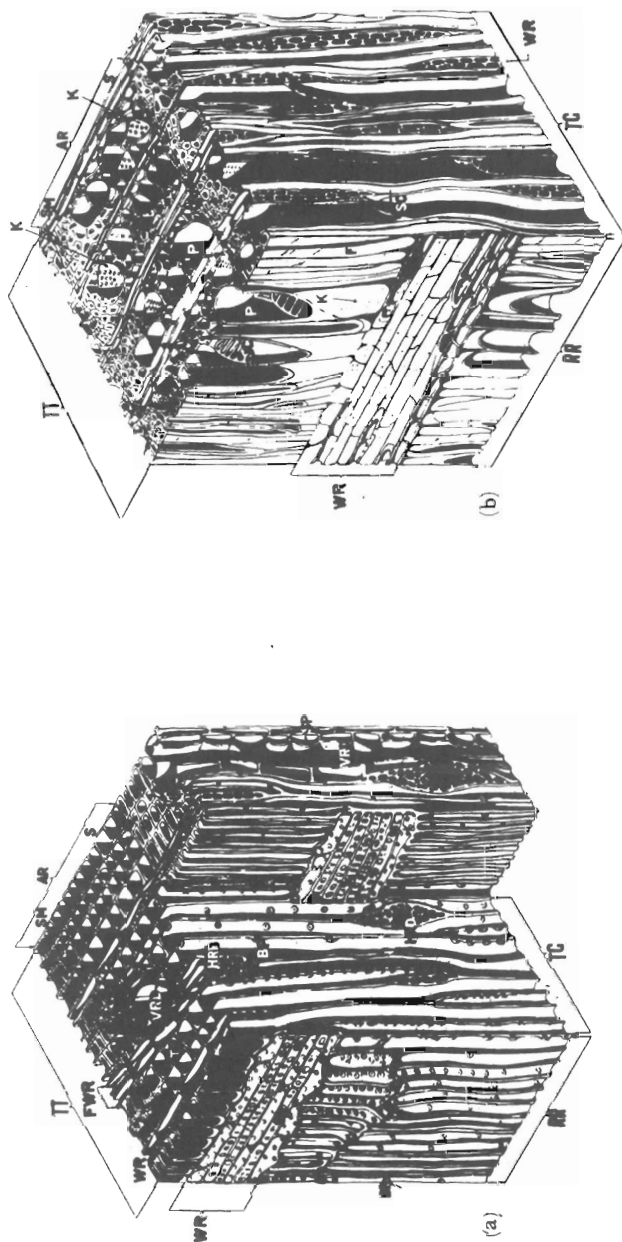
FIG. 2.5a and b. Drawing showing the detailed structure in wood blocks of gymnosperms (nonflowering seed plants) and of angiosperms (flowering seed plants). TT is the transverse plane, RR the radial plane, and TG the tangential plane (See Fig. 2.4). (a). Gymnosperm wood showing an annual ring, AR, including earlywood, S, and latewood, SM, which are made up mostly of tracheids, TR, with walls perforated by simple pits, SP, and by more complex structures called bordered pits, BP. Horizontally oriented parenchyma cells are wood rays, WR, and FWR. HRD designates horizontal resin duct, and VRD designates vertical resin duct. (b). Angiosperm wood including earlywood, S, and latewood, SM, which include (1) large water-conducting vessels or pores, P, with end walls open or ending with a grate, SC, and with walls perforated by pits, K, (2) small vertically oriented thick-walled fibers, F, and (3) horizontally oriented parench; ma cells which form the wood rays, WR. (Courtesy of U.S. Forest Service, Forest Products Laboratory, Madison, Wisconsin)

The transition in cell size and wall thickness from earlywood to latewood is gradual in many species. In the so-called hard pines, such as *Pinus ponderosa*, the transition from earlywood to latewood is more abrupt. Some workers describe and have tried to distinguish as many as five different layers within growth rings (Studhalter *et al.*, 1963). However, such minute distinctions, when discernible at all, are not needed for dendroclimatic analysis at present, although the future for such distinctions looks good through the use of X-ray densitometry. Two basic types of cells as represented in the earlywood and latewood will be the focus of this discussion.

A widely used quantitative definition of latewood in *Picea* was put forward by Mork (1928), which includes as latewood all tracheids in which the width of the common wall between two cell cavities is equal to or greater than the width of one cell cavity. All measurements are made in a radial direction. Mork's formula is simple and objective, and has been applied to a variety of other gymnosperm genera, but Larson (1957) and others have found that the marked color change from earlywood to latewood in the rings of certain gymnosperms is equally satisfactory and much simpler to use. The formula is not applicable to *angiosperms* (the flowering plants) because they form vessels and fibers rather than tracheids (Fig. 2.5b).

The sharp transition between the last-formed latewood cells of one growth layer and the first-formed earlywood cells of the next is usually distinct from the more gradual transition between the earlywood and latewood within the same ring. Usually a trained worker with an adequately surfaced specimen will have little difficulty using low (10–20 ×) magnification to distinguish the sharp boundaries between most rings from the more diffuse variations of structure within the annual ring.

Figures 2.3 and 2.5 show most of the cell types which make up the wood of gymnosperms. Thin-walled cells forming lines or ribbons radiating from the pith are called *wood rays* and often remain alive for many years in the *sapwood*, the outer light-colored portion of the stem. Metabolic wastes move inward through the living rays and are dumped at the point where these cells are no longer living so that the wood inside the sheath of living rays turns darker and is referred to as *heartwood*. The sapwood–heartwood boundary is influenced by the vigor of the tree, the retention of leaves, and the area of the crown (Grier and Waring, 1974).

In gymnosperms the vertically oriented tubular spaces sheathed by living parenchyma are *resin ducts*, which form an interconnected intercellular system both horizontally and vertically within the tree (Figs. 2.3 and 2.5a). Resin ducts may be scattered throughout the annual

growth ring, clustered, restricted to the outer ring boundary, or totally absent. The exudation of resin fromᵣthe ducts into wounded tissue helps to protect the living tissue from insect attacks or disease. As the vigor of a tree decreases with increasing age, or with increasing stress of the environment, the pressures of the resin in the ducts usually declines and the tree thereby becomes more vulnerable to disease. ·

The wood of angiosperms, or so-called hardwoods, is made up of *vessels*, various types· of *fibers*, and longitudinally oriented parenchyma called wood rays or *xylem rays* (Fig. 2.5b). The most prominent feature is the vessels, which consist of joined vertically oriented tubular cells from which the end walls have disappeared. The widths of vessels range from 20 to 400 or more microns, and their lengths vary from a few centimeters to many meters (Kramer and Kozlowski, 1960).

· The wood of angiosperms is designated as either *ring-porous* or *diffuse-porous*. In ring-porous wood, such as *Ulmus, Fraxinus,* and ·*Quercus*, the vessels in the earlywood are markedly wider than those in the latewood, and therefore yearly growth rings are relatively simple to identify. In diffuse-porous wood, such as *Fagus, Acer,* and·*Liriodendron*, the vessels are approximately the same diameter throughout the ring. The greater part of the xylem in angiosperms consists of thick-walled and narrow diameter wood fibers which are smallest or most dense in the latewood portion of the ring. In some genera, such as *Populus*, a distinct layer of parenchyma is formed at the boundary of the ring.

III. The Vascular Cambium

The growth of a cell involves many physical and biochemical processes. There are three basic growth phases that can be recognized, though the phases overlap and involve more or less continuous changes. (1) Cell division involves the duplication of hereditary materials and formation of a new wall which partitions the cell into two smaller daughter cells; in the case of *Pinus strobus* the actual divisions are reported to take approximately one·day (Wilson, 1964). Skene (1972) reports that the time from the beginning of one division to the next for a given cambial cell in *Tsuga canadensis* decreases during the course of the growing season from 28 to 10 days for vigorously growing trees and from 35 to 20 days for slowly growing trees. (2) Cell enlargement or expansion occurs by means of pressures developed within the cell which stretch the wall as new materials are added to the cell. Skene (1972) found that in *Tsuga canadensis* the enlargement of newly formed tracheids continues for 18 days in the early portion of the growing season but later in the season for only 9 days. (3) Cell differentiation and maturation follows cell

enlargement or accompanies the late stages of the growing period as further materials are added to the wall and protoplasm. Early in the growing season the time required for deposition in the walls of *Tsuga canadensis* tracheids is 10 days. Near the end of the growing season wall deposition continues for up to 50 days (Skene, 1972). Wodzicki (1971) has shown that in *Pinus sylvestris* the rate of cell wall thickening increases from a low rate in late May to a maximum rate in early July, and for the rest of the season a steadily greater number of days is required before wall thickening is complete.

Differentiation and *maturation* as the names imply are the processes by which the growing cells take on the structural features of the tissues of which they will become a part. When cell enlargement is complete and the structures are fully formed, no more growth occurs. In the case of vessels and tracheids, death of the cells must occur before they can become functional in water transport. According to Skene (1972) this transition of function occurs over a period of about four days. When a cell is dead, no further change in structure is possible, though it may expand and contract slightly due to changing hydrostatic pressures and tensions within the tree.

Diameter growth of a tree occurs as the cambium divides and derived cells undergo enlargement and differentiation, producing new xylem and new phloem. Simultaneously, the cambial sheath expands as new cells are formed on the inside of the cambium. The term *vascular cambium* is sometimes used to designate only a single layer of cells which is capable of dividing and differentiating new cells on either side of the layer, but the term is more commonly applied to the entire meristematic zone, including portions of the phloem and xylem where the cells are enlarging but are still able to divide (Wilson *et al.*, 1966; Fig. 2.6).

During those months of the year when the vascular cambium is inactive, the cambium is usually two to four cell layers thick. These cells are rectangular in cross section, and the walls are sharply and distinctly outlined (Ladefoged, 1952). In the spring, the walls become semitransparent and more plastic. The protoplasm changes from a viscous semisolid state to a more fluid or liquid state, the cells become extended in a radial direction, and the cambial zone may double in thickness. At this time, bark slippage can occur and the young cells are easily damaged by severe freezing or other adverse conditions. Injury may interrupt growth, causing some cells to remain in an immature state and causing other cells to become anomalous in size or structure. These abrupt changes in structure can be used to identify both the cells which were growing when the tree was injured and the year and season of injury.

At the onset of the growing season, the active cambium may be discontinuous with cell division beginning beneath the buds (Kozlowski, 1971b), but reactivation progresses *basipetally* (Fig. 2.4) that is, from the stem tip down to the base of the tree. Basipetal movement of cambial initiation appears to be most rapid in ring-porous trees, and sometimes the lapse in time between initiation in the top and bottom of the tree is too short to be detected. There is some evidence (Phipps, 1967) which suggests that the earlywood cells of some ring-porous species are produced by division of the cambium during autumn prior to the beginning of the current growing season. When environmental conditions are favorable, the cells start to enlarge and differentiate almost

MATURE PHLOEM

	MATURING PHLOEM	
DIFFERENTIATING PHLOEM	RADIALLY ENLARGING PHLOEM	
	DIVIDING PHLOEM (Phloem mother cells)	
CAMBIUM	CAMBIAL INITIAL (dividing)	CAMBIAL ZONE
	DIVIDING XYLEM (Xylem mother cells)	
DIFFERENTIATING XYLEM	RADIALLY ENLARGING XYLEM	
	MATURING XYLEM	

MATURE XYLEM

FIG. 2.6. The relative positions of tissues in the cambial zone. (From Wilson *et al.*, 1966)

simultaneously throughout the tree. Actual reactivation of the cambium may not occur until much of the earlywood is fully developed.

In large conifers, the basipetal migration of cambial initiation takes about a week before it reaches the stem base (Kozlowski, 1971b), and in large, diffuse-porous trees, intervals from three weeks to more than a month can elapse before basipetal migration of cambial initiation is complete.

Approximately 90% of the cambium is made up of elongated, spindle-shaped cells called *fusiform initials*. They give rise to the longitudinally arranged elements in the xylem and phloem (Fig. 2.5a and b). Growth of the stem in a radial direction occurs by division of the fusiform initials throughout the entire length of the cell and by formation of the new wall along the tangential plane (Fig. 2.4) (Kozlowski, 1971b). There are also cube-shaped cells in the cambium which divide along the tangential plane and give rise to the horizontally oriented rays of the xylem and phloem.

Division of the cambial cells forming a wall along a radial rather than a tangential plane occurs about 1% to 2% of the time. Sometimes a wall along the radial plane is formed by a division oblique to the radius and the newly formed short cells elongate as well as enlarge in a circumferential direction (Kozlowski, 1971b). Such division increases the number of cambial initials and allows the circumference of the cambial sheath to increase.

The active cambial initials may include 12 to 40 cells in the radial direction in fast-growing trees and six to eight cells in slow-growing trees (Figs. 2.1, 2.3). Once cambial activity is initiated and the size of the active zone is established, it usually remains more or less the same size until latewood begins to be differentiated. As the rate of cell division gradually declines, the width of the cambial zone decreases to that of the dormant state, although some of the last-formed cells can continue to enlarge and differentiate after cell division ceases.

A model proposed by Wilson (1964) and Wilson and Howard (1968) is useful for describing how cells are produced from the cambium of *conifers*, the conebearing gymnosperms. The cambium is treated as a factory in which building material and energy sources are continuously fed in from the active xylem and phloem. Complex structures are manufactured from these building materials, and they are transferred to the xylem and phloem as new cells. It is assumed for the model that the number of cells in the cambial zone is constant during the period of rapid growth, that all cells in the zone divide at the same rate, and that the division cycle for all cells takes the same length of time. The cambial cell is at a minimum size immediately after division. The cell manufactures new structural

components, doubles in size, and then divides. This division increases the cell number in the cambial zone. Assuming that the number of dividing cells must remain at a constant number, the division results in the transfer of a cell on the periphery of the cambial zone to the zone of radial enlargement, where it can no longer divide (Fig. 2.7). If a cell in the center of the cambial zone divides, then both daughter cells reenter the division cycle, and another cell from the edge of the cambial zone differentiates. If a cell on the edge of the zone divides, then the outer daughter cell differentiates and the inner reenters the division cycle. Hari and Sirén (1972) describe a more general model dealing with varying physiological conditions of the tree and the changing ecological factors of the site.
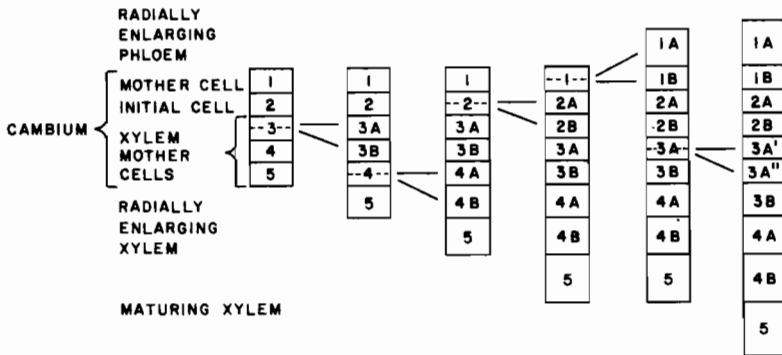
FIG. 2.7. A hypothetical radial section of a population of cambial cells developing from five cells in the cambial zone. The initial cells give rise to mother cells which are capable of further division. Five cambial divisions give rise to four xylem cells (3B, 4A, 4B, and 5) and one phloem cell (1A). (Redrawn from Wilson, 1964)

Cell enlargement is readily followed by differentiation and maturation, which are most apparent in the structure of the cell wall. A variety of materials makes up the cell wall constituents (Wardrop, 1964a); some contribute to the matrix and framework of the first-formed cell wall, while others are added at later stages. The primary substance in the framework is *cellulose*, and the first substances produced in the cell wall matrix are *polysaccharides* such as *hemicellulose*. At later stages in differentiation a hard material, *lignin*, is added. After the cell wall is fully impregnated with lignin, the protoplasm disappears and differentiation of the tracheid is complete. The walls of ray cells are usually less lignified, and they can remain alive as long as they are a part of the sapwood, as has been mentioned. The walls of xylem cells often contain thin areas or pits,

and in conifers the wall near the pit is raised so it is referred to as a *bordered pit* (Fig. 2.5a).

The bark in a several-year-old stem (Fig. 2.3) consists of an outer layer of corky tissue and an inner layer of living phloem. The cortex and epidermis formed on the one-year-old twig (Fig. 2.1) is ruptured and sloughed off. The phloem includes cells that are large, nonwoody, and thin-walled called *sieve tubes* and associated cells that are smaller, called *companion cells* (Fig. 2.1). The sieve tubes are involved in translocation of organic substances throughout the tree. In many species, the sieve tubes become nonfunctional after one season, and they are crushed by the newly developing phloem. Sometimes, however, the sieve tubes become reactivated during the first part of a second season, and in a few species they remain functional for a longer time. The phloem region also includes parenchyma and thick-walled fibers (Fig. 2.1), the latter of which sometimes occur in vertical bundles scattered throughout the bark.

Divisions of elements in the outer phloem cells give rise to arcs of cork cambium (Fig. 2.3). These cells divide toward the outside of the stem and form cork cells technically called *phellem*. While the phellem cells differentiate, the cellulose walls become impregnated with a waxy water repellant called *suberin*. As the stem grows in width and the bark is pushed outward, parenchyma cells in the inner bark divide and expand, thus accommodating the strains of circumferential expansion. The cork cambium and the layers of parenchyma cells create zones of weakness which are eventually ruptured, causing the bark to exfoliate in patterns which differ among species (Kozlowski, 1971b). The thickness of bark is a function of the tree's heredity, the vigor of the tree, and its age. Trees with thick bark, such as old or rapidly growing individuals, have additional protection which insulates the enclosed cambium from extreme temperatures due to fire or frost and protects the fragile tissue from mechanical injury.

IV. Growth—A Variable Process

It has been stated in the previous section that growth includes the basic processes of cell division, cell enlargement, and cell differentiation as the cells take on the attributes of the various plant tissues. It will be shown later that there are many other processes that can affect the three basic growth processes, and that their rates can be limited directly or indirectly by a wide variety of external environmental factors and internal conditions within the tree. As a result the rates of growth may vary throughout the day, throughout the season, and throughout the lifetime of the tree. For example, many growing tissues exhibit diurnal expansion

and contraction which is traceable in large part to varying environmental conditions around the tree (Kramer and Kozlowski, 1960). Likewise, the activity of apical meristems and the vascular cambium varies throughout the year. These growing tissues are dormant during the winter; dormancy is broken in the spring; and they become most active during the early part of the frost-free season. This activity slows down as the season progresses, until it ceases totally and dormancy again sets in. Usually growth is most vigorous and the active season longest for young trees and less vigorous and the season shorter for old trees.

The period of growth also varies for the many organs and tissues of the tree. For example, height and radial growth at the stem apex begin at about the same time, but height growth can cease earlier in the season than radial growth. Root growth may begin somewhat later in the spring than stem growth, and it can continue later in the season. Under a warm winter climate, there is evidence that roots can grow almost any month of the year (Fig. 2.8; Krueger and Trappe, 1967). Apical growth in roots may occur at a different time than diameter growth (Kozlowski, 1971b).
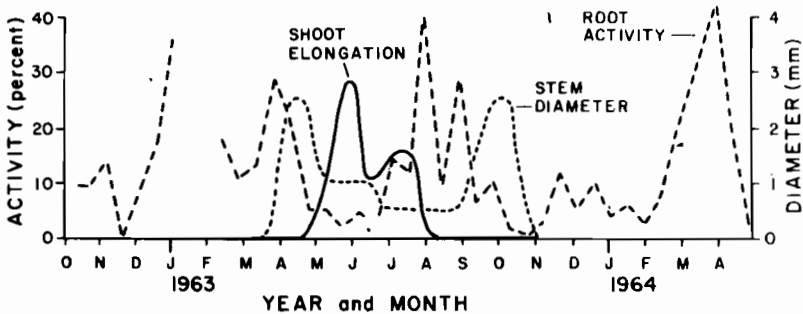
FIG. 2.8. Periodicities in growth throughout the year in shoots, stems, and roots of *Pseudotsuga menziesii* seedlings. (Redrawn from Krueger and Trappe, 1967)

Complicated interactions can occur among the growth processes in various parts of the tree. The interactions often involve the movement of growth regulators, the distribution of foods, and the changing rates of processes in different parts of the tree. In the following sections, growth of the shoot (height growth) and growth in width (radial growth) will be discussed as they vary (1) throughout the 24-hour day, (2) throughout the year, and (3) throughout the life of a tree. Variations among the different parts of the tree, among different species, and among different habitats will also be described.

V. Variations in Shoot Growth

The cambial activity in both conifers and hardwoods is initiated and maintained by growth hormones or regulators (see Chapter 4). The size and structure of the xylem cells, as well as the rate of cell division, also may be controlled by these growth regulators, which are produced by the actively growing stem apex or by the leaves. Therefore, the width and structure of the annual ring in trees are intimately related to the amount and duration of shoot growth (Kozlowski, 1971b).

A daily rhythm in shoot growth can be observed, most often with more rapid elongation occurring at night than during the day: At other times, when nights may be unusually cold and limiting to growth processes or when daytime conditions are especially favorable, growth may be more rapid during the day. Kienholz (1934) reported a high degree of correlation between the amount of night growth and minimum air temperature. Growth of shoots for certain species was observed to be negligible when temperatures were 42°F (5.6°C) or lower. Thus, during the beginning of the growing season when nights are unusually cold, the rate of shoot growth may be markedly reduced.

The general cumulative pattern of height growth in temperate species follows a *sigmoid* (*s*-shaped) *curve* throughout each season. Growth starts, accelerates rapidly, reaches a relatively high but constant rate during what is referred to as the "*grand*" period of growth, and finally decreases as the cumulative curve levels off sometime during the summer (Fig. 2.9). Hari *et al.* (1970) present an interesting dynamic model describing the variations in the daily height increment of plants as they change throughout the year.

As soon as temperatures are sufficiently high and days are sufficiently long, shoot growth is initiated. Most species in a given locality begin growth within a short time span in the spring. However, cessation of shoot growth may vary over a wide range of time (Fig. 2.9). Cessation often occurs as a result of internal limiting factors long before air temperatures or day lengths have changed sufficiently to become directly limiting to the growth processes. However, the internal limiting factors may sometimes be traced to physiological factors that in turn are limited by unfavorable conditions of climate. Severe water deficits late in the spring or in early summer can inhibit cell enlargement and affect shoot growth, especially in those species which have a long growth period and exhibit intermittent flushes of shoot growth (Kozlowski, 1964). However, the climate of the prior growing season (the time when buds are formed) often exerts a greater influence on the amount of height growth than the climate for the period in which the stem is elongating.

During a particular season, growth of individual shoots may deviate from a smooth, sigmoid curve. Such variability is especially common in the tropics where internal conditions are usually the most limiting and growth can occur theoretically at any time. The growing point of some tropical trees may be permanently active, while in other species it is intermittently active, with growth temporarily slowing down or ceasing after a certain number of leaves are formed (Alvim, 1964). For *deciduous* trees in areas where one season is unfavorable to growth, the period and rate of growth will be more highly correlated among individuals and among species. However, the synchronization of growth with a particular
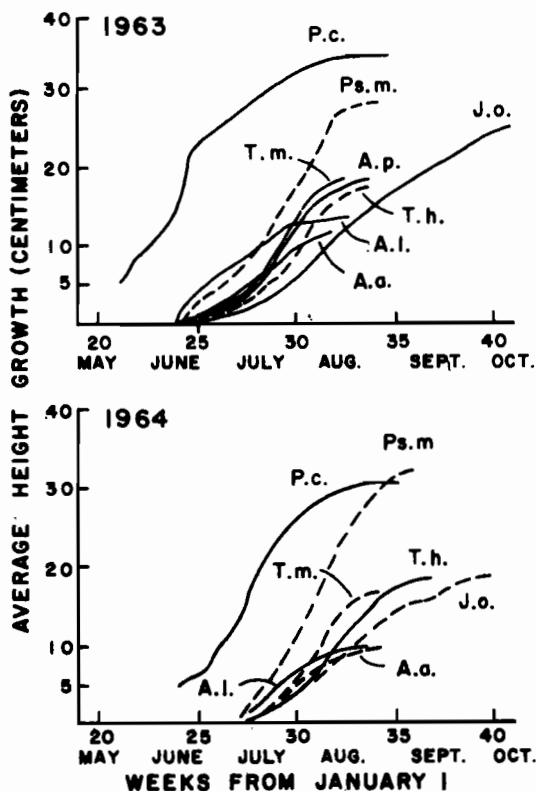
FIG. 2.9. Cumulative height growth for different coniferous species from western North America. P.c.—*Pinus contorta*, lodgepole pine; Ps.m.—*Pseudotsuga menziesii*, Douglas-fir; T.m.—*Tsuga mertensiana*, mountain hemlock; A.p.—*Abies procera*, Noble fir; J.o.—*Juniperus occidentalis*; T.h.—*Tsuga heterophylla*, western hemlock; A.l.—*Abies lasiocarpa*, subalpine fir; and A.a.—*Abies amabilis*, Pacific silver fir. (Redrawn from Williams, 1968).

season does not assure that the amount of growth will be correlated with the climate of that season.

Certain angiosperms and gymnosperms in temperate regions also can reinitiate apical growth several times during a given season (Kozlowski, 1964). Growth may resume, after apparent dormancy has set in, with the bursting and elongation of the apical bud or by development of lateral buds at the base of the apical bud. Many *Pinus* species appear to be *uninodal* in that only one series of needles is produced each year by the apical bud. Others, such as *P. echinata* and *P. taeda*, are *multinodal*. Buds in these species may produce several series of needles during one season's growth, and the xylem may exhibit multiple growth rings (Kozlowski, 1971b).

Vigorous branches of *Pinus edulis* are reported to produce summer shoots from the growth of buds that are formed after initiation of apical growth but have not passed through a period of rest (Lanner, 1970). Several cycles of growth occur in stands of *Pinus halepensis* in southern France under conditions of the Mediterranean climate (Serre, 1973). Despite recurrent growth flushes, the location of the primary whorl of numerous thick branches is usually distinguishable from the secondary height increments that succeed the initial growth flush. Recurring growth flushes in shoots are not necessarily accompanied by similar growth variations in the main stem, though multiple growth rings are often attributed to multiple flushes in the shoot apex.

There are certain variations in the seasonal pattern of shoot growth associated with tree age. In the spring, shoot growth for all age classes begins at approximately the same time, although the younger individuals close to the warm ground layer may slightly precede others breaking dormancy. The period of rapid shoot growth is shorter in mature trees than in seedlings, however. Likewise, multiple flushes are more likely to occur in young trees than in older trees. The flattened crowns so typical of old trees result in part from the decreased vigor of shoot growth that accompanies increasing age.

Growth of most lateral buds is inhibited by active growth of the stem apex. This inhibitory action controls crown form and is referred to as *apical dominance*. For example, the young apical buds in several species of *Pinus* and *Pseudotsuga menziesii* are strongly dominant, so that a single main stem with few lateral branches is almost always formed. On the other hand, trees of *Pinus longaeva* and many species of *Juniperus* and *Ulmus* have apical buds which exert less dominance, and as a result multistemmed trees are common. Growth rings formed in trees having multiple stems and several actively growing branches can exhibit variable widths as the branches feeding different segments of the cambium change in mass and

change in their relative importance to the total foliage of the tree. For example, a period of rapid growth in one of several branches may temporarily inhibit the growth of the lesser branches, which in turn may cause a reduction in the widths of rings receiving nourishment from them. Those trees in which growth varies among several branches throughout the crown may exhibit associated variations of ring widths along the main stem depending upon the proximity and location of the branches.
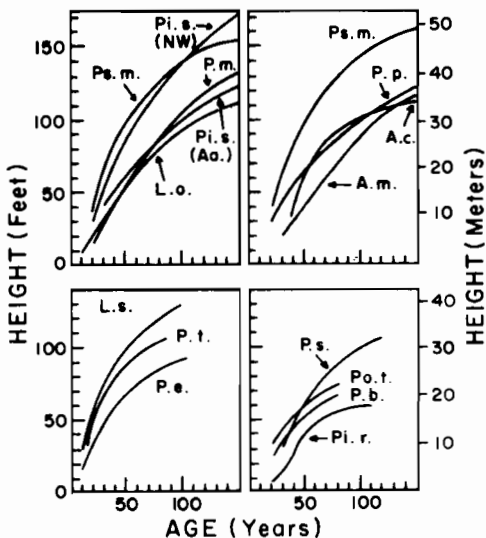
FIG. 2.10. Cumulative height growth for different species with increasing tree age. A.c.—*Abies concolor*, white fir; A.m.—*Abies magnifica*, red fir; L.o. *Larix occidentalis*, western larch; L.s.—*Liquidambar styraciflua*, red gum; P.b. *Pinus banksiana*, jack pine; P.e.—*Pinus echinata*, shortleaf pine; P.m.—*Pinus monticola*, western white pine; P.p.—*Pinus ponderosa*, Ponderosa pine; P.s.—*Pinus strobus*, eastern white pine; P.t.—*Pinus taeda*, loblolly pine; Pi.r.—*Picea rubens*, red spruce; Pi.s.—*Picea sitchensis*, Sitka spruce. (Aa. = Alaska, NW = Northwest); Po.t.—*Populus tremuloides*, aspen; Ps.m. *Pseudotsuga menziesii*, Douglas-fir. (Redrawn from Baker, 1950)

The rate of growth can be expressed as a function of increasing age. When cumulative shoot growth is plotted as a function of tree age, it approximates the sigmoid curve. A brief period of increasing growth rate occurs during the seedling stage, a period of high growth rate occurs during the sapling stage, and a decreasing growth rate occurs as the tree matures and approaches old age (Fig. 2.10). The sigmoid curve is stretched over a longer period of time for trees with long life spans. For trees on stress sites, the period of rapid juvenile growth may be shorter

than for those on more optimum sites, but the period of declining growth rate can be longer. Since the juvenile stage for trees on adverse sites may be shorter than for trees on optimum sites, the trees are not as tall and the crown becomes more spherical and flattened unlike the conical shaped crowns of young trees.

The rates of shoot growth as shown in Fig. 2.10 may vary for different species as well as for *ecotypes* representing variants of the same species. For example, when seeds from populations differing in elevation or latitude such as *Picea sitchensis* from Alaska and the Pacific Northwest (see Fig. 2.10) are grown together on the same site, differences may be observed in the response of shoot growth to the temperature and the length of the daylight period. These differences occur because the local environments have favored the survival of certain heredities which are most in tune with the natural climatic regime (Billings, 1957). Squillace and Silen (1962) found inherent differences in the rate of height growth of *Pinus ponderosa* related to differences in seed source over the species range. Such hereditary variations may influence the way a tree is affected by climate, but these factors are constants throughout the life of an individual tree and therefore are not contributors to year-to-year variations in ring width.

VI. Variations in Radial Growth

Usually climatic information derived from tree rings is based upon differences in width and stem girth that occur from one year to the next; but climatic information may also be found in wood density, a parameter which varies as a function of cell size and cell wall thickness. Both sources of climatic information reflect daily and seasonal variations in growth rates as they are affected by environmental conditions. However, these same growth rates are also influenced by other factors such as conditions of the plant in prior years, the age and structure of the tree, limitations of the site, and the hereditary potential of the particular tree. All variations in growth can be traced to variations in limiting and interacting plant processes which can vary through time and throughout the particular tree. It is, therefore, impossible when dealing with growth to compartmentalize completely a discussion of factors, for no one factor can operate independently of prior conditions or of other factors occurring at the same time. The remaining portion of this chapter will describe the ways radial growth can vary throughout the stem and root, from short to long periods of time, from young to old trees, and from site to site. Detailed description of the causal factors and the plant processes linking

them to variations in ring width and wood density will be dealt with in subsequent chapters of the book.

A. Measuring Radial Growth

Although the annual increment of radial growth is easily measured by examining the ring width, it is often helpful to know when and how the ring was formed by measuring the amount of growth that occurred over a number of time intervals throughout the growing season. This can be accomplished by sampling a piece of the wood and bark at the beginning and end of the interval and examining any differences in the outermost ring. Samples can be obtained by means of a simple tubular leather punch. The collected materials are then fixed to preserve the cells, and sections are made with a microtome or razor.

A major disadvantage in using wood samples is that wounding is severe, and growth rates of the cambium may be altered as a result of the sampling technique. Wolter (1968) circumvents this difficulty by periodically inserting thin insect mounting pins horizontally through the bark into the wood. The insertion injures a few growing cells and marks those differentiating into xylem. The pin is left in the tree for future reference. The injured cells are examined after growth is complete, and the cell rows forming at each insertion date can be identified microscopically. Serre (1973) successfully uses a microsampler to obtain cambial material every two weeks without undue injury to the tree. However, the various means of sampling here described involve materials from different locations as well as for different times during the growing season so that large errors of measurement often are present and prohibit detailed analysis of growth rates. For the more precise analyses it is better to measure the same location on the stem throughout one or more growing seasons.

A variety of instruments and techniques has been used to measure and record the changes in stem girth or in a single radius. They range from devices such as forks, calipers, and range finders, all of which are used to measure gross size, to extremely precise mechanical or electronic sensors which record minute changes in size occurring over minutes and hours.

Dendrometers are widely used instruments which are installed on stems and are read to obtain a measurement of gross stem size. One type of dendrometer consists of a thin metal band with a vernier scale which allows precise measurement of the stem circumference (Hall, 1944; Liming, 1957). Other types of dendrometers measure the size of a single radius from a fixed point anchored into the wood of the tree (Reineke, 1948; Daubenmire; 1945; Bormann and Kozlowski, 1962). A

measurement is made by placing a dial indicator on a permanently installed mount which guides the instrument to the same measuring point. Differences in the measurements between successive readings supposedly represent the amount of growth, but sometimes there can be substantial variations due to changes in *hydrostatic* forces, temperature changes, or ruptures in the bark.

Among the limitations of these dendrometers are the following. (1) They all require visual reading at some designated time. (2) Diurnal variations in stem size which may not necessarily represent growth may be large, so that the reading must be made early in the morning when the stem is most fully distended. (3) Since two measurements are involved to obtain a size change, a reading error causing an overmeasurement for one period will be accompanied by an undermeasurement for the following period. A permanently attached dendrometer constructed by Kuroiwa (1957) uses mirrors to obtain an exceptionally precise measurement.
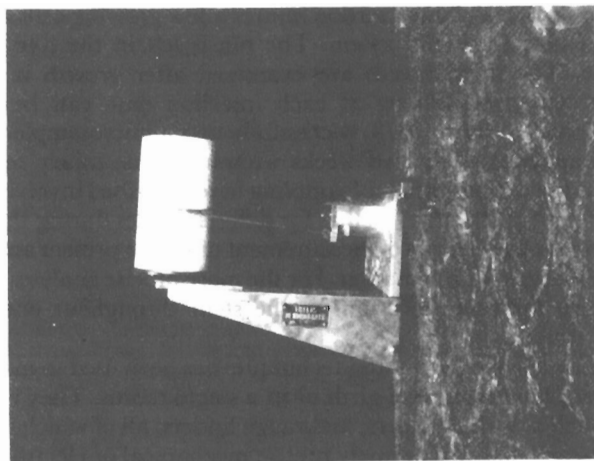
FIG 2.11. A dendrograph used to continuously record the size of single radii in the stems of trees. The instrument is mounted on three lag screws inserted into the wood. A rod resting on a prepared bark surface bears on a lever connected to the arm and pen. Any change in the distance between the instrument and the bark surface is magnified 100 times and recorded by the pen on the clock-driven drum which rotates once every eight days. (Fritts and Fritts, 1955)

Dendrographs involve the same kind of measuring systems as dendrometers, but the stem size is continually recorded. Mitscherlich uses a dendrograph designed by Friedrich that continually recorded changes in size of a band stretched around a tree stem (Mitscherlich *et al.*, 1966). A different kind of dendrograph was developed by Fritts and Fritts (1955) which mechanically magnifies and continuously records the size along a single stem radius (Fig. 2.11). A number of electronic devices have been developed to monitor stem size changes on electrical data loggers and recorders (Cooper and Herrington, 1959; Kuroiwa, 1959; Phipps and Gilbert, 1960; Impens and Schalck, 1965; Mitscherlich *et al.*, 1966; Dobbs, 1969; Odin and Openshaw, 1971; LaPoint and VanCleve, 1971; Phipps and Yater, 1974).

In order to avoid error due to disturbance, dendrographs must be mounted carefully. The contact points of measurement should be prepared with hardened and waterproof surfaces to eliminate bark swelling and abrasion. Charts must be changed without disturbing the record or the mounting of the instrument. However, the continuity of measurement from dendrographs is an important advantage over the records from dendrometers because it allows assessment of diurnal variations in stem size which, along with seasonal variations, can be related meaningfully to growth, to the plant processes affecting growth and cell hydration, and to variable environmental conditions around the tree.

Some workers, especially those who have used dendrometers, have been impressed with the differences that they have observed at various locations throughout the same stem. For example, some have reported that one side of a stem can grow more during some weeks while the opposite side can grow more during other weeks (Young, 1952; Small and Monk, 1959; Bormann and Kozlowski, 1962; Kozlowski and Winget, 1964). Some of these variations result from difficulties inherent in the particular measuring device. Dendrometers are especially susceptible to errors due to differences in the placement of the reading instrument, while dendrographs, the mirror dendrometer, and electronic devices which obtain relatively continuous records are subject to these errors only when disturbed by changing of charts and other adjustments. Differences are also traceable to real features of the stem, including differences in internal water stress, wood structure, flexibility of the radius which is measured, the effective size of the radius measured, hygroscopic changes from wetting and drying of wood and bark, variations in instrument pressure, and variations in patterns of upward water transport.

Numerous records of stem size have been made by this writer using dendrographs mounted on a number of different species and on different

sides and heights of the same trees (Fig. 2.11). Some dissimilarities are often apparent within and among trees, but they are rarely as large and marked as the similarities that occur. For example, the same patterns of diurnal and seasonal variations can be discerned easily at different locations in the same as well as in different trees, and even in those of different species.

Worrall (1966) found good correlation between short-term changes in stem diameter and internal water stress. Xylem sap tension, as well as diameter changes, were measured, and a linear regression analysis was applied to adjust the observed diameter to a standard tension. In this manner the growth measurements were separated from those reversible changes resulting from variations in water stress.

Dendrograph records show radial growth most clearly when diurnal reversible variations in stem size due to hydration changes are small and the annual net increase in size which is due to cell growth is large (Fritts, 1958, 1962c). However, the diurnal and seasonal reversible changes in stem size for trees in arid sites may be greater than the annual increment of growth (Fritts et al., 1965c; Fritts, 1969), and stem diameters may

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FIG. 2.12. Selected records of stem size for 1966 as obtained from a dendrograph (Fig. 2.11). The height of the pen was usually adjusted whenever charts were changed. An adjustment factor representing the difference in the trace before and after the change must be added to the reading. The instrument is dendrograph B, which was mounted at middle stem position on an arid-site *Pinus ponderosa* (see Figs 2.15, 2.19, 2.20, 2.21, and 2.23). The June record shows the characteristic stem size fluctuation at a time of low soil moisture and high potential evaporation. Diurnal variation in size of the stem is small because little soil moisture is available, little water is moving through the stem, and growth is slow. Deviations from the smoothly varying expansion of the stem at night and shrinkage during the day are irregularities related to varying amounts of cloud cover and variations in temperature, both of which influence loss of water from the tree. During the afternoons of 6/25 through 6/28 the small irregularities are the result of cloud cover in the afternoons and of light rains which fell in the evening of 6/26 (0·10 inches or 2·54 mm) and in the afternoon of 6/28 (0·73 inches or 18·54 mm). A 1·10 inch (27·94 mm) rain fell on 6/29. There was consequently more moisture available for both absorption and loss by the tree, so the dendrograph trace for the following week shows more variation in stem size. Periods of cloud cover in the morning and in the afternoon of 7/4 are reflected in the irregularities of the dendrograph trace. Dense clouds during midday on 7/8, 7/9, and 7/12 cause marked irregularities in the record of stem size. Light rains fell on 7/16 and 7/17. A 0·70 inch (17·78 mm) rain on 7/18 and a 0·36 inch (9·14 mm) rain on 7/19 accelerated stem rehydration and caused considerable expansion in stem size. Light rains and dense clouds during midday for the week of 7/20 to 7/26 produced the most marked midday irregularities in stem size. During 10/6 to 10/8 there were scattered clouds producing slight variations in stem size during midday. Other days for October were clear. The daily maximum stem size declined at this time due to an inactive cambium and increasing water stress. Fig. 2.21 provides more information on the climatic régime for the tree.

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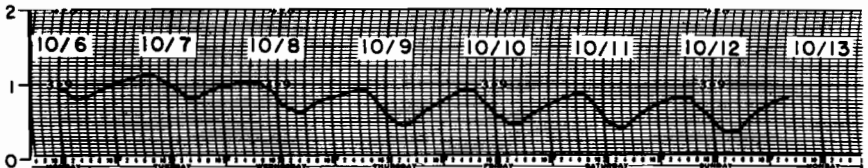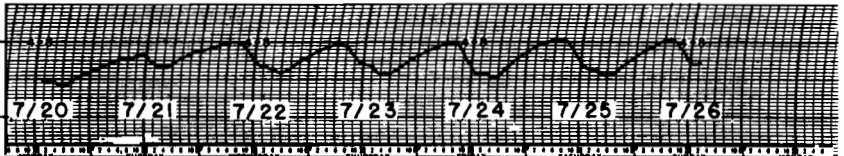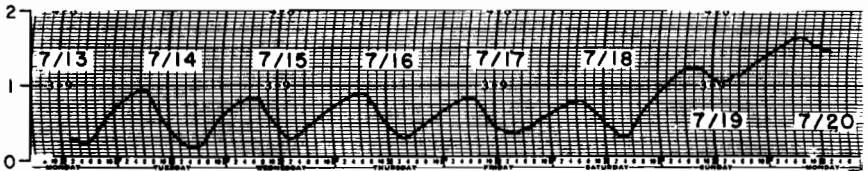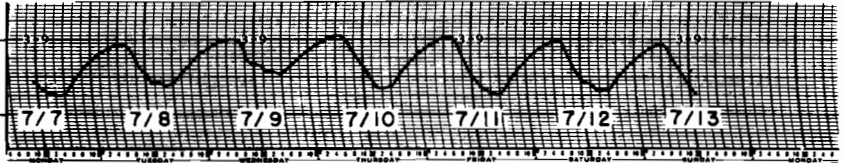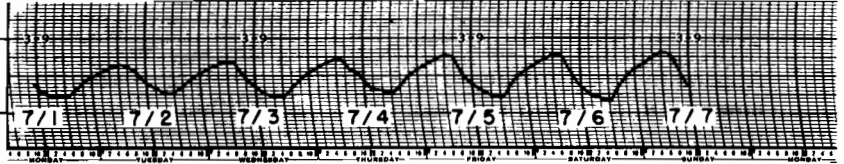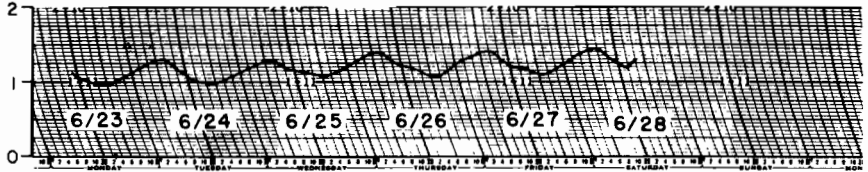
decrease even though the cambium remains active. In these cases, the dendrograph record is a valuable measurement of water status in the stem and must be supplemented by some more direct measurement of cambial growth if annual increment of cells is to be determined. Shrinkage and expansion similar to that in stems has been reported for leaves, roots, branches, and reproductive structures (Kozlowski, 1965, 1971b).

B. Diurnal Periodicities in Radial Growth

It might appear that diurnal variations in the rates of various processes occur too rapidly and are too transient to significantly affect ring width. Apparently, transient factors may affect the structures within the tree, however, if they occur repeatedly. It is therefore important to consider the minute-by-minute and hourly changes occurring in processes, because they are the basic ingredients accumulated over days, months, and years which produce the variations in ring width.

Figure 2.12 shows a portion of the dendrograph record from a single tree for June 13 through October 13, 1966. The variations in stem size reflect changes in cell volume resulting from variation in their water content. During the day, loss of water from the leaves, called *transpiration*, removes moisture faster than it is absorbed by the roots and thus produces a net decrease in cell water content. During the night transpiration from the leaves occurs more slowly than water absorption in the roots and there is a net increase in cell water content. During June and July cell division in the example tree was occurring in the cambium and expansion of the growing xylem and phloem resulted in a net increase of these tissues. The expansion each night was greater than the shrinkage during the day and there was a net increase proportional to the amount of growth.

The rate of change in size of tissues in the stem can be shown to be a function of both the difference between water uptake and water loss by the plant, and the ability of water to move, to be absorbed, and to be held by the tissues of the plant. For example, the growing tissues can often compete with the surrounding nongrowing tissues for water, so they are not as likely to shrink during the day and may even continue to expand while other tissues shrink. Whenever a plant is full of water and both water loss and water gain are small, the cells remain fully distended and little diurnal variation in size of the stem can occur except for expansion resulting from growth. Likewise, under conditions of severe water deficit, as may occur during an extended drought, little variation in stem size can occur. Cell water content is depleted, little water enters the roots because the soil is dry, and the loss of water by transpiration is low because there is little water to evaporate. Neither expansion nor contraction of the stem is

possible. However, if rain replenishes soil moisture, water moves rapidly into the roots, and there is rapid expansion of the tissues within the tree (see day 7/19 in Fig. 2.12).

Under environmental conditions favorable to both rapid water absorption and rapid water loss, changes in stem size can be used to infer hydrostatic conditions within the tree. For example, the relative rate of transpiration can be deduced from the changes in stem size during the day (see Chapter 3, Figs. 3.14 and 3.15). During the morning the dendrograph traces in Fig. 2.12 record declining stem sizes when the rate of water loss from leaves is accelerating rapidly. However, continued transpiration during the day leads to increasing water deficits which cause increased absorption of water by roots, so that a unit change in stem volume in the afternoon represents a somewhat larger amount of transpiration than it does in the morning. Midday cloud cover and showers may markedly reduce the rate of water loss, shrinkage may diminish, and expansion of the stem may begin (see Fig. 2.12, days 7/8, 7/9, and 7/24). Conversely subsequent clearing weather may enhance evaporation, increase the rate of water loss, and cause the rate of shrinkage to increase again. As evening approaches, the rate of water loss diminishes until it equals water gain, at which time shrinkage ceases. Subsequent reduction in the rate of water loss or increase in water gain causes cell volumes to increase, and swelling begins. This swelling of the stem is rapid early in the evening when water content of tissue in the stem is low and moisture gradients throughout the plant are steep. As water uptake continues during the night and cells become more distended, moisture gradients within the plant diminish and the rate of swelling declines (Fig. 2.12). Usually shrinkage begins on the next day at sunrise before cells are fully distended and before the stem reaches potential maximum size.

The combination of temporary reduction of water loss and rehydration of cells during the afternoon cloudy weather so common in summer may in itself favor continuation of growth, which in turn could lead to the formation of a wider ring.

Since the stem radius measured by a dendrograph includes the bark, the cambium, and a few centimeters into the wood, the record of changes in stem size (Fig. 2.13) includes the net effect of moisture changes in the outer bark, mature phloem, and mature xylem, as well as growth resulting from cell division in the cambial region. If the mature tissues are shrinking faster than the growing tissues are expanding, it is possible that a net decrease in stem size can be obtained at a time when the cambium is active. However, if such progressive shrinkage has not set in, the changes in the maximum stem size from one day to the next can be used as an
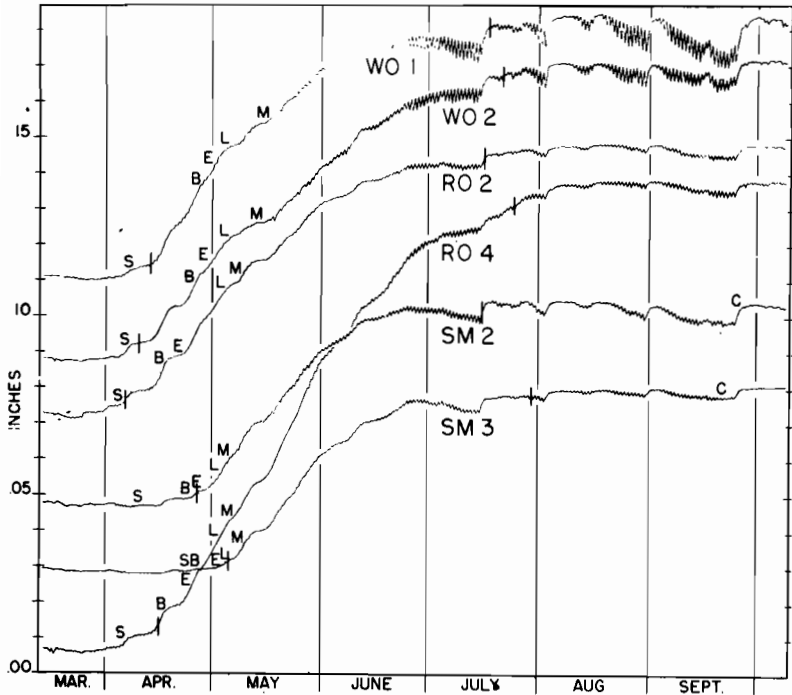
FIG. 2.13. Daily maximum and minimum size of tree stems recorded by dendrographs show cumulative growth. Both *Quercus alba*, white oak (WO 1 and 2), and *Q. rubra*, red oak (RO2 and 4), began growth during early or mid-April following swelling of the buds (S). The vertical bar on the left delineates 5% of the total season's growth. Several periods of rapid swelling, especially marked in mid-April, may be noted as buds opened (B) and as the leaves began to expand (E). Leaves expanded to ½ their full size (L) and matured (M) more rapidly in *Q. rubra* than in *Q. alba. Acer saccharum*, sugar maple (SM2 and 3), started growth at the end of April and reached peak rates of stem expansion after leaves reached maturity early in May. Coincident changes in the rate of stem expansion in the six trees during May are associated with variations in temperature. As soil moisture declined and air temperatures rose in June, daytime water loss exceeded water uptake, and diurnal shrinkage and swelling occurred. The rate of stem expansion in June was proportional to the amount of moisture in the soil of the site (RO 4>RO 2; WO 2>WO 1; SM 3>SM 2). Although 95% of the growth was not completed until July (vertical bar in middle), a pronounced reduction in growth occurred earliest in *Acer* and latest in the moist site *Q. rubra* (RO 4). Several drying cycles during July through September enhanced diurnal variations in stem size and initiated shrinkage in the stems. Each drying cycle was terminated by cloudy weather and replenishment of soil moisture, which resulted in expansion of all measured radii. At the end of September, leaf coloration commenced in *Acer* (C), abscission of leaves occurred, and diurnal variations in stem size were reduced. The leaves of the *Quercus* began to change color at about the same time, but they did not abscise as rapidly from the tree.

index of daily growth (Fig. 2.13; Fritts, 1962b), though the measurements may include some increases in size by tissues other than those of the ring. In spite of this limitation, these indices of daily growth provide useful data for statistical analysis of factors affecting growth (Fritts 1958, 1959, 1960, 1962c, 1969). Plots of such data (Figs. 2.13 and 2.14) can also be used to infer when water relations and other factors are most favorable to cell expansion, when and how fast cell enlargement proceeds, and, indirectly, how rapidly cell division occurs.
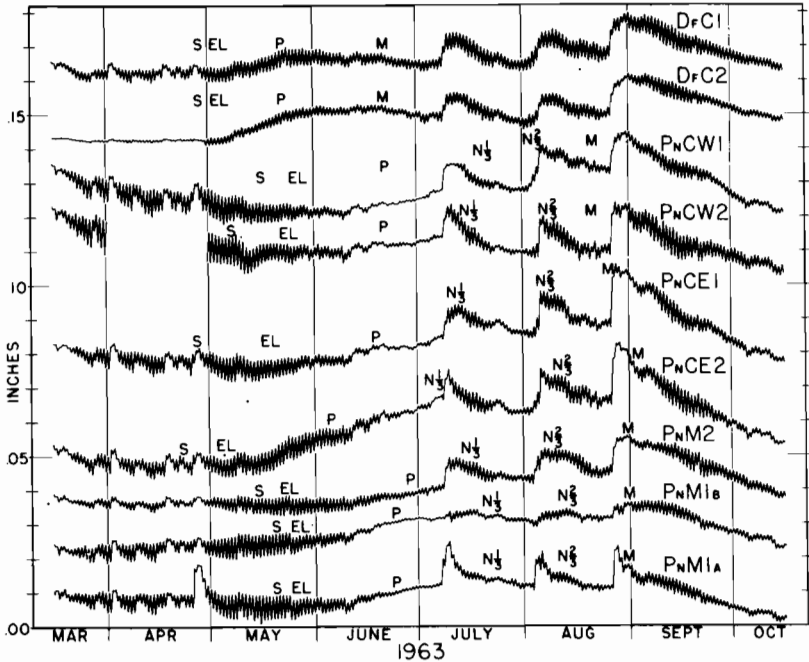
FIG. 2.14. Daily maximum and minimum size in the radii of mature tree stems which show diurnal and seasonal variations for 1963. Trees are on semiarid sites in Mesa Verde National Park, Colorado. Stems swell during moist periods and shrink during periods of drought. Shrinkage in dry years may exceed the total annual increment of growth. Df— Douglass fir, *Pseudotsuga menziesii*; Pn—pinyon, *Pinus edulis*; S—bud swelling; EL—bud elongation; P—pollen shed; N 1/3 and 2/3—needles 1/3 and 2/3 of mature size; M—needles mature size. The letters on the right designate different sites: C—canyon bottom, W—west-facing slope, E—east-facing slope, M—mesa-top. For details and/or similar plots during 1962, see Fritts *et al.*, 1965c.

D

Some trees, especially those which are slow-growing and subject to frequent and severe drought, exhibit diurnal variations in stem size induced by hydrostatic conditions within the tree which can mask the changes in stem size due to cambial activity (Fig. 2.14). Dendrograph or dendrometer measurements from such trees must be supplemented by other growth measurements if the exact period and rates of cambial activity are to be ascertained (Fritts *et al.*, 1965c).

C. Seasonal Periodicities in Radial Growth

It is apparent from many observations, including dendrograph measurements, that significant variations in stem size occur throughout the 24-hour day. When the daily stem sizes are plotted throughout the season, longer-term variations also appear (Figs. 2.13, 2.14, and 2.15). Such seasonal periodicities in radial growth may involve (1) differences in time between the initiation of cambial activity and its cessation, that is, the length of the growing season; (2) differences in the rates of cell division and cell enlargement leading to various rates of increase in stem girth, and (3) differences in size and structure of cells that become a part of the annual ring.

1. Length of the Growing Season

In general, cambial growth begins about the same time as in other meristems, but it may remain active later in the season than shoot growth. The period of cambial activity varies from one year to the next, as a function of differences in the yearly climates, differences in the environment from one site to the next, and differences in species (Ladefoged, 1952). Radial growth in trees of temperate climates may start in April, May, or June and cease in August or September. The growing season for broad-leaved trees usually lasts from two to more than three months. For some trees at high latitudes or high elevation sites it can be as short as four to six weeks. For other trees on warm, moist, and low latitude sites it can continue for a period as long as six months and in some cases for longer periods of time.

Conifers in temperate and moist environments generally have a longer period of cambial activity than broad-leaved trees in the same environments. The period of cambial activity in both types of trees tends to be longer for young than for old trees, and longer in tropical climates than in temperate climates.

The duration of cambial activity for conifers on arid or cold sites is generally less than for conifers in more optimum habitats. Fritts (1969) reports that ring growth in high elevation drought-subjected *Pinus*
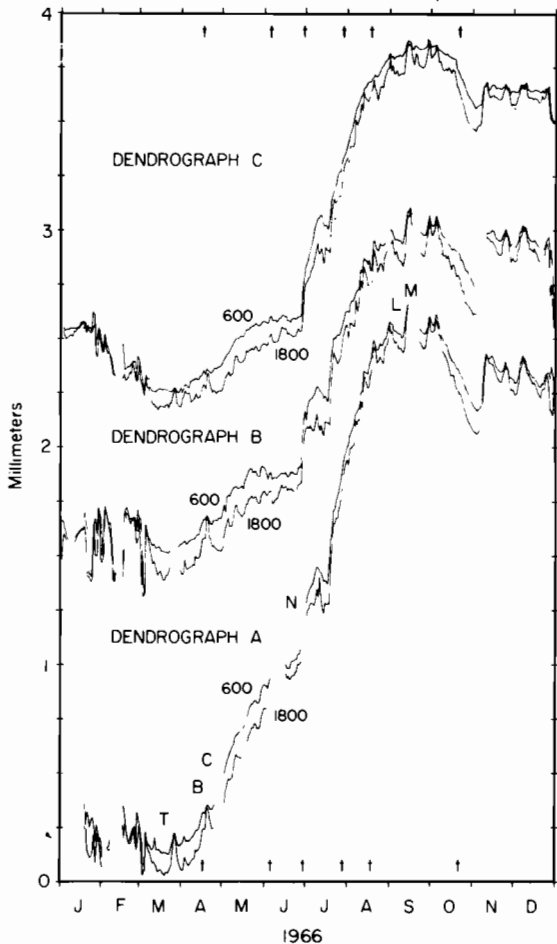
FIG. 2.15. The stem size measured by dendrographs each day at 6.00 a.m. (0600) and 6.00 p.m. (1800), 1966, at the base (A), middle (B), and upper (C) positions in the main stem of an arid-site *Pinus ponderosa* in southern Arizona. T—apical buds swelling; B—buds opening; C—cambial activity initiated; N—needles emerge; L—latewood cells lignified; M—needles reach mature size. The symbol *t* marks the days when the tree was enclosed in a plastic tent to obtain physiological measurements. See Chapters 3 and 4, and Figs. 2.19, 2.20, and 2.23.

longaeva continues for approximately 45 days. Growth cessation occurs even though environmental factors appear favorable. Giddings (1943) and Rees (1929) report that radial growth of tree line *Picea* at high latitudes continues from four to six weeks, while Fraser (1962) and Žumer (1969) report a two- to three-month growing period for the same genus in southern Canada and southeastern Norway near its low-latitude limits.

As stated earlier, growth initiation begins at the shoot apices and proceeds down the stem. However, in suppressed or old trees, especially during years of severe drought, the wave of cambial initiation may not always reach the ground line. In severe cases the initiating stimulus from the shoot apex is so weak that small patches of cambial cells become active beneath only the most vigorous branches. In less extreme cases, growth may be initiated throughout the stem except in localized cambia where the amount of growth is usually the least.

Some authors have reported that cessation of growth occurs first in or near the buds, and progresses basipetally with varying rapidity (Studhalter *et al.*, 1963). A larger number of workers report that cessation occurs first near the stem base, often in patches of cambia that are far removed from vigorous branches and roots. Acropetal growth cessation appears to occur in environmentally limited or forest-grown conifers such as *Pinus ponderosa* (Fritts *et al.*, 1965a; Budelsky, 1969). The basipetal migration of growth initiation and the acropetal migration of growth cessation helps to account for the observation that rings are generally narrowest in the lower *bole* (main stem) of the tree, where the growing season would be shortest. However, differences in growth rates do occur between the bole and top, and these differences are probably more important in causing differences in ring width than the growing season length (Skene, 1972).

Kozlowski and Peterson (1962) report that young trees continue growth throughout the stem, but many large dominant trees stop growing at the stem base during midseason while continuing to grow higher up in the stem. They also report a greater difference in duration of growth between upper and lower stem heights of dominant trees than for trees not included in the dominant class. Radial growth may cease sooner in suppressed trees with small crowns entirely below the forest canopy than in dominant trees with large exposed crowns (Winget and Kozlowski, 1965; Mitscherlich *et al.*, 1966). Trees in unthinned stands frequently have a shorter growing season than trees in thinned stands. The lower branches along the main stem of old trees grow for a shorter time than the young twigs and upper portions of stems.

Pinus edulis, a species widely distributed throughout Mesa Verde, Colorado, and well adapted to the arid environments on the mesa, begins

to increase in stem size early in June. By mid-July the stems, which have been monitored by dendrographs, reach their maximum sizes and then progressive shrinkage of the stems begins (see Fig. 2.14). Samples from the cambium of *Pinus edulis* for 1962 (Fritts *et al.*, 1965c) show that initial swelling and differentiation of the phloem occurs in mid-May, with the first xylem cells being formed during the last week of May. Latewood cells are not evident until early August, several weeks after the stems have begun to decrease in size. By August 9, 1962, all cells had been differentiated and all, except the last-formed row of latewood cells, were lignified.

2. Rate of Increase in Stem Girth

The cumulative curve of radial growth throughout a season is similar in form to the cumulative curve for shoot growth over the life of a plant; it approximates a modified sigmoid curve (Figs. 2.13 and 2.15). The rate of radial growth increases rapidly to a peak near the beginning of the growth period and declines more slowly. The early, short period of increasing growth rate may last from one to several weeks; it is followed by a period of rapid growth which can continue for several weeks. Then the growth rate gradually declines, though the activity of some cambia can continue for a period of several weeks to several months after the period of maximum growth rate (Studhalter *et al.*, 1963).

The increasing size of a stem is rarely a smoothly varying function, however. Growth rates change and there are many variations in the cumulative curves. Short-term variations in growth rates are more apparent when plotted as growth-per-unit-of-time, rather than as a cumulative curve. For example, the cumulative curves of growth reported by Young and Kramer (1952) (Fig. 2.16) appear to be very similar at the stem base and at the top, though at the end of May there is a change that is obvious only in the growth of the stem base. The plots of weekly growth bring out variations from one week to the next. Except for the last of May and the third week of June, the periods of high growth rate at the top of the stem coincide with periods of high growth rate at the stem base. Measurements were also obtained at two intermediate stem heights and on trees with reduced amounts of foliage. Young and Kramer (1952) noted that when growth at one stem location either increased or decreased from that of the previous week, the growth usually changed in like manner at other stem locations and in trees in different crown classes. Many of these coincident changes were attributed to variations in environmental factors which influenced the water content of the trees.

As shown by the plots in Fig. 2.16, growth late in the season is often more rapid in the upper portions of the stem than in the lower portions.
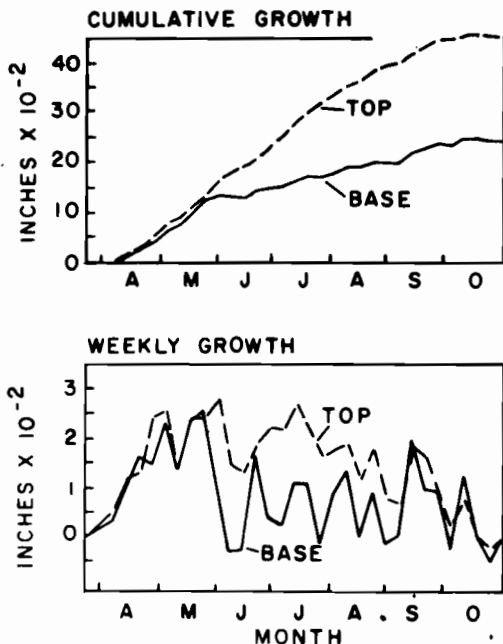
FIG. 2.16. Cumulative growth and weekly rates of growth as shown by stem diameter changes during the 1947 growing season at the base (4·5 ft = 1·37 m above ground) and at the top (80% total height) as measured by growth bands on *Pinus taeda*. The crowns of the trees occupied approximately 50% of the stems' height. (Redrawn from Young and Kramer, 1952)

The growth of young trees or of the younger tissues of the main stem frequently exhibits higher growth rates than older tissues and trees. Resumption of growth after a midsummer cessation is more likely to occur in young twigs than in the bole of the tree. Some variability in radial growth rate arises from strictly genetic differences among the trees.

Certain ring-porous trees, such as some species in the genus *Quercus*, exhibit two maxima in the rate of stem enlargement, one maximum occurring at the time of bud break and the other occurring after the leaves have enlarged to their full size (Fig. 2.17). Many trees representing diffuse-porous species growing under the same environmental regime show only one peak in growth rate coincident with the second maximum in *Quercus* (Fig. 2.18). Phipps (1961) attributes the first surge in stem growth in ring-porous trees to rapid enlargement of vessels formed before cambial activity begins.

Fritts (1960) could not attribute the reduction in rate of stem enlargement between the first and second growth maxima in *Quercus alba* and *Q. rubra* to any change in the external environment. He noted that the first peak in growth was correlated with other phenological changes such as bud break and leaf growth, and that the total increase in size during the first growth peak was comparable to the full width of earlywood in *Quercus alba* and to two-thirds of the earlywood in *Q. rubra*. This suggests that the period of reduced growth rate may be governed by internal conditions, perhaps associated with the transition from expansion of preformed earlywood to cambial activity and differentiation of latewood.
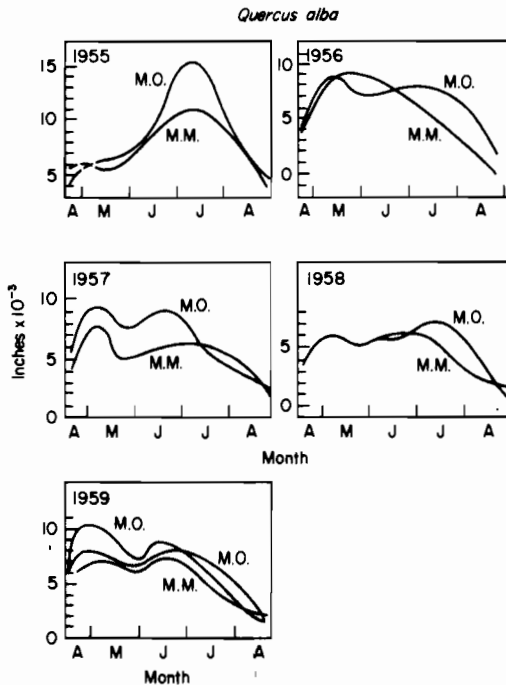
FIG. 2.17. Seasonal variability in the amount of stem enlargement per week, as measured by dendrometers on *Quercus alba* (a ring-porous species) growing in different plant communities in southern Ohio. MO—mixed oak; MM—mixed mesophytic. Five-week moving averages were calculated and the resulting smoothed curves were fitted to data points. (Redrawn from Phipps, 1961)

Data published by Kozlowski *et al.* (1962) show two periods of rapid growth in *Quercus ellipsoidalis* which correlated with two periods of precipitation. They did not recognize any indigenous rhythm in their trees. Zasada and Zahner (1969) report a continuous rate of cell enlargement in the xylem layer of *Quercus* throughout the period in which the reduced growth rate is supposed to occur. Their work suggests that the apparent bimodal peaks in growth cannot be attributed to xylem differentiation and suggest the possibility that the first peak in growth arises from rapid differentiation of phloem at the beginning of the growing season and not from xylem growth.
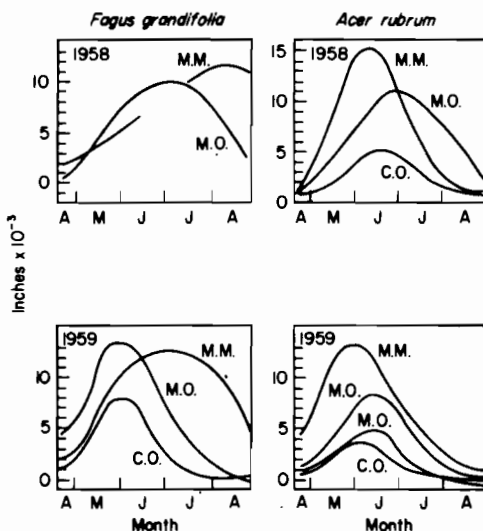
FIG. 2.18. Seasonal variability in the amount of stem enlargement per week, as measured by dendrometers on two diffuse-porous species in three plant communities in southern Ohio. MO—mixed oak, MM—mixed mesophytic, CO—chestnut oak. Five-week moving averages were calculated and the smoothed curves were fitted to data points. (Redrawn from Phipps, 1961)

Many of the fluctuations in growth rate during the year can be explained by variations in limiting factors of the environment. For example, low temperatures may become limiting to cell division or may affect other growth-controlling processes. Cold soils may restrict water uptake by the roots, thus retarding the hydration phase of growth. When

soil moisture is low or when it is extremely high (causing low soil oxygen), the absorption of water by the roots may be low and growth may be reduced. High air temperature, high wind, high solar radiation, and low humidity are among the many factors which can enhance water loss, cause water deficits to occur, and thereby limit growth. And whereas clear weather followed by rain and cloudy conditions can favor increased hydration and induce swelling of tree stems, prolonged cloudy weather can cause the growth rate to decline by reducing photosynthesis and influencing the production of growth regulators in leaves. When clearing weather follows cloudy weather, there can be an increase in water loss and reduction in water content of the stem. This may reduce the rate of stem enlargement (Fritts, 1958) and can cause shrinkage to occur in the stem until high photosynthetic activity is resumed and increases the substances available for growth. A thorough discussion of environmental factors, particularly those affecting water relations and food-making processes, is presented in Chapters 3, 4, and 5.

Variations in rates of growth may arise from a variety of interactions within the tree. Reinitiation of apical growth or an increase in activity of the apical meristems may induce resurgence of radial growth in the twig and occasionally some growth resumption in the older portions of the stem. Defoliation, fire, pruning, or other mutilation of the crown can cause growth to increase, to decrease, or to stop entirely. Any injury to living tissue due to factors such as frost, lightning, or extracting a core from the stem, will produce wound tissue which, in turn, may induce anomalously high or low growth in the area surrounding the wound.

Phipps (1961, 1967) reports that the data shown in Fig. 2.17 were collected from dendrometers mounted on the tree stem in the spring of 1955. Anomalously high growth was noted in the second growth peak for 1955 but not the first, while in 1956 the first growth peak was higher than the second. These observations were offered as evidence that the earlywood cells were cut off from the cambium prior to insertion of the dendrometers. Since the cells of the earlywood were produced in the autumn, the wounding due to insertion of the dendrometer screws affected only the latewood of the same year and then the earlywood of the next.

Localized injury can result from the feeding activity of forest animals, the impact from falling limbs and rocks, and a variety of miscellaneous damaging events. A certain amount of the statistical error in tree-ring analysis is due to localized damage or effects of this sort. For more detailed reviews of the voluminous literature on radial growth rates, the reader may refer to Glock (1955), Bannan (1955), Studhalter et al. (1963), Agerter and Glock (1965), and Kozlowski (1971a and b).
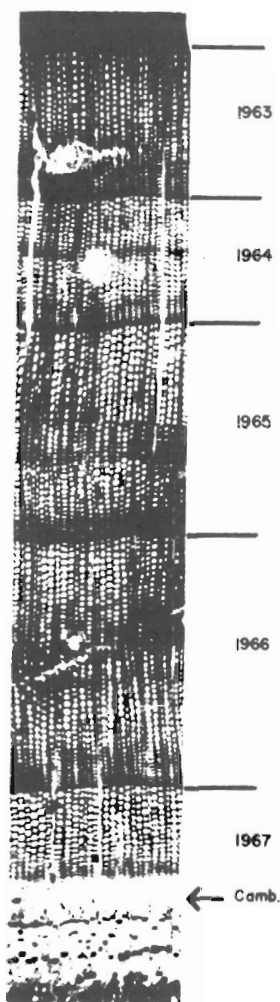
FIG. 2.19. The variability in cell size as shown in five annual rings from the base of a 110-year-old *Pinus ponderosa* growing in southern Arizona on a semiarid site at an elevation of 8,500 ft (2591 m). The photograph shows rings along a cross section of the stem sampled on August 8, 1967. A number of enlarged, but as yet unlignified, tracheids lie inside the cambium and outside the small diameter lignified cells that have already matured in the 1967 ring.
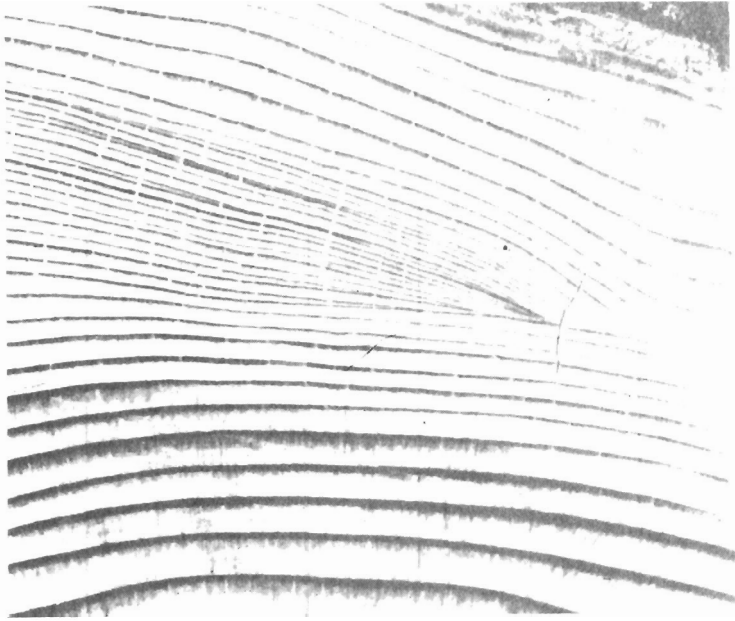
FIG. 2.28. A cross section from a coniferous stem with 18 growth rings absent on the right side of the photograph but present on the left. (Photo by James Harsha)

by neighboring trees, and the sheath is about the same width throughout the lower stem. As the tree ages some of the lower limbs may die, others become more shaded, and a zone of maximum ring width occurs near the crown base especially near those branches bearing the most foliage.

If the plantation is thinned and neighboring trees are removed, the rings will thicken, especially in the lower part of the stem, while in the crown the thickness may remain relatively unchanged. The ring width may increase from the stem apex to the stem base. As the canopy closes during subsequent years, shading of the lower branches increases and the xylem sheath resumes its normal form with maximum thickness near the area of maximum foliage and at the stem base.

As many conifers increase in age, there is an increase in specific gravity of the wood, an increase in the percentage of latewood, and a decrease or no change in the density of earlywood. The slow-growing, more suppressed trees exhibit a greater change in percentage of latewood from the center of the stem to the outermost ring, than fast-growing and dominant trees (Kramer and Kozlowski, 1960). However, Larson (1957)

3. Variations in Cell Enlargement and Cell Differentiation

Variations in cell enlargement and differentiation occur throughout the growing season and give rise to variability in the cell structure and the general appearance of annual rings. At the beginning of the growing season, conifers form large-diameter tracheids with thin walls. As physiological conditions change within the plant and the surrounding environment becomes generally warmer and drier, the diameters of tracheids begin to diminish and the walls thicken. Usually, the smallest tracheids with the thickest walls are those formed at the end of the growing season along the outer margin of the ring (Figs. 2.3, 2.19, and 2.20).

The diameter and the location of the largest earlywood cells may vary from ring to ring (Fritts, 1969). Frequently, there is an increase in diameter along the *radial file* (or tier) of the first few rows of earlywood cells. Then a gradual reduction in tracheid diameters occurs throughout the remaining portion of the annual ring (Fig. 2.20). In ring-porous angiosperms the large earlywood vessels are differentiated early in the season and mature quickly, often prior to full expansion of the new leaves. Small vessels and thick-walled fibers are formed throughout the remaining portions of the growing season (Fig. 2.5b).

The large-diameter tracheids found in the rings of coniferous species are associated with periods of optimum soil moisture, favorable temperatures, rapid shoot and root growth, and a high rate of physiological activity within the tree (Zahner, 1968). Larson (1960, 1962) emphasizes the importance of rapid stem elongation and needle growth to the formation of large earlywood-type cells. As the activity of the apical bud and elongating needles declines and the amount of soil moisture diminishes, the size of mature, differentiated tracheids declines. This decrease in size of cells may be noted first in the lowest levels of the stem and last in the one-year-old twig. In older stems an increase in wall thickness normally accompanies the decrease in cell diameter, while in young stems which are close to the stem apex, the walls of tracheids in the latewood frequently remain thin. The initiation of wall thickening commonly occurs subsequent to cessation of stem elongation, sometimes preceding and sometimes following the decrease in cell diameter (Larson, 1964).

Replenishment of soil moisture or the reduction in water stress may be accompanied by a resurgence of shoot and radial growth, causing the unlignified tracheids to expand to the larger earlywood size. This increase in size of maturing cells can produce a band of earlywood between layers of latewood, forming a false ring as has been shown in Figs. 1.7 and 2.3. The resumption in growth usually occurs first in the one-year-old twigs or
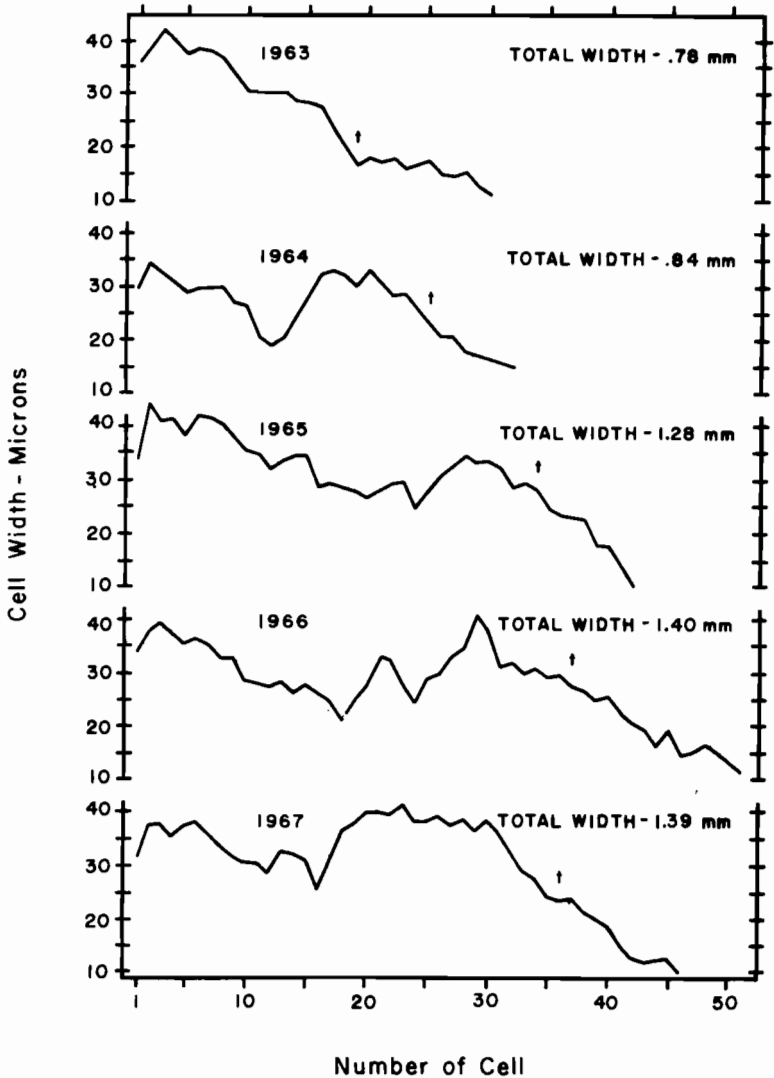
FIG. 2.20. A plot of average diameters of cells from five radial files in each of five annual rings shown in Fig. 2.19. Tracheid widths are plotted against cell number in the radial file. The letter t indicates the first cell with a thickened wall marking the late-season change from the thin-walled earlywood to the thick-walled latewood. Small cells occurring before t form intra-annual bands of latewood associated with drought in June.

in the uppermost portion of the stem, and a wave of increased expansion of tracheid diameter progresses down the stem of the tree. The wave may travel to the base of the stem or stop part way down if less favorable environmental conditions return and activity of the shoots declines. Since the resumption in formation of earlywood-like cells within the zone of latewood is closely associated with flushes in shoot growth, false rings are most typically found in small branches and twigs, in the stem portions near large, vigorous branches, and in young fast-growing trees. As the end of the season nears and activity of the shoots diminishes, the mature size of tracheids diminishes, cell walls thicken throughout the stem, and growth cessation progresses acropetally up the stem.

Budelsky (1969) noted that the sizes of mature tracheids in *Pinus ponderosa* were reduced and walls were thickened in the upper bole during a dry period in June, while no marked changes in the tracheid size and wall thickness occurred in the lower bole. Similarly, Fritts *et al.* (1965a) found that in the outer portions of a stem from an old tree, there is a greater tendency for intra-annual bands to be formed in the upper bole than in the lower bole, and they occur most commonly in the latewood portions of the ring. In a young stem, however, intra-annual latewood bands occur more frequently in the earlywood than in the latewood.

The annual rings of conifers which grow in an area with a long frost-free season and in an environment which may alternate between favorable and unfavorable conditions, such as moist winter, dry spring, and wet summer, are particularly likely to exhibit one to several intra-annual bands of latewood (Glock *et al.*, 1960; Glock and Agerter, 1962). In extreme cases, complete growth cessation may occur before the onset of the second period favorable to growth. For arid sites summer rains usually initiate the second growth flush, and if they are ample and early enough, a resurgence of growth may occur throughout the stem with the formation of wide tracheids next to very narrow ones, and thus more than one distinct ring is formed in a single growing season. The cambium, however, usually is not dormant in all radii of the same tree or in all trees, so that some growth layers formed in the same year have a recognizable growth band within a larger obvious annual ring. Crossdating among trees allows recognition of such circumstances so that the growth layers are placed in the appropriate growing year.

There is an increasing number of studies of tropical woods in which a variety of techniques has been used to ascertain the seasonal behavior of the cambium and the nature of the growth layers (Chowdhury, 1940; Mariaux, 1967). Some species are reported to produce distinct annual layers so that the rings can be counted to determine tree age. As yet there has been no definitive study demonstrating crossdating in tropical

species. Much work is needed on species which do have distinct annual rings as to possible relationships between ring characteristics and variations in climate. It is hoped that botanical surveys in the tropics will utilize dendrochronological techniques as well as densitometry, dendrometry, and anatomical analysis to help find species which offer potential for dendroclimatic work.

4. Variations in Cells within Ring. of Pinus ponderosa

Figures 2.19 and 2.20 show the variability in width of tracheids in five annual rings of an arid-site *Pinus ponderosa*, growing under the biseasonal precipitation regime in southern Arizona. The growth of several trees was monitored from 1963 through 1967, and the climatic regimes for the particular growing seasons are shown in Fig. 2.21. The tree which was sampled bore three recording dendrographs mounted at different levels on the stem (see Figs. 2.11 and 2.12). Cambial activity was assessed by periodic sampling of the cambial tissue, and measurements or observations on the development of buds, needles, and fruiting structures were obtained and used to characterize the *phenology* (the changing appearance of the tree during its yearly cycle including bud growth, needle development, flowering, fruiting, and cambial activity).

The environmental regime and factors of climate were monitored during the five years by means of a thermograph, a rain gauge, and soil moisture sensors which were buried in the soil around the roots of the tree (Fig. 2.21). Information on environment and growth was collected most systematically and frequently during the 1966 and 1967 seasons (Fig. 2.15) and, as a result, the changes in growth and the tree's environment are defined most precisely at that time. The climate and environmental occurrences, the general phenology, and growth of the tree and its effect on cell structure are described in the following pages.

(a) Environment and Growth of 1963. The environmental regime of the spring of 1963 (not shown in Fig. 2.21) was dry, and only 0·04 inches (1 mm) of rain fell during May and June. However, little rain falls in Arizona during this time. Dry conditions persisted throughout most of July (Fig. 2.21), as rains were sparse throughout the desert region and amounted to only 2·86 inches (72·6 mm) of moisture on the particular tree site. Heavy rains in August added 8·70 inches (221·0 mm) of water and replenished soil moisture, which was then plentiful through the remainder of the growing season.

Shoot growth was rapid in May but decreased with the greater water stress in June, and little growth occurred in July because rains were light. Some resurgence of growth was measured in August associated with the onset of heavier rains.
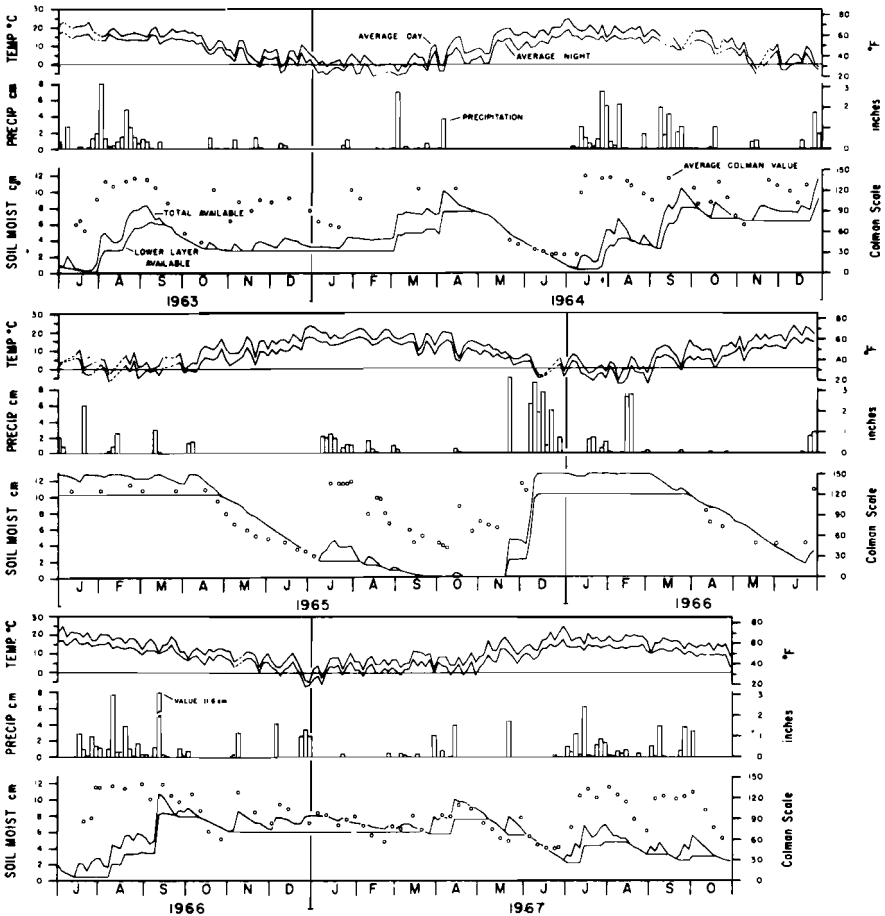
FIG. 2.21. Environmental regimes during the five years which included the seasons of growth for the rings shown in Fig. 2.20. Air temperature, precipitation, and soil moisture were measured by means of a thermograph, rain gauge, and Colman soil moisture meter. Total available and lower layer soil moisture were calculated using a soil moisture accounting scheme.

The first rows of tracheids formed in the ring averaged 40 microns along their radial dimension, but the size of successively formed cells declined (Fig. 2.20). This decrease in cell size correlates with the diminishing water supply of June. Cells in row 19 of Fig. 2.20 mark the beginning of latewood, and their thicknesses in the radial dimension average 17 microns. The period of latewood formation appears to

correspond roughly with the onset of heavier summer rains. The moderate resurgence in shoot growth did not result in any increase in tracheid size at the base of the stem, but the period of cambial activity appeared to be extended so the percentage of latewood in the particular ring was greater than for rings formed during the other years. However, in the upper portions of the stem and in a nearby young tree resurgence of radial growth occurred, and enlarged thin-walled cells were formed in the outer portion of the ring.

(b) *Environment and Growth of 1964*. Soil moisture during the autumn and winter of 1963 and the spring of 1964 was the lowest of the five years studied. Above-average temperatures and a total lack of rain in May and June resulted in extreme water stress within the trees. Heavy rains started in mid-July and totaled 7·36 inches (186·9 mm) by the end of the month.

The radial diameter of the first 10 rows of tracheids (which would reflect early season growth when shoots were elongating rapidly) ranged from 25 to 35 microns. Their average sizes were less than those formed in the other four years reported here. The sizes of cells at rows 11 and 13 were only 19 to 20 microns wide and formed an intra-annual latewood band which correlates with the severe June drought. Rows 14 through 16 included larger cells associated with the period of improved hydration due to the July rains. The radial dimensions of all cells formed at that time increased to a maximum diameter of 33 microns. After row 20, the radial cell size began to decline again, and the first true latewood cells with heavy walls occurred in row 25 and are 24 microns wide.

It appears that the large earlywood cells formed after row 15 represent the response of the tree to the summer rains in mid-July. In this case more than half the ring width (the first 15 cells) was formed under the influence of moisture stored in the soil from the prior winter and spring rains. As would be expected, the change in cell size in the upper portions of the tree stem was more marked than the changes observed at the base of the tree, and very small cells produced during the June drought formed an even more distinct intra-annual latewood band.

(c) *Environment and Growth of 1965*. The precipitation of the winter of 1964 was moderate, and by January the soil moisture was completely recharged. However, soils again began to dry during a rainless May and June. July brought a moderate 3·92 inches (99·6 mm) of precipitation, while only 1·61 inches (40·9 mm) fell in August, making this the driest August of the five years.

Both radial growth and shoot growth were rapid from May through August, and even though the tracheids produced in June were somewhat smaller than those formed earlier, the activity of the cambium remained relatively high.

As a result, cells are wide, exceeding 40 microns at first, and then they are narrower with row 24 exhibiting the narrowest earlywood cells averaging 24 microns wide. These appear to have been formed early in July before the rains. Cells formed after row 24 are associated with the mid-July rains and they increase in size up to row 28. Latewood cells averaging 28 microns wide appear in row 34. Low moisture in August limited the growth rate, and cell diameters declined more rapidly across the latewood than in any other ring. The average diameter of the last-formed latewood cells in row 42 is less than 10 microns. The ring produced in one of the upper branches of a tree contained a distinct and marked cell size change representing a false ring. This suggests that more stressful conditions were present in the upper portions of the stem.

(d) Environment and Growth of 1966. The autumn of 1965 was dry, the winter was wet and cold, and the spring of 1966 was warm, with less than average precipitation. However, 1·98 inches (50·3 mm) of rainfall replenished soil moisture for a short period near the end of June. Drier conditions returned briefly in July, and heavy rains started on July 19; by the end of September over 16 inches (406·4 mm) of moisture had fallen since the beginning of summer rains. As would be expected, intra-annual latewood bands were formed in some of the trees during this growing season (Figs. 2.20 and 2.22)

The first radial growth on the monitored tree was measured in April, but the increase in stem size was slow (Figs. 2.12 and 2.15). In May the most rapid growth occurred, followed by drier conditions in June which caused a slight reduction in the rate of both shoot and radial growth. A temporary and limited resurgence of growth was measured in this tree during the brief moist interval of late June and early July (Figs. 2.12 and 2.15). The rainy season began on July 19 and the growth rate increased. Needle elongation ceased early in September, but some radial growth occurred until late September or early October.

A decrease in cell diameter is apparent up to cells in row 18 (Fig. 2.20), at which point diameters averaged 21 microns. Cell rows 19 through 21 are associated with temporary rehydration in late June and exhibit an increase in maximum size, while the smaller cells which follow in rows 22 through 24 reach a minimum diameter of 24 microns and reflect the declining soil moisture. Cells in rows 25 through 29 exhibit a second increase in maximum size which is associated with the onset of the summer rains on July 19. Rings observed in the branches of the tree show the same two distinct alternating layers of small and large diameter cells that were observed at the base of the tree. The remaining cells in rows 30 through 51, shown in Figs. 2.19 and 2.20, exhibit a gradual reduction in mature tracheid size, although soil moisture in August and September

remained high. Latewood began to form with cells in row 37 with diameters averaging 28 microns. Another tree measured by Budelsky (1969) exhibited only one band of narrow latewood cells (Fig. 2.22), and it was best developed in the upper portions of the stem.
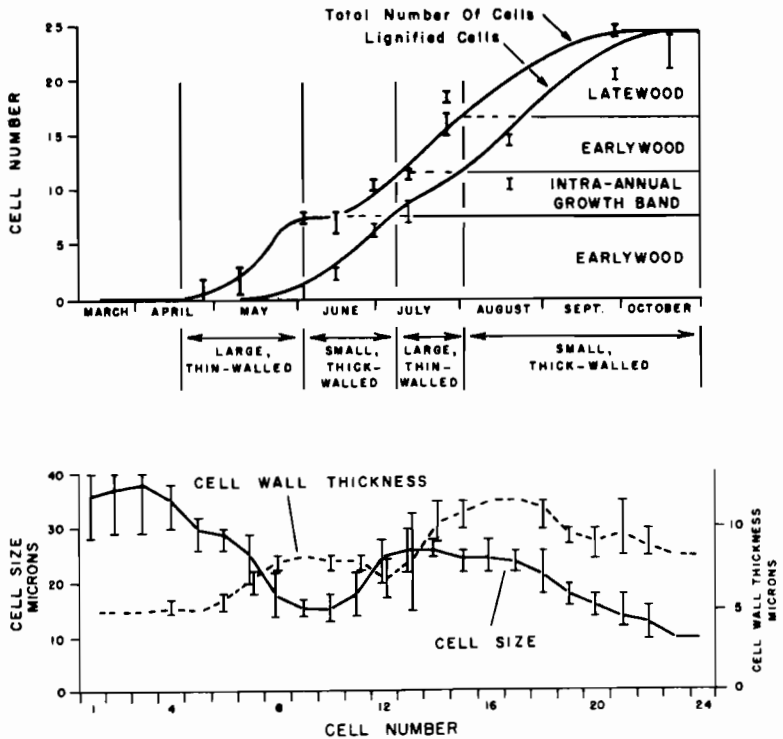
FIG. 2.22. Numbers and wall thickness of cells that were differentiated during the growing season of 1966 in the upper stem of a *Pinus ponderosa* in southern Arizona. A dry period in June (Fig. 2.21) reduced cell size and caused wall thickening which formed a latewood band within the earlywood portion of the ring. The number of tracheids was estimated from cambial samples harvested throughout the growing season. The size of the cells in a radial direction and wall thickness were measured along four radii of the stem sampled during the following spring. Brackets show the range of individual measurements. (Redrawn from Budelsky, 1969)

(e) Environment and Growth of 1967. Ample soil moisture was available during the winter of 1966 and was further sustained by precipitation during March, April, and May in the amounts of 1·57, 1·97, and 1·78 inches (39·9, 50·0, 45·2 mm), respectively. April, May, and June were unusually cool, and light rains fell in late June. Heavy rains started early in July, and by the end of the month 6·76 inches (172 mm) of moisture had fallen.

Shoot and radial growth were initiated during April, but early growth was slow during the cool weather, and mature xylem cells were not evident until June. With somewhat drier conditions in June, the rate of shoot growth declined, although cambial activity appeared unchanged. The rate of shoot growth increased in July but declined again in late August and September.

The first 15 cells of the growth ring for 1967, as shown in Fig. 2.20, reveal less change in cell size than any of the earlywood cells of the four previous rings. Cool and moist conditions maintained slow rates of shoot growth and a favorable water balance in the tree. Xylem cells produced throughout May and June were relatively large, with minimum diameters of 29 and 26 microns in cells of rows 12 and 16. Rows 13 through 15 represent larger diameter cells which were apparently produced during the first light rains of summer. The diameters of cells in rows 17 to 20 exhibit an increase in size, which coincides with the onset of the heavy summer rains. The cells in rows 20 through 30 were formed in late July and early August when moisture was not particularly limiting, and cell diameters averaged 35 to 40 microns. Cells in rows 31 through 46 are associated with declining late summer growth rates and exhibit a gradual reduction in size. Latewood formation with cells averaging 24 microns in diameter starts in row 36. The five outer rows of latewood cells are unusually narrow and produced an especially distinct annual ring boundary.

5. Variations in Cell Sizes and Ring Widths throughout the Length of the Main Stem

It may be noted from the results described in the prior sections that certain features of the latewood in the form of intra-annual growth bands were marked in the upper portions of the tree stem. In order to document this variation in more detail, certain growth rings were examined along 18 cross sections through the main stem of the tree. Four particular rings were selected which portray the kinds of variations that were observed. Fig. 2.23 presents the results as a plot of the ring width at each cross section and as a plot of earlywood and latewood thickness wherever they were observed. Much variability in ring width was observed to occur

throughout the stem. The 1951 ring is the thickest of the four rings, indicating a season of very rapid growth. The intra-annual band of latewood within the earlywood undoubtedly marks those cells forming in the dry period of late June prior to the summer rain. A band of latewood within the earlywood was also formed in 1954, but the rate of cell growth throughout the tree was less, as indicated by the short distance from the beginning of the ring to the first-formed latewood. In 1955 there appeared to be no resumption of rapid growth and no band of earlywood associated with the beginning of summer rains. During 1956 the resumption of growth occurred only in certain stem segments within the lower crown and at the stem base. The data in the figure also support the inference that rings formed in the stem within the lower crown are the
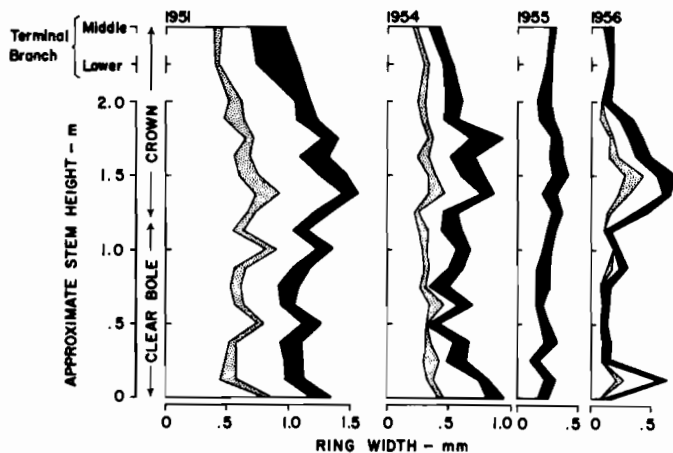
FIG. 2.23. The ring widths and location of latewood within selected growth layers in an arid-site *Pinus ponderosa* that was frequently subjected to water stress prior to the summer rains. Measurements were made along four radii on 18 cross sections cut from the main stem in 1969. The positions of each section are shown in relation to the terminal branch, crown, and clear bole. Heavy shading indicates latewood formed in the normal position along the outer margin of the ring. The light shading represents thick-walled cells forming intra-annual growth bands. The first thick-walled cells are usually formed at about the same time each year and represent the cells that were enlarging and differentiating during the hot, dry weather of June. Earlywood outside these first formed thick-walled cells indicates resumption of rapid growth in July, usually attributed to increased moisture from rains. If the summer rains are late or the growth rate low, the cambium may become dormant and a second layer of earlywood will not form (see 1955). The cells comparable to those formed as intra-annual rings in more moist years become the normal latewood. In other years, the resumption of earlywood formation may occur only in the crown or at the base of the tree so only in these portions of the stem will an intra-annual ring be formed (see 1956). Additional information about the tree and its environment is presented in Figs 2.15, 2.19, and 2.20.

widest and are the ones most likely to show a second earlywood layer resulting from resumption of rapid growth in midsummer. However, the abruptness between the intra-annual latewood and the subsequently formed earlywood is often more marked in the upper portions of the stem.

The details included in the diagram and the discussion of cell size and cell wall thickness show that considerable environmental information may be locked in the cell structure of the annual ring. It is not always information that is easily disentangled from the many complexities of cell growth, but, as new techniques are developed, cell structure producing wood density variations should be more easily and more objectively measured as well as better understood.

VII. Phenology and Its Relation to Ring Growth

It should be noted from the foregoing discussion that certain phenological phenomena such as the swelling, elongation, and opening of buds, the elongation of the stem and needles, maturation of the needles, flowering, and fruiting are often associated with specific stages in cambial activity and certain structural variations in the ring. In fact, observations solely on phenological development can provide much useful information on the timing and behavior of growth processes.

In the case of *Quercus* (Fig. 2.13), a ring-porous species, the first growth is observed at the base of the stem when the buds first begin to swell, and the initial surge of early growth has passed at the time the first-formed leaves are fully expanded. In the case of *Acer saccharum* radial growth does not commence until just before the unfolding of buds and the cambium becomes most active after the leaves attain full size. In *Pseudotsuga menziesii* (Fig. 2.14), the flush of needle growth occurs when the cambium becomes active, pollen is shed several weeks later, and needles reach mature size well before cambial activity ceases. Various arid-site *Pinus* species have slightly different phenological sequences (Figs. 2.14, 2.15). Cambial activity begins at about the time of bud swelling, but a month or more may elapse before the needles emerge from the bud and the pollen cones open. Cell division in the cambium ceases at about the time needles become fully elongated.

Phenological observations can be used to ascertain what limiting conditions are possible. For example, observation of the early rapid growth of *Pseudotsuga menziesii* needles suggests that full photosynthetic capacity of the newly formed foliage is attained sufficiently early in the growing season to influence the food-making potential for that summer and to affect the ring that is forming. In the case of arid-site *Pinus*, however, the needles appear much later and they are not fully formed until near the end of the growing season. Because of this delay, the effect
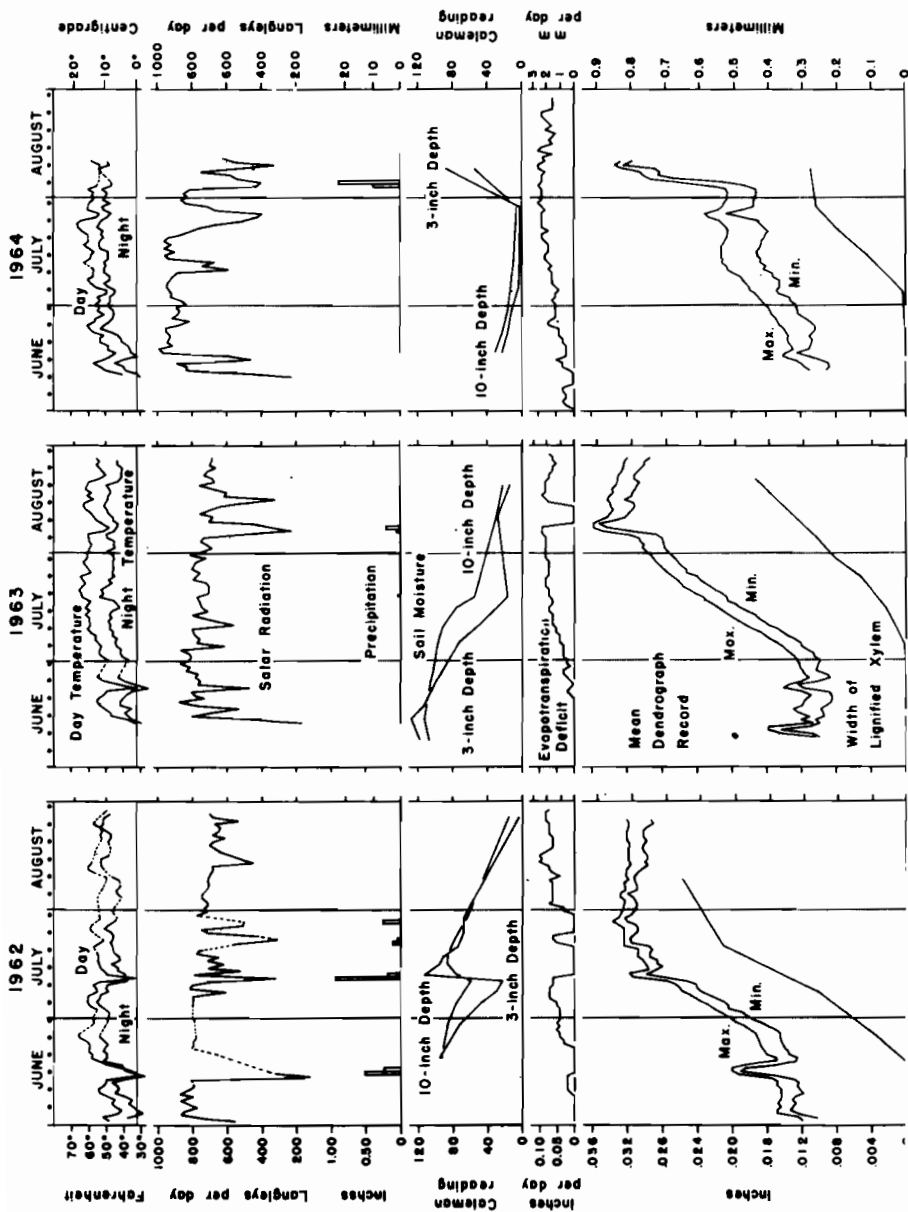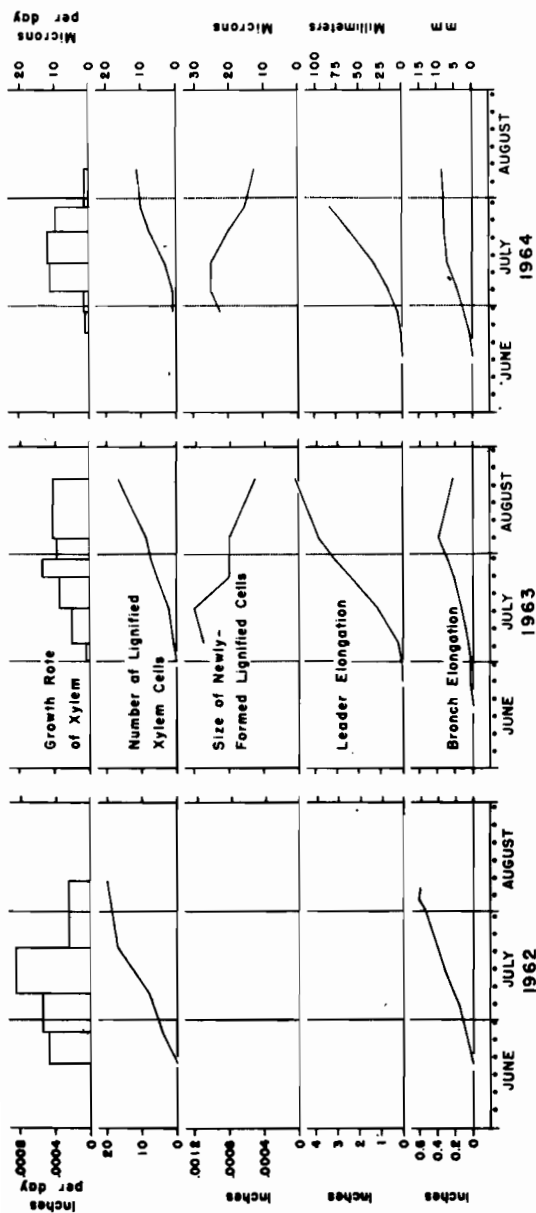
FIG. 2.24. The seasonal march of selected environmental parameters and various measurements of growth in *Pinus longaeva* in the White Mountains of California at an elevation of 10,400 ft (3171 m) for three growing seasons. Environmental parameters are mean day and night temperatures, daily solar radiation, precipitation, soil moisture in Colman units (where 0 is near the wilting point) and calculated evapotranspiration deficit. Growth measurements include stem size as measured by dendrographs, the width of the lignified xylem, the growth rate of xylem, the number of lignified cells in the xylem, the size of the newly formed lignified cells, leader elongation, and branch elongation. (Reprinted by permission from "Bristlecone Pine in the White Mountains of California, Growth and Ring-width Characteristics", Paper of the Laboratory of Tree-Ring Research at the University of Arizona, No. 4, by H. C. Fritts, Tucson: University of Arizona Press, © 1969.)

of climate on ring-width growth is most likely to be transmitted to the next year's ring through the effect on needle length. However, growth regulators produced by the expanding needles can modify cambial activity and cell structure and in this way exert some indirect influence on the character of the currently forming ring.

Fig. 2.24 is an example of the correlation between growth measurements and certain environmental parameters for *Pinus longaeva* (Fritts, 1969) during three growing seasons, while Fig. 2.25 shows the dates of certain phenological stages along with dendrograph measurements. The 1962 season was relatively moist with two major storms, which caused marked swelling in the tree stems. Temperatures in
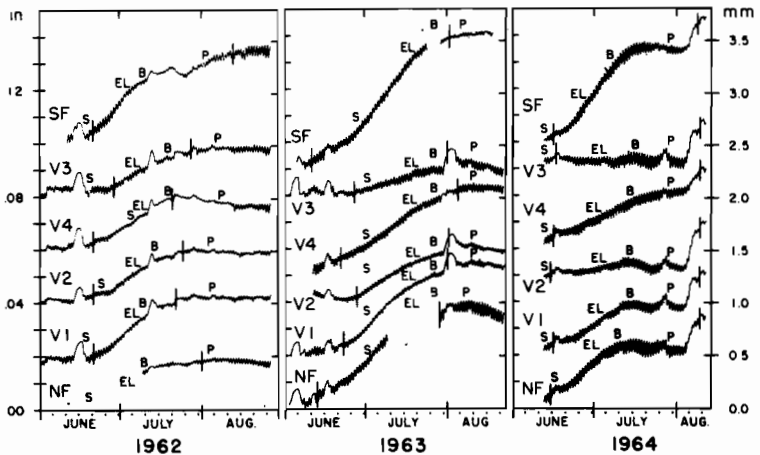
FIG. 2.25. The daily maximum and minimum stem size measured by dendrographs mounted on six *Pinus longaeva* trees during 1962, 1963, and 1964. Phenological changes in each tree are indicated as follows: S—bud swelling; EL—buds elongating; B—buds opening, needles beginning to emerge; and P—pollen shedding. Vertical lines designate time of 5% and 95% of total stem enlargement. Trees V1 through V4 are in the valley floor. The tree SF is on south-facing slope, and the tree NF is on a north-facing slope. The growth for the valley trees is summarized in Fig. 2.24. (Reprinted by permission from "Bristlecone Pine in the White Mountains of California, Growth and Ring-width Characteristics", Paper of the Laboratory of Tree-Ring Research at the University of Arizona, No. 4, by H. C. Fritts, Tucson: University of Arizona Press, © 1969.)

June were warmer than in the following two years; buds began to swell after the June storm, and the first cells of the ring were differentiated. The period of most rapid bud elongation, meristematic activity, and radial growth coincided early in July. Rain and snow in mid-July enhanced cell enlargement, though temperatures were near 0°C (32°F). The buds opened fully near the end of the growing period, and pollen was shed early in August after most of the cambial activity had ceased.

Bud and stem swelling began around the first day of July in 1963. Cell differentiation was observed several days later, but xylem growth reached its maximum rate late in July, while the buds were elongating. Pollination occurred and most growth was complete five or more days after a storm in early August.

The season of 1964 was the driest because of the lack of winter and spring precipitation. Bud swelling and the beginning of growth occurred in mid-June, approximately five days earlier than in 1962, but temperatures dropped shortly thereafter. The most rapid apical growth and cambial activity occurred near the end of June while the buds were elongating. However, stem swelling was slow, apparently as a result of low soil moisture and low temperatures. Pollen was shed two to three days before the end of July, as swelling in the stem and cambial activity diminished. Rain occurred during the first week in August and was accompanied by stem swelling, but not by any additional growth activity. The growing season averaged 45 days for all three seasons, and it ranged from 47 to 56 days for the younger trees and from 35 to 43 days for the older trees (Fritts, 1969).

Phenological development was observed on a variety of *Pinus longaeva* trees at different elevations, exposures, and slopes including those shown in Figs. 2.24 and 2.25 (see Fritts, 1969). Initial bud swelling and cambial activity began at low elevation sites at 9,400 ft (2,866 m) on June 20; at high elevations of 10,900 ft (3,323 m) and on north-facing slopes bud swelling and cambial activity began about 10 or 12 days later. Elongation of the buds began at low elevations on July 8–10, needles emerged from the bud scales on July 28–30, pollen was shed on August 6, and cell division ceased by August 17, but lignification was still in progress. At the high elevations the same phenological stages occurred about eight days later. For additional examples of phenological and tree-growth analysis see Douglas and Erdman (1967), Fritts (1958, 1960), Stokes (1965), and Serre (1973).

VIII. Systematic Variations in the Width and Cell Structure of Annual Rings

The annual growth layers of a tree exhibit systematic changes in width and cell anatomy which arise from the changing anatomy, physiological conditions, and environment of the aging tree. As was shown in Fig. 2.10, a young seedling may grow slowly at first, but as roots penetrate and spread throughout the soil and the crown enlarges, annual shoot growth may increase significantly. The seedling soon becomes a flourishing

sapling in which both the apical meristems and cambia are growing at maximum rates. Eventually, the sapling becomes a maturing tree in which certain physiological and environmental conditions become limiting and the rates of shoot and ring growth decline. As the tree
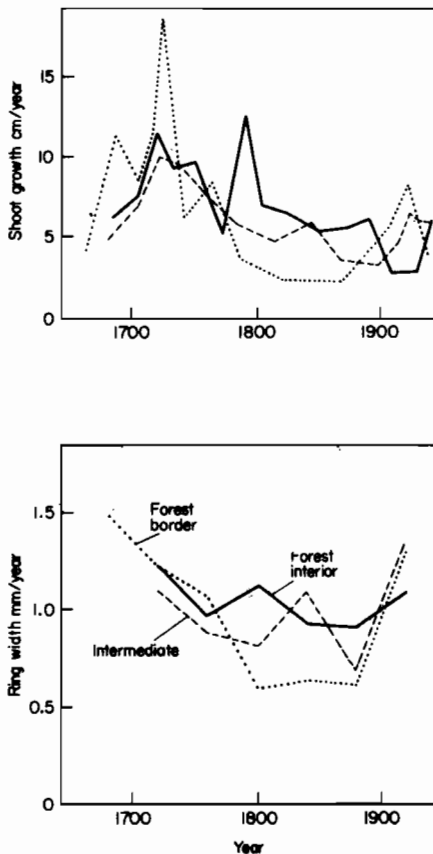
FIG. 2.26. Shoot growth and average ring widths observed on a number of transverse sections from the stems of *Pinus ponderosa* on three different sites near Flagstaff, Arizona. Length of shoot growth is reconstructed by comparing the distance along the stem between sections and the differences in dates of the innermost rings. Ring-width measurements are averages for 40-year intervals of time on all available sections. The forest border tree grew more rapidly than the other trees during the sapling stage, while the forest interior tree grew more rapidly than the other trees when they matured. The forest border and intermediate trees exhibited greater increase in growth rate with change in climate after 1900 than the tree on the forest interior site. (Data from Glock *et al.*, 1963, recompiled and described by Fritts *et al.*, 1965a)

approaches old age, the level of growth stabilizes to about the same rate throughout the main stem of the tree.

The changes in growth associated with increasing age may vary from site to site. Fig. 2.26 shows the changes in rate of shoot growth and average ring width throughout the entire stem of three trees of *Pinus ponderosa* growing in northern Arizona. The data on shoot growth are based upon distances between and ages of cross sections obtained from the main stems of the trees, while those on ring width are 40-year means plotted as a function of time. One tree was on a dry, forest border site (Glock *et al.*, 1963), a second on an intermediate site, and the third on a moist, forest interior site. The rate of shoot growth during the first 20 years was lowest for the tree on the driest site. However, at an approximate age of 80 years, the rate of shoot growth in the arid-site tree exceeded that of the trees on more moist sites. However, all three trees attained high rates of growth before their one hundredth year, and in the case of the forest interior tree, a maximum in shoot growth occurred at an age somewhat greater than 100 years. Rings at the base of the main stems attained maximum widths at an earlier age. In general, after the first 100 years, the rates of both shoot and ring width declined. This decline in growth rate was most marked for the tree on the dry site and least marked for the tree on the moist site. The growth rates approached a state of apparent equilibrium, where the mean growth rate remained about the same, first in the arid-site tree and last in the moist-site tree. A period of unusually high precipitation occurred in the early 1900's (Fritts, 1965; Fritts *et al.*, 1965a) and caused shoot growth and ring widths to increase, especially in the arid-site tree.

Certain systematic variations in the annual growth layer are associated with the circumference of the ring, the development of the crown, and the amount of competition with neighboring trees. Farrar (1961) illustrates how the width of a ring in a young forest-grown tree may vary from the stem apex to the stem base (Fig. 2.27A). The ring is comparatively narrow at the stem apex and reaches its first maximum width in the stem nearest the branches with the most foliage. The ring is often narrower in the lower part of the crown and along most of the bole. Ring width increases slightly to a second maximum at the ground line where there is root flare. However, if ring-width data are converted to cross-sectional area (dashed line in Fig. 2.27) the plot of growth as a function of bole height takes a different form. There is a marked increase in area from the stem apex to the portion of the stem just below the crown. Below this point there is only a slight increase in area with decreasing height until near the base where there is an increase in area associated with the root flare (also see Phipps, 1967).
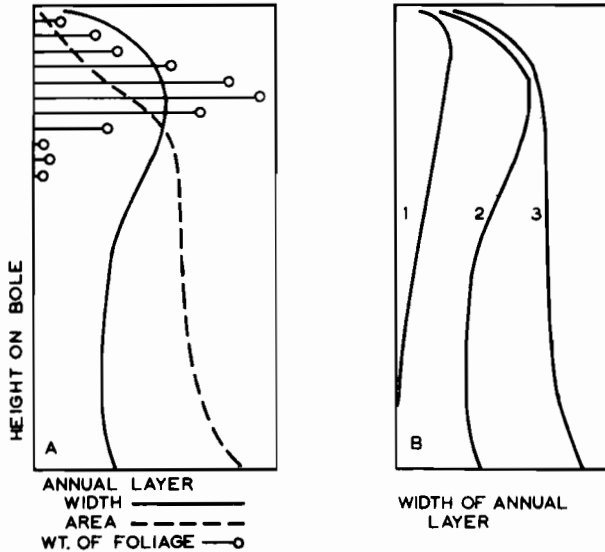
FIG. 2.27a and b. (a) The size of an annual growth layer as measured by its width and cross-sectional area and plotted as a function of height in the bole. The weights of foliage are indicated by length of the horizontal line at the indicated height. (b) The size of the annual growth layer as a function of height in the bole for (1) a crowded or pruned tree with a small crown, (2) a dominant tree in a young stand, and (3) an open-grown tree with live branches extending to the stem base. (From Farrar, 1961)

Figure 2.27B illustrates how the width of the annual ring can vary with differences in the density of the forest stand and tree crown. The rings are narrower in trees that are crowded or pruned to have a small crown (B1). In such a tree the rings become narrower in the bole the greater the distance from the tree crown. If the tree is severely crowded and the crown sufficiently small, the sheath of xylem may be discontinuous or absent in certain areas of the bole, especially near the stem base. Figure 2.28 is an extreme and obvious example where the xylem sheath produced during 18 continuous years was absent along a portion of the stem. In trees growing in more open stands (Fig. 2.27, B2 and B3), the rings are more nearly the same size throughout the lower portions of the stem.

Farrar (1961) further illustrates in Fig. 2.29 some of the changes in width that may occur in the stem of a young plantation-grown tree. During the first few years when the tree is free from competition, the xylem sheath may increase in thickness from stem apex to the stem base. A few years later the lower limbs become shaded by the upper limbs and

reports that there is apparently a certain intermediate ring width in the development of a tree at which point the specific gravity of the xylem is maximum. In the wide rings of young, fast-growing trees, such as six to eight year-old *Pinus* saplings, and in the very narrow rings of over-aged trees, a smaller percentage of latewood is formed and the wood is less dense.
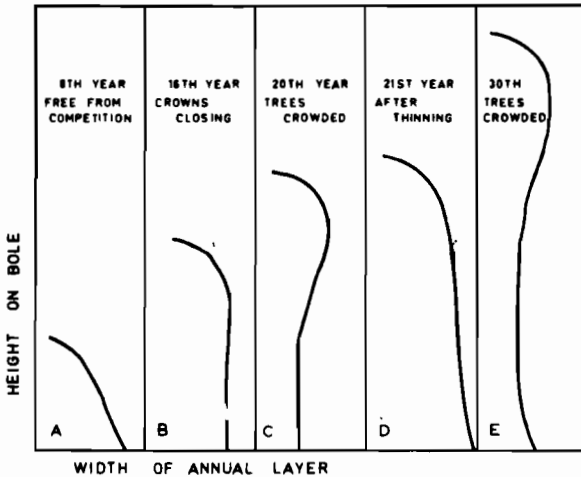
FIG. 2.29. The width of the annual growth layer throughout the tree bole for selected years in the life of a plantation-grown *Pinus resinosa*. Foliage covers the entire stem base in A, but by the 15th year lower branches become shaded (B), and by the 20th year (C) the lower branches have died. Thinning exposes the crown to full light in the 21st year (D), but by the 30th year (E) the crowns have closed again and the trees are crowded. The horizontal scale of width is approximately 1,000 times the vertical scale of height. (From Farrar, 1961)

The widths of both the earlywood and latewood in ring-porous angiosperms usually decrease with the increasing age of the tree, but the earlywood occupies an increasing proportion of the total width (Brown and Panshin, 1940) and there is decreasing year-to-year variation in width of earlywood (Phipps, 1967). Also, the percentage of latewood may vary systematically with varying site characteristics (Larson, 1957) and with varying seasonal environmental regimes (Larson, 1957; Smith and Wilsie, 1961; also see Fig. 2.22). Since a variety of factors can contribute to systematic variations in ring structure, there is no simple equation or general function that can describe all variations in growth that occur with increasing tree age. However, certain statistical methods are described in

Chapter 6 which can be used to fit a curve to some types of systematic variations, such as diminishing ring widths that are associated with increasing tree age. The curve represents a statistical assessment of all systematic changes related to tree age regardless of their causes.

The rings in leaning stems and lateral branches exhibit another kind of systematic variation leading to eccentricity in the width and structure of the ring. Such eccentricity is usually associated with particular characteristics in cell anatomy and is designated *reaction wood*. In coniferous species the reaction wood occurs on the lower side of the tree and is therefore referred to as *compression wood*. The rings with compression wood are wider and they contain a larger proportion of latewood than the rings on the upper side of the lean. Compression wood is also denser and more brittle than normal wood; the tracheids are heavily lignified and tend to be circular in transverse section so that more intercellular spaces are visible than in normal wood (Westing, 1968).

Reaction wood in angiosperm species occurs on the upper side of the lean, and is therefore referred to as *tension wood*. There are fewer and smaller vessels in tension wood than in normal wood; and there is a corresponding increase in the proportion of fibers which are conspicuously thick-walled. However, there is a reduced amount of lignification in tension wood (Hughes, 1965) and some fibers develop a gelatinous layer (Wardrop, 1964b). The presence of reaction wood in rings can be interpreted as evidence for a nonvertical orientation of the stem (Westing and Schulz, 1965) and changes from normal wood to reaction wood are often used to establish the date of events affecting the orientation of a tree (see Chapter 5; Alestalo, 1971).

IX. Growth of Roots

The apical growth of roots, unlike growth of stems, may exhibit no inherent dormant period, and it is not certain whether there is any inherent periodicity in root elongation (Kramer and Kozlowski, 1960). However, many workers have reported rapid root elongation in the spring and autumn, and less active growth in the dry period of summer. Radial growth in roots, unlike apical growth, appears to be influenced by what is occurring in the stem and neighboring roots, as well as by the surrounding environment. Thus the distribution, timing, and anatomy of radial growth in any part of the root system appear to be affected by growth conditions of the stem, the location of the root with respect to the stem, the activity of the root tips, and environmental conditions (Fayle, 1968).

Roots, like stems, produce annual growth layers, but in roots the

distinction between layers is more difficult to discern with increasing distance from the stem base. The width of the growth ring generally tapers along with the diameter of the roots so that the widest part is nearest the stem and the narrowest at the root tip. Near the stem, the anatomy of the growth layer in roots appears much like the annual ring in the stem. Cell walls are thinner in the latewood of roots than in stems, the vessels in the earlywood of ring-porous species are smaller, and the cells are somewhat larger toward the distal portions of roots so that the tissues resemble diffuse-porous wood. For hardwood species, the farther the root is from the stem base, the greater the proportion of vessels and the less the proportion of fibers (Fayle, 1968). Near the root apices, however, some of these changes in structure may reverse. Fayle reports that the specific gravity of root wood in his trees was 20% lower than the specific gravity of stem wood.

Initiation of cambial activity in roots appears to be a continuation of that in the stem. The wave of growth initiation in the cambium is triggered by activity in the shoots and moves down the stem to the ground line where it may be delayed before it proceeds toward the root tip. The rates of cambial growth in roots are more variable than in the stem (Fayle, 1968). Growth cessation follows a more irregular pattern than growth initiation, but it generally proceeds from the root apices toward the stem-root base (Fayle, 1968).

Whereas the patterns of ring width along a cross section of the main root may show a marked similarity to the ring-width patterns in the lower portions of the stem (Schulman, 1945; LaMarche, 1968), there may be less or no correlation with the stem ring-width patterns in the finer subdivisions of root systems, at greater distances from the stem base, or with increasing age of the root. The growth layer is frequently distributed around the circumference of roots in a more eccentric manner than in the stems. Mechanical stresses transmitted into the root system, soil pressure, burial or exposure of the root, the development of adventitious shoots, and changes in the availability of growth regulators and food all affect root growth and contribute to the irregularity and multiplicity which are characteristic of the annual xylem sheaths, especially in the distal portions of roots (Fayle, 1968).

If the stems of stream-side trees are buried by flood deposits and they survive, new xylem tissue produced in the buried stems will appear more like root wood than like stem wood (Sigafoos, 1964). The incline of trees, the age of wounds, and the age of sprouts, along with changes in anatomy of stems buried by sediments, can be used to date and reconstruct past history of floods (Sigafoos, 1964).

Also, trees on *talus slopes* with exposed roots yield information on

extant geological processes that are taking place in the sites (Eardley and Viavant, 1967; LaMarche, 1968). *Buttress roots* (which are elongated vertically) are formed by *Pinus longaeva* as a direct result of exposure (LaMarche, 1968). The cambia along the exposed surfaces die, leaving only the lower surfaces of living bark, which continue to grow and eventually produce an asymmetric vertical slab form. A well-preserved buttress root will show concentric growth rings around the root axis corresponding to the time when the root was fully buried in the soil. Reduction of the cambial area in old exposed roots may continue until only a narrow strip of living bark remains along the protected underside. The ages of trees and measurements of maximum depth of the highest (what was initially the shallowest) exposed roots, plus an estimate of the depth of initial root development, allowed Eardley and Viavant (1967) and La Marche (1968) to estimate the rates of slope degradation occurring around the trees.

X. Significance of Growth and Structure to Dendroclimatology

It has been shown in this chapter that growth of a tree may vary in many ways and over a wide range of time scales representing different frequencies. For example, there are hourly variations in tissue size that occur primarily as a response to changes in temperature and moisture or to changes in the diurnal variations between water uptake and water loss. There are seasonal changes that occur at frequencies of a few days to a few months, which may result from varying activity of the apical meristems, varying vigor of the cambial tissues, or varying environmental factors that become limiting to one or more growth-controlling processes. Many factors vary over the annual cycle and there are changes at frequencies of one or more years which often, but not always, result from year-to-year variations in one or more aspects of climate. Many of these variations can be complicated by internal preconditioning, structural changes in the roots, stems, and leaves, and by changes in the general physiological condition of the tree. Still longer-term variations in growth can occur at frequencies of several decades to several centuries, depending on the longevity of the tree. These often arise from systematic changes within the tree due to increasing age and alterations of the local environment. Sometimes long-term macroclimatic changes may be involved, but if this is so, similar growth changes will be found in many trees regardless of their age and position within the forest.

Ring widths can be influenced by environmental variations occurring

at all of these frequencies. The annual variations in width are averages of the day-to-day and season-to-season variations in processes that have limited growth. They also reflect both the year-to-year variations and the longer-term changes which may or may not reflect variations in climate.

Certain dendrochronological techniques, including standardization, have been developed to emphasize variations at particular frequencies and to minimize others. For example, the standardization curve of some prescribed form may be fitted to the change in ring widths expressed as a function of tree age (Fig. 1.9). Such curves are designed to be flexible enough to take into account many of the systematic variations that can occur over the life of the tree, including those variations due to the location of the cross section throughout the stem or root and those variations that are a function of the changes in the surrounding competition, stand history, and productivity of the site.

The techniques of curve fitting do not distinguish whether the long-term variations are due to climatic or nonclimatic factors, though there is circumstantial evidence that most of these changes in both arid- and mesic-site trees is nonclimatic. However, long-lasting drought may produce changes in the forest density, causing death of certain trees and expansion of others into the vacated environment. The resulting gradual adjustment in the plant community causes ring widths to return to the average state even though the drought persists. Thus, curves fitted to century-long changes in growth in arid- and mesic-site trees are necessary in order to remove important nonclimatic variations; and fortunately there is so little climatic variation left in the ring widths at these time scales that little climatic information is lost.

Trees that are long lived and in cold sites such as *Pinus longaeva* at high elevations or *P. sylvestris* at high latitudes, do not appear to lose as much climatic information at time scales of centuries and millenia as do short-lived trees on warmer sites. This appears to occur because the changes in community structure and forest density resulting from long-term variations in temperature accentuate and reinforce the year-to-year climatic effects rather than leading to adjustment and a return to the average state as occurs in warmer sites. If the trees are of this type, the variations due to tree age and site factors may be considerably smaller than the variations due to changes in climate. In such cases curve-fitting procedures are applied with caution or not at all. It is still necessary, however, to identify and to try to separate any changes due to tree age and site conditions from those due to climate. This can sometimes be accomplished if the ring records are of sufficient length by discarding the first few decades of vigorous growth that are obviously not the result of climate. After these are removed, the remaining ring widths can be

compared for intervals in common, adjusted, averaged, and the mean record used to infer variations in climate.

Considerable attention has been given in this chapter to the variations that occur in cell structure within the annual ring. It has been stated that these variations can be attributed to particular characteristics of the growing season and the associated climates. While such small-scale variations in cell size have little net effect on ring widths, they are an important source of information that can be measured by densitometric analyses. The close association between cell size, wood density, and factors of the environment point to a tremendous amount of information that must be present in the rings and which should be extractable by measuring density variations along with ring widths. If these new data on density can be successfully related to and calibrated with environmental data, the simultaneous analysis of density and ring width may provide significantly more information on past climate than is possible using only the widths of rings.

Chapter 3

Basic Physiological Processes: Movement of Materials and Water Relations

1. Limiting Factors and Plant Processes

It was pointed out in Chapter 1 that a climatic factor can affect structural characteristics such as ring width only as it influences the operational environment of the plant and limits the rate of physiological processes that in turn influence growth. The actual relationships that are involved may vary, depending upon the condition of the growing tissues, the relative activities of the controlling processes, and the operational history of the plant's environment that has preconditioned it. Also, the most limiting conditions to plant processes can change markedly throughout the year, so that one particular climatic factor may be directly correlated with ring width at one time, inversely correlated with it at another time, and totally uncorrelated at still other times. For example, during the spring, growth may begin earlier in a warm year than in a cool year, because low temperature is most limiting to the growth-initiating process.

In such a case, temperature would be directly correlated with ring width. Later in the growing season, when temperatures are higher, the hottest weather may be most limiting because it can limit the production of enzymes and hormones which are necessary for certain processes to occur and because it accentuates the loss of water from tissues in which water is already deficient. Thus, temperature at this time of year becomes inversely correlated with ring width. During the dormant winter period, freezing temperatures may prevail so that variations in temperature do not affect any particular process, and therefore temperature variations are uncorrelated with growth. On the other hand, if warm weather in winter is associated with thawing of tissues and increased physiological activity, certain biochemical changes may occur which affect subsequent growth and lead to correlation of winter temperatures and ring width.

This example is only one of several possible explanations for the correlation of temperature with variations in ring width. In the following discussion it will become apparent that there are a number of physiological processes involved.

As implied by the law of limiting factors mentioned in Chapter 1, only a small number of environmental factors can limit a process at a given instant in time. This was first recognized in 1843 by Liebig who proposed what he called the Law of the Minimum: "When a process is conditioned as to its rapidity by a number of separate factors, the rate of the process is limited by the pace of the 'slowest' factor" (Meyer, *et al.*, 1973). Liebig's law has been shown to be an oversimplification because at times more than one factor can be limiting to a process. Thus, in 1909 Mitscherlich suggested that "plant yield" is sometimes limited by deficiencies in several factors. He modified Liebig's law to include interactions between several factors but he accepted the essential feature of Liebig's law, that usually the greatest change in yield will be produced by the one factor which is most deficient (Meyer *et al.*, 1973).

Lundegårdh (1931) stated the same principle in a different form, which he calls the Law of Relative Effects:

The more nearly a factor is in minimum in relation to the other factors acting upon the plant, the greater is the relative influence of a change of that factor upon the growth of the plant. As a factor increases in intensity, its relative effect upon the plant decreases; and when the factor is in the region of its maximum, the effect of a change upon the plant is nil.

It was also noted that some environmental factors appear limiting to a plant when they are in extreme superabundance as well as when they are deficient (Lundegårdh, 1931; Daubenmire, 1959; Glock and Agerter, 1962). However, a careful analysis of the situation usually reveals that the so-called "superabundance" of one factor is often the result of another

factor which becomes sufficiently minimal to limit the process. For example, an excess of soil moisture appears to limit certain processes because air is driven out of the soil and oxygen diminishes to sufficiently low levels that metabolism is limited in the roots. Thus, it was soil oxygen that was the operationally limiting factor, not high soil moisture. Both low and high temperatures appear to limit the rates of certain chemical reactions. However, the high temperatures may not limit the rates of a reaction directly, but rather alter enzyme systems that in turn become the operationally limiting conditions producing the effect.

Liebig's Law of the Minimum and Lundegårdh's Law of Relative Effects are important in the following discussion of physiological processes. They imply that it is not necessary to consider all factors at all times as limiting. Actual conditions and circumstances can usually be ascribed to a small number of critical factors. The following pages describe the most important growth-controlling processes and the factors most likely to limit them. The treatment will emphasize those relationships important to the growth processes in order that they may be properly handled in the models to be developed later in the book. The remainder of this chapter includes a discussion of the processes affecting the movement of materials, and the next chapter deals with the food-making processes and various types of physiological interactions that occur among the organs and tissues of a tree.

II. Some General Terms and Basic Concepts

The movement of substances through the soil, into the plant, from one cell to the next, and out of the plant is accomplished by two basic processes: *mass movement* and *diffusion*. Mass movement is the transfer of molecules or particles from one place to another through the application of some external force. Such external forces include gravity, hydraulic pressure, or surface phenomena affecting cohesion and adhesion of molecules. Mass movement is a flow of particles which are swept or moved all in one direction. Examples of mass movement are the percolation of water into the soil after a rain, the rise of moisture in the soil due to capillary action, the movement of water and minerals up through the xylem from the roots to the leaves, the movement of foods and minerals through the sieve-tube elements of the phloem, and the discharging of water droplets (*guttation*) from turgid leaves.

The movement of materials into and out of living cells in the plant occurs mainly by the process of diffusion. Unlike mass movement, diffusion results from the energy of molecules and ions, which produces ceaseless, random motion of the particles. Diffusion is the kinetic

dispersion of molecules or ions of a particular kind from a region where there is a large number of them to a region where there are fewer numbers of them. The relative number of molecules for a substance is expressed as *concentration*, while the combined effects of concentration and molecular activity are referred to as *free energy*. In conceptual terms, free energy is a measure of the relative movement (kinetic energy) of molecules of a given substance. This movement will increase with an increase in the number of molecules (concentration). Diffusion may therefore be defined as a net movement of molecules (or ions) of a given substance from a region of high free energy (concentration) of that substance to a region of low free energy (concentration) of that substance (Meyer *et al.*, 1973). The difference in molecular activity between two areas is called the *free energy gradient*. Each substance diffuses relatively independently of the diffusion of another substance until a state of equilibrium is reached. At equilibrium all molecules in an open system are randomly dispersed and the free energy of each substance is nearly uniform. Molecular motion continues, but no further change in concentration or net movement of molecules occurs.

The kinetic energy of molecular motion is essentially the heat within the substance, and the motion is directly proportional to the absolute temperature. Theoretically, then, at absolute zero $(-273°C)$ there would be no molecular motion and no diffusion. Diffusion rates are highly dependent upon temperatures and, therefore, the radiant energy from the sun and the resulting heat energy of the environment may be regarded as the source of energy causing molecular movement and diffusion to occur throughout the plant. As temperatures increase in an open system, molecular movement is greater, and diffusion occurs more rapidly. Ordinarily materials move into and out of a plant more rapidly during the warm days of summer than during the cold days of winter. In general the rate of diffusion can be shown to increase by a factor of 1·2 to 1·3 for each 10°C rise in temperature (Meyer *et al.*, 1973).

The size of the moving particles also affects the rate at which they can diffuse. Thus small, light molecules move more rapidly than large, dense ones. The steepness of the energy gradient, that is, the difference in free energy over a given distance, affects the rate of diffusion. The greater the free energy difference, the steeper the gradient and the faster the diffusion rate.

The diffusion of molecules and ions can also be affected if there is resistance to their movement by substances surrounding them. Thin layers or membranes in the cytoplasm, which lie inside the cell walls (Fig. 3.1), may vary in their permeability to different molecules diffusing throughout them. Such layers, which are referred to as *differentially*
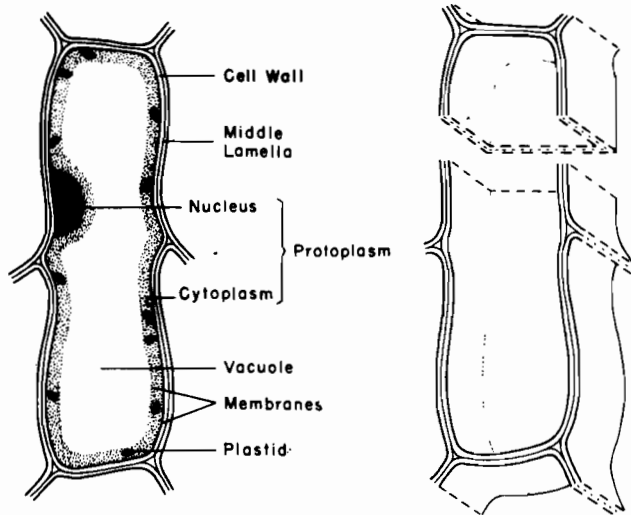
FIG. 3.1. Parts of a plant cell as seen through a microscope. The drawing on the right shows the cell wall in three-dimensional perspective. (Drawing by M. Huggins

permeable membranes, may change in permeability and in this manner may regulate the movement of substances within the plant.

The cell wall is not alive and is generally permeable to most molecules. Exceptions occur when the cell wall is impregnated with waxy or fatty substances, such as *suberin* or *cutin*, which are usually found in the epidermis or bark. Since water is insoluble in these substances, it can move only with considerable difficulty through cell walls impregnated with them.

Diffusion is a very important process to the growth environmental relationships, because it is involved in the transport of all materials into and out of living cells and it is responsible for many of the size changes that occur in the growing tissues of plants. Foods, minerals, water, and gases utilized in growth processes generally move through the membranes and into the growing cell by diffusion (Fig. 3.1); all substances made within cells must diffuse out of the protoplasm of the cell before they can be translocated (by either diffusion or mass flow) to other locations in the plant; and gases move between the leaf and atmosphere by diffusion.

The diffusion of water is so important to the plant that special terms are used for it. The loss of water by evaporation from the leaves and stems is referred to as *transpiration*. For the purposes of this text the diffusion of

water through the differentially permeable membranes in the cytoplasm of cells is called *osmosis*.

There is one type of movement which is not strictly diffusion nor is it a mass flow phenomenon. It involves minerals or ions which are moved across cell membranes against a free energy gradient. Such movement may occur in well aerated roots and is referred to as *active transport*. It requires an expenditure of energy which is released by the metabolic activity of the plant.

III. Cell Water Status

The growth of trees is undoubtedly controlled more by the movement of water than by the movement of any other single substance. Growth cannot occur unless water is plentiful enough to maintain erect developing structures and expanded cell walls. The normal functioning of the physiological processes which control growth must occur in a water solution, raw materials move into and out of the growing cells in a water solution, and all variations in the sizes of growing cells are due to the movement of water into and out of the tree. This movement is regulated by the osmotic properties of the cells in the roots and leaves, and by pressures and resistances to water movement exerted by the various tissues within the tree.

Living cells consist of a viscous *cytoplasm* and *nucleus*, together called the *protoplasm*, which is surrounded by a differentially permeable membrane and a more or less rigid cell wall (Fig. 3.1). The cell wall is flexible but places some limit on the maximum cell volume. Thin-walled cells generally are more flexible than thick-walled ones. The cytoplasm is commonly distributed as a thin layer along the inner surface of the cell wall within the membrane, and it encompasses a nucleus containing the genetic material, and sometimes includes specialized protoplasm called *plastids*, and other bodies. A vacuole commonly occupies the central portion of the cell and is filled with a solution of water and dissolved substances, sometimes referred to as the *cell sap*. A second differentially permeable membrane separates the cytoplasm from the vacuole.

All water movement in plants may be viewed as occurring along gradients of decreasing free energy of water (Fig. 3.2). A measure of this free energy, called the *water potential*, is expressed in units of pressure, called *bars*, as the difference in free energy of pure water at atmospheric pressure and that in the system under consideration (Kozlowski, 1968; Kramer, 1969). In Fig. 3.2 water potential of the soil is shown to be near zero, the water potential of the plant ranges from -1 or -2 bars to -30 bars, and the water potential becomes markedly lower along the external

cell surface of the leaf. The curves in Fig. 3.2 portray the differences that occur in profiles of the energy gradient under (1) normal moist conditions, (2) temporary wilting, and (3) permanent wilting after a prolonged drought.
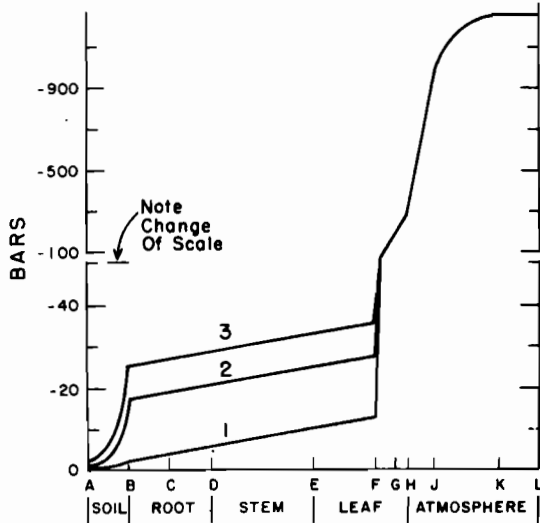
FIG. 3.2. Energy profiles in the stream of water passing through the soil/plant/atmosphere continuum under conditions of normal transpiration (curve 1), temporary wilting (curve 2), and permanent wilting (curve 3). The ordinate represents water potential as shown in units of pressure called *bars*. The abscissa represents locations along the transpiration path (A) soil, (B) root surface, (C) root cortex, (D) root endodermis, (DE) xylem in root, stem, and leaves, (F) mesophyll cells, (FG) intercellular space, (GH) stomate, (HJK) adhering boundary layer of air, and (KL) free atmosphere. (Redrawn from Philip, 1957)

The water potential (designated as Ψ) of an unconfined solution is simply a function of the amounts of dissolved solutes and hydrostatic forces. The component of water potential due only to the dissolved materials is referred to as *osmotic potential* (Ψ_s). However, if a solution is confined, as in the protoplasm and vacuole of a cell, the water potential is higher due to the positive pressure that develops inside the cell. This component of water potential is the *pressure potential* (Ψ_p) or the *turgor* pressure, and generally it has a positive value (Kramer, 1969). The water potential of a nonturgid cell (where the pressure potential is zero) will be the same as the water potential of an unconfined solution, except in the case where *colloids* may hold water or surface phenomena may exert an additional force. These forces due to surface phenomena are expressed as

the *matrix potential* (Ψ_m) and like the osmostic potential have negative values.

Using the above symbols, the water status of a plant cell can be expressed as the sum of the various potentials by the following equation:

$$\Psi_{cell} = \Psi_s + \Psi_p + \Psi_m \tag{3.1}$$

When a cell is placed in a solution of water, it will not change shape if the water potential inside the cell is the same as the water potential outside (Fig. 3.3). However, diffusion (in this case, osmosis) will occur if there are differences in water potential between the inside and outside of
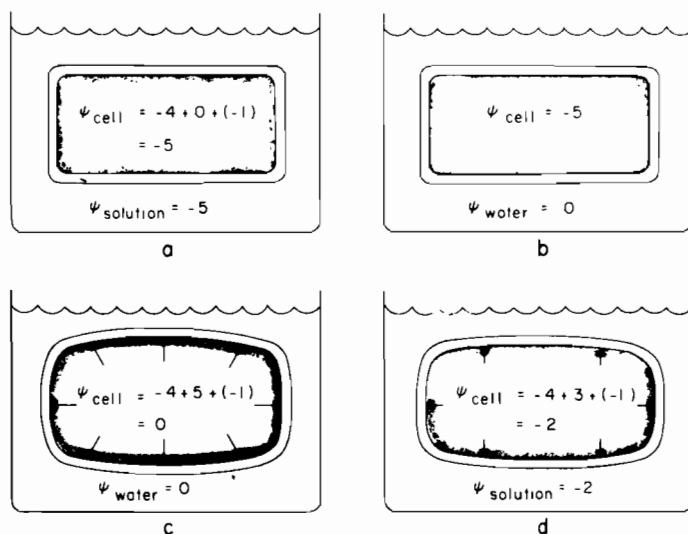
FIG. 3.3. (a) A hypothetical cell in which osmotic potential equals -4 bars, pressure potential equals 0, matrix potential equals -1 bar, and the total water potential for the cell is -5 (see equation 3.1). If the cell is placed in a solution with the same water potential as the cell, as in (a), there is no water potential gradient and the water is in a state of equilibrium. However, if the cell is placed in pure water (b), a difference amounting to 5 bars exists between the water potential inside and outside the cell. Water diffuses into the cell (c) until the pressure potential (arrows) exerts an outward force equal to the difference in water potentials (assuming changes in cell volume are insignificant) and a gradient no longer exists. The cell swells and is said to be turgid. If the water potential of the bathing solution is then changed from 0 to -2 bars (d), water will diffuse out of the cell until the pressure potential (arrows) is reduced from 5 bars to 3 bars, at which time the water in the cell reaches a new equilibrium and the cell is less swollen. Under actual conditions, water diffusing into the cell dilutes the solute, increasing the osmotic potential and decreasing the pressure potential to some value slightly less than indicated in the example.

the cell. For example, water diffuses into a cell if the water potential of the cell is lower than that of its surroundings. As water enters a cell, the water potential increases and the pressure potential exerted by the cell wall increases until the water potential inside the cell equals the water potential outside the cell. The water potential gradient no longer exists and osmosis ceases.
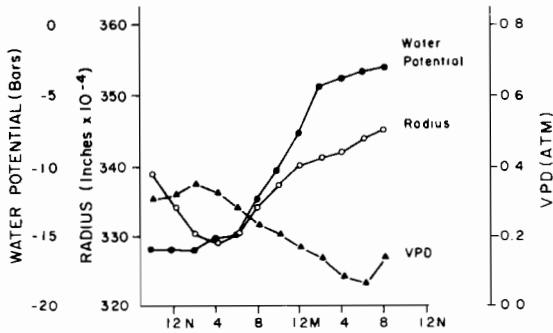
FIG. 3.4. Water potential of needles, measurement of the stem radius, and vapor pressure deficit in the air (VPD) surrounding a semiarid *Pinus ponderosa* at various times during May 22–23, 1965. The water potential was measured for needles periodically removed from a branch, the radius was measured by a dendrograph, and the vapor pressure deficit was measured as the difference between the actual vapor pressure of the air and the saturation vapor pressure at the same temperature. (Redrawn from Cunningham and Fritts, 1970)

Changes in water potentials and cell size reflect the movement of water through the plant. The changes in stem size and needle water potential that can be observed throughout the day in arid-site *Pinus ponderosa* are shown in Fig. 3.4 (Cunningham and Fritts, 1970). Early in the afternoon (before 4:00 p.m.), the water potential in the needles reaches its lowest value at a time when the stem is shrinking as water is drawn from it faster than it is replaced by the roots, and the *vapor pressure deficit* (the difference between the actual vapor pressure of the air and the saturated vapor pressure at the same temperature) is near its maximum for the day. After 4:00 p.m. the vapor pressure deficits of the atmosphere begin to decline in absolute value because air temperature and the resulting saturation pressure decrease. The water potential gradient decreases and the amount of water lost from the tree becomes smaller than the amount absorbed from the soil, more water moves into the stem than is drawn from it, and the sizes of cells in the stem and water potentials of the needles begin to increase. At 8:00 a.m., when the needles are turgid and exhibit the highest water potential, the tree attains its greatest water

content. However, the vapor pressure deficit between the leaf and the air
begins to decline by this hour and this causes the water loss by
transpiration to increase. When water loss exceeds water uptake by the
roots, the stem begins to shrink again and the water potential in the
needles begins to decline.

Such diurnal variations in the water status of a tree can have
substantial effects on a variety of processes involved in cell division, cell
enlargement, the making and utilization of food, and the production of
cell parts. Therefore, environmental conditions which alter the water
status can also affect growth and are undoubtedly responsible for many of
the short term variations in growth described in Chapter 2. Such effects
may appear small in magnitude, but if they occur day after day their
cumulative effects can substantially affect ring width.

IV. Transpiration

Transpiration includes the loss of water by evaporation from all parts of
the exposed plant including stems, flowers, and fruits, as well as the
leaves. That portion of transpiration which is attributed to the leaves
occurs in two stages. Water evaporates from the moist cell walls into the
substomatal cavities and other intercellular spaces within the leaf (Fig.
3.5), and the water vapor then diffuses from the intercellular spaces
through the leaf epidermis to the outside air. Passage through the
epidermis occurs through microscopic holes in the epidermis called
stomates or through the epidermal cells. As mentioned earlier in the
chapter, the outer walls of the epidermal cells are impregnated with a
waxy substance called *cutin* (Fig. 3.5). This impedes diffusion so that the
amount of water lost through the epidermal cells is usually considerably
less than the water lost through the open stomates. Small amounts of
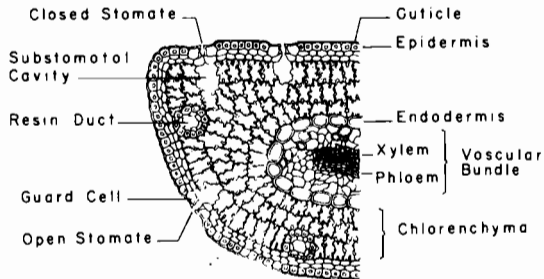
FIG. 3.5. A diagram of a cross section of half a pine needle showing various tissues and
examples of open and closed stomates. (Drawing by M. Huggins)

water are also lost from the stem and twigs through *lenticels*, which are ruptures in the bark.

The stomates are generally numerous, but varied in structure, shape, and number from one species to another. Two cells called *guard cells* surround each stomate and govern the size of the opening. Stomates open whenever water diffuses into the guard cells and their volume increases. They close whenever water diffuses out of the guard cells and the volume decreases (Meyer *et al.,* 1973). The opening and closing occur because walls of the guard cells are thicker near the pore opening than on the side away from the pore and, as a result, the cell stretches more easily away from the pore, causing the two cells to arch away from each other as the volume of the guard cells increases. In general the stomates open in the light of morning and close with darkness in the evening. The opening and closing has a marked effect on transpiration rates.

In addition to the size and number of stomates on a leaf, the amount of energy absorbed by the leaf and the amount radiated from it can substantially affect leaf temperatures and influence the transpiration rates. During the night and in shade, the leaf may radiate more energy than it absorbs, and its temperature may drop well below the temperature of the air. Under conditions of high solar radiation during the day, the leaf may absorb more energy than it dissipates, and its temperature can rise above the temperature of the air (Fig. 3.6). Wind may cool the leaf and lower the leaf temperature during the day, but it can also transfer energy to a cooled leaf at night and raise its temperature closer to that of the air. Transpiration itself consumes energy because of the cooling power of evaporation.

The driving force of transpiration, according to Gates (1968b), is essentially the difference between the water potential or the vapor within the leaf and the water potential of the free air outside the leaf surface. Both moisture and temperature govern the free energy gradients, but several resistances may be encountered as the water diffuses from the inside of the leaf out to the free atmosphere. The cuticle layer on the walls of the epidermis offers resistance, the changing sizes and shapes of stomates can cause large variations in resistance, and any moist layer of air adhering to the external surface of the leaf can add further to the resistance.

Gates (1968b) has constructed a physical model of the various resistances and pathways affecting transpiration from the leaf and uses the model to calculate transpiration as a function of varying wind velocities, temperature, and humidities of the air, assuming that the stomatal pores remain unchanged. His calculations (Fig. 3.7) illustrate that transpiration can markedly increase or decrease with slight increases
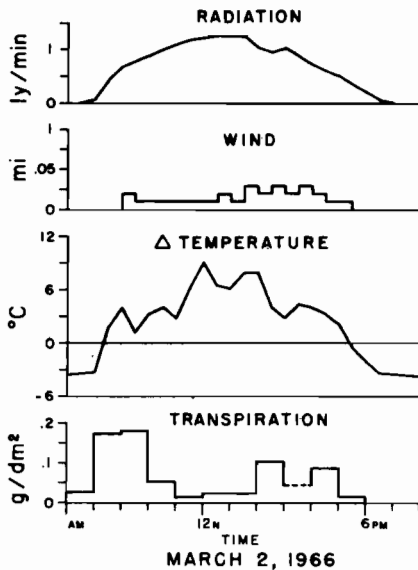
FIG. 3.6. Incident radiation on a horizontal surface, wind velocity, difference between temperature of leaf and surrounding air, and transpiration from a seedling of *Pinus ponderosa*. Early in the morning (8:00 to 10:00 a.m.) transpiration is rapid because stomates are fully open and water potential of the needle is high. Cooling by transpiration prevents needle temperatures from rising more than 3° or 4° above air temperature. By late morning water deficits and high needle temperatures cause reduction in the size of the stomates, increased stomatal resistance, and decreased water potential gradient between the needle and air. Less of the absorbed radiation is dissipated by transpirational cooling, and the needle temperatures rise considerably above those of the air. At times in the afternoon when wind velocities are greater than in the morning, they dissipate a portion of the absorbed energy and the temperatures of needles exhibit less departure from temperatures of the air. Later in the afternoon conditions favor more rapid transpiration, differences between needle and air temperatures decline until stomatal closure occurs with declining light levels after 5:00 p.m. At night the needles radiate energy and their temperatures fall below those of the surrounding air. (Redrawn from Brown, 1968)

in wind speed from conditions of still air. For example, a gentle breeze of less than 50 cm per second (Fig. 3.7) can increase transpiration substantially by removing the boundary layer or by increasing the temperature of the leaves. On the other hand, a 50 cm per second breeze can decrease transpiration if it dissipates the heat of radiation absorbed by the leaf and reduces the temperature of the leaf. Wind will increase or decrease transpiration depending upon which conditions are most limiting. The figure indicates that some changes in transpiration rates
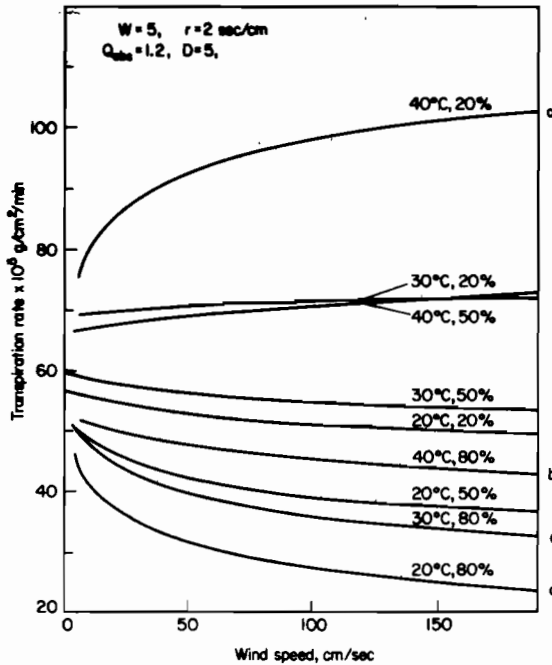
FIG. 3.7. Transpiration rate expressed as a function of wind speed as calculated from a model which takes into account differences in air temperatures and relative humidity percentages. Computations are for the same leaf area, leaf diameter, internal resistance, and radiant energy absorbed by the leaf. Under certain temperatures and humidities (curve a) transpiration rates increase with increasing wind speed, but under other conditions (curves b, c, d) transpiration rates decline. The greatest changes in transpiration rates occur between conditions of still air and wind speeds 50 cm per sec or less. See text for further discussion. (Modified from Gates, 1968b)

occur when wind velocities rise to 100 and 150 cm per second, but they are not as large as the difference between still air and velocities of 50 cm per second.

In the case of drought-sensitive trees which are growing exposed on windy and sunny sites, the leaves are highly ventilated. This simplifies the relationships, since leaf temperatures during the day are likely to remain close to the temperature of surrounding air and the stomates remain open during clear days unless large water deficits occur. In this case there is no boundary layer of high humidity near the leaf surface as occurs in still air or within a closed forest canopy, and the free energy gradient of water vapor near the leaf surfaces is steep. When humidity in the air is low for

such ventilated trees, air temperature can be the most limiting factor to water loss and it can become highly correlated with changes in water status leading ultimately to changes in growth. However, the transpiration rates from such exposed trees can be limited by high air humidity, which in turn is directly correlated with moisture conditions of the area and antecedent precipitation falling on the site.

As mentioned earlier, stomatal sizes may change with variations in light intensity which can produce marked changes in leaf resistance and transpiration rate. For example, the opening of stomates at dawn and their closure at night has a very pronounced effect upon transpiration rate. Low light levels during cloudy weather may induce stomatal closure and reduce transpiration. The transpiration from shaded trees within a forest throughout the day is often affected more by variations in light which affect stomatal opening and leaf resistance than by variations in temperature and wind which affect the water potential gradient. Water status for such trees would be less well correlated with air temperature and more correlated with variation in light than for trees on more exposed and arid sites.

One method of measuring the size of stomatal pores in conifers is to pluck needles from trees, enclose them in a pressure chamber filled with an alcohol-water solution, and gradually increase the pressure while observing the needles under a microscope. At a given pressure the ethanol is forced through the stomatal opening, and the air in the leaf is displaced by the solution, so that the color of the needles becomes darker. The size of the stomatal opening is inversely proportional to the pressure required to induce infiltration (Fry and Walker, 1967). The infiltration pressure for needles of *Pinus ponderosa* can be expressed as an index where a value of 20 represents low infiltration pressures when the stomates are fully open, and an index of 60 or higher represents high pressures when the stomates are fully closed.

The infiltration indices throughout a 24-hour day are shown in Fig. 3.8. The tree used in this example was enclosed in a transparent, air-conditioned tent, so that the transpiration and net carbon dioxide exchange could be measured as well (Drew *et al.*, 1972). As light levels increased during the early morning, photosynthesis commenced and the stomates opened, causing the infiltration index values to decline. The stomatal opening reduced the internal resistance of the needles and transpiration increased. From 8:00 a.m. until noon, transpiration varied as a function of the difference between the water potential of the air and the leaf, because the fully opened stomates offered little resistance. Clouds at noon reduced light intensities, and by 1:00 p.m. the stomates began to close, causing leaf resistance to increase and transpiration to decline.
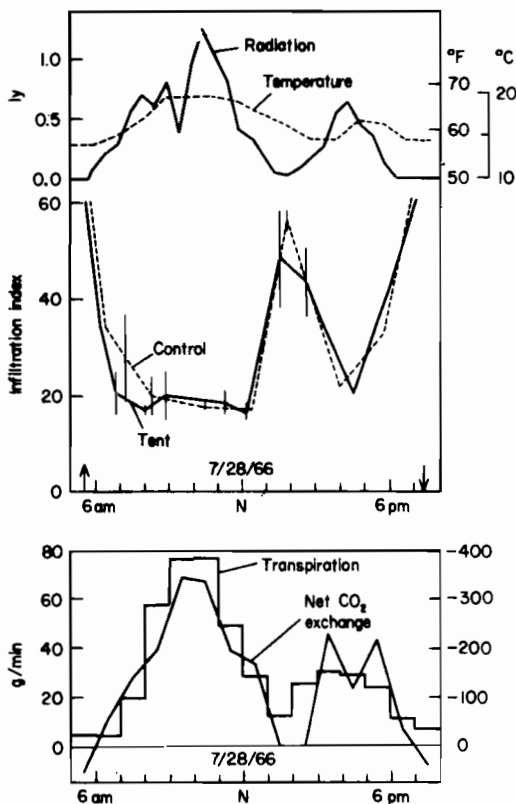
FIG. 3.8. Radiation and temperature of air in the crown of an arid-site *Pinus ponderosa*, the infiltration indices showing stomatal opening (low index) and closing (index of 60), and measured transpiration and exchange of carbon dioxide. The tree was enclosed in a polyethylene air-conditioned tent, and a nearby unenclosed tree was used as a control. Arrows indicate sunrise and sunset. (Drew *et al.*, 1972)

Later in the afternoon the clouds dissipated, light intensities increased, stomates opened, and transpiration increased. By 5:00 p.m., light levels had declined sufficiently to cause stomates to close again and for transpiration to decline.

Figure 3.6 shows a different situation where declining rates of transpiration from a drought-subjected pine were measured while in full sunlight from 10:00 a.m. to 12:00 noon. It was inferred by Brown (1968) and substantiated by later measurements (Drew *et al.*, 1972) that the stomates closed during the day in response to internal water deficits and

high leaf temperatures, which in turn caused transpiration rates to decline. Other examples of diminished rates in transpiration during the day, apparently due to water deficits and stomatal closure, are illustrated later in the book (see Figs 3.14, 3.15, and 4.7).

V. Soil Moisture

Due to certain forces among water molecules and between water and soil particles, the water potential of the soil varies depending upon the soil moisture content (Figs 3.9 and 3.10). When all pore spaces within the soil are filled with water, the soil is said to be saturated and the water potential is near zero (high) (Fig. 3.9). A certain amount of this water, the *gravitational water*, is not available to plants since it drains from the soil in one or two days. Drainage ceases at potentials of -0.33 bars, and the soil water retained at this potential is said to be at *field capacity*. A large portion
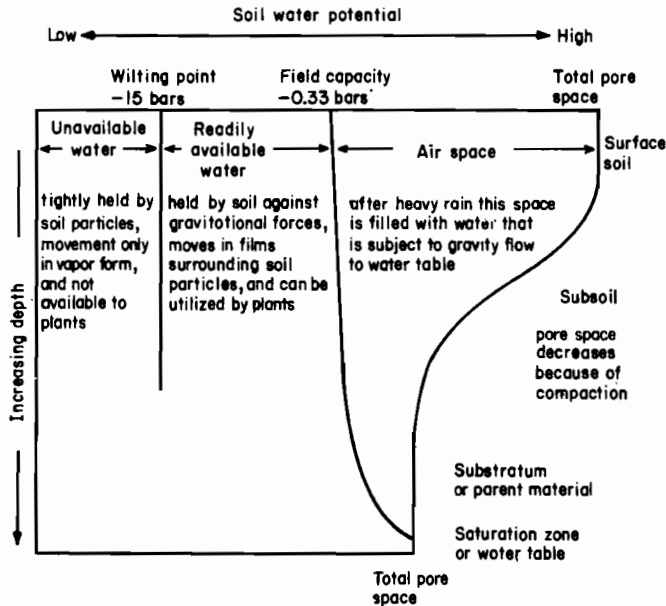
FIG. 3.9. Diagram of the types of water in a hypothetical soil of uniform texture. Most of the water that is held at extremely low water potentials (less than the wilting point) will not diffuse into the root and is unavailable to the plant. Similarly, water held at potentials greater than field capacity is subject to gravitational pull, drains from the soil, and so is also largely unavailable to the plant. Pore space and aeration capacity decrease with increasing depth because of soil compaction.
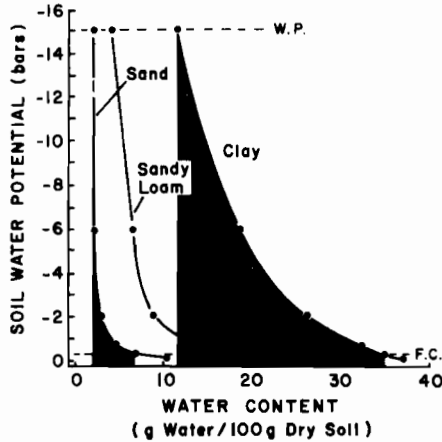
FIG. 3.10. Varying amounts of water are held in different soils by water potentials ranging from 0 bars (water saturation) to −15 bars (wilting point). The water available to plants is the difference between field capacity (F.C.) and wilting point (W.P.), which for sand and clay is represented by the shaded areas under each curve. Since more water is available in clay than in sand, water potentials decline more slowly per gram of water lost, and it often takes longer for such soils to reach wilting point. Though less water is available in sand than in clay, a larger proportion of this water is removed before water potentials are low enough to greatly reduce diffusion gradients in the plant. (Redrawn from data presented by Kramer, 1969)

of the water held in the soil at field capacity is readily available to plants and it can move in the soil as thin films around the soil particles or by molecular diffusion.

Soil moisture is lost by evaporation into the air and diffusion into the roots. At first relatively large amounts of water can be lost from the soils with little change in water potential (Fig. 3.10), but as the soil dries, smaller amounts of moisture are lost per unit change in water potential (Fig. 3.10). Plants begin to wilt during the day, and when water potentials approximate −15 bars many plants become permanently wilted and the soil water is said to be at the *permanent wilting point*. Though small amounts of water can diffuse into roots after the wilting point is reached, this water is generally considered to be unavailable (Figs 3.9, 3.10). For purposes of this discussion we can assume that saturation, field capacity, and wilting point are soil constants, though they actually vary over a range of values depending upon the species, soil temperatures, and other conditions of the site.

A moderate rainfall of 1 inch (25 mm) on a dry soil may wet only the upper 10 inches (254 mm) of soil raising its water content to field

capacity, while the lower layers may remain dry. Unless more moisture is added, water will not move to deeper levels by gravity flow, although water can move slowly by capillary action and by diffusion. If more rain falls, the moisture at the soil surface temporarily rises above field capacity, moisture drains to lower levels wetting the soil until the entire moist layer reaches field capacity. At this point the downward movement of water due to gravity flow ceases.

Soils may differ greatly in the quantity of water they hold at field capacity $(-0.33$ bars) and at the wilting point $(-15$ bars). The maximum amount of soil water that is considered to be available to a plant is the difference between the water held at field capacity and that held at wilting point (see shaded areas in Fig. 3.10). Since soils of different *texture*, such as sands, loams, and clays can differ greatly in the water content at both field capacity and wilting point, they also can vary substantially in the amount of water available to the plant. For example, clay may hold five times as much available water as sand, whereas loam holds intermediate amounts (Fig. 3.10). Also, the grams of water remaining in clay at wilting point can be greater than that held by sand at field capacity. The sharper bend of the curve for sand than for clay in Fig. 3.10 indicates that there is a greater change in water potential per amount of water lost from sand than from clay. Thus, in sandy or gravelly soils, practically all the available water is loosely held at -2 bars or more, but in heavy clays, less than 40% of the available water is held that loosely. Thus, water potential gradients may be steeper for sands than for clay, even though the sand has less water content.

According to Kramer (1969), water in capillary films, pores, and cracks in the soil moves primarily as a liquid. The rate of water movement is materially affected by soil texture and conditions of moisture. Capillary movement in a moist soil is most rapid in the coarser sands and slowest in the finer clays, because there are more large pore spaces in the former. Under drier conditions, however, when the films of water are thinner, the effects of texture are reversed. The movement is most rapid in the latter, because there is greater surface area and more contact among the films of water.

A small amount of water may rise by capillary movement from the water table for short distances. The height of the capillary rise is greatest in clays and least in sands. However, in both kinds of soil, capillary movement of water from moist to dry regions is a very slow process, especially when the soil moisture is less than field capacity. During periods of rapid transpiration, the available water on soil particles in contact with roots moves into the roots faster than it is replaced by capillary action or molecular movement. This produces a cylinder of soil

surrounding each absorbing root that is depleted of water, although a few millimeters away the moisture content of the soil may be near field capacity (Kramer, 1967). Over a period of time, capillary movement may replace some of this water. When soil moisture is low, long distance transport in the soil, including capillary rise from the water table, cannot provide enough moisture to meet the demands of a vigorously growing tree. However, capillary movement may provide sufficient moisture to prevent death of the tree in times of drought.

VI. The Soil System and Factors Affecting its Development

The previous section dealt with the soil as if it were a simple porous medium important only because it affects the water supplied to the roots of a plant. Actually, the soil is a highly complex physical–biological system that develops in the upper weathered layer of the earth's crust and which, according to Jenny (1941, 1958, and 1961) is a function of five soil-forming factors: (1) climate, (2) organisms growing in or on the soil, (3) topography of the site, (4) parent material from which the soil is derived, and (5) time. This section of Chapter 3 includes a brief description of how the soil profile—the assemblage of generic horizons—can vary with small changes in topography and drainage, and it illustrates how the distribution of the horizons and their characteristics can influence plant processes, which can in turn affect root distribution, water absorption, water balance, and ring width.

As soil development progresses, the original *parent material* becomes differentiated into distinct layers called *soil horizons*. Soil horizons are distinguished by their morphological, physical, chemical, and

FIG. 3.11. Soil texture percentages, the soil moisture constants, percent air space and numbers of roots vary with increasing depth and from one soil type to the next. Three soils are shown which form in the gently rolling glacial till in central Ohio. The Cardington soil is a moderately well-drained silt loam which supports a beech–maple forest, the Bennington soil is an imperfectly drained silt loam which supports an almost pure stand of beech, and the Marengo soil is a poorly drained silty clay loam which supports a swamp-forest. A, B, and C designate the relative positions of the three master soil horizons. The sand, silt, and clay are expressed in relative amounts, the percent moisture is shown for wilting point (W.P.), field capacity (F.C.), and saturation (Sat). The difference between wilting point and field capacity represents the potential volume of moisture available to plants, while the difference between field capacity and saturation represents the water that can fill much of the air space immediately after a rain but drains from permeable soils in one or two days. The roots were counted along the face of a soil pit and their numbers vary with the amount of air space, textural features, and permeability of the respective soils. (Redrawn from Fritts and Holowaychuck, 1959)
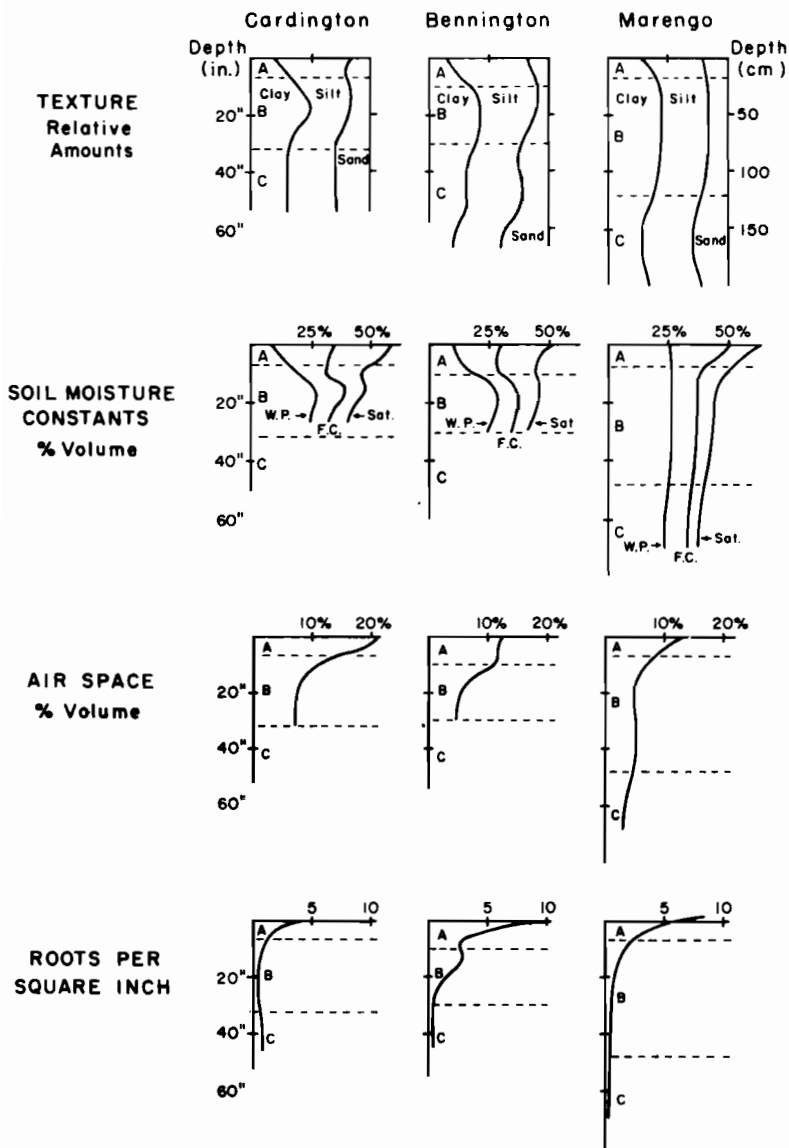
mineralogical properties. The vertical assemblage of soil horizons from the soil surface down to the lowermost layer of undifferentiated unweathered material is referred to as the *soil profile* (Fig. 3.11). It may be divided into four master horizons, one organic and three mineral. The organic horizon is often on the mineral soil surface and includes leaf litter and decomposed organic matter. The uppermost mineral horizon, the *A horizon* in Fig. 3.11, represents the portions of the soil from which certain materials have been removed and other materials added by the soil-forming processes; this is called the horizon of *eluviation*. The second mineral horizon, B, is the level into which many of the materials have moved from the A horizon above. The *B horizon* is called the horizon of *illuviation*. The third and lowermost layer is the *C horizon*, which includes relatively undifferentiated parent materials from which the two upper horizons were derived (Fig. 3.11). Horizons A and B constitute the *solum*. The A, B, and C horizons can be further subdivided into *A1, A2, A3, B1, B2, B3, C1, C2*, etc. Details on the morphogenesis, designations, and definitions of soil horizons are available from the publications of the Soil Survey Staff (1951, 1960, 1962, and 1967).

The relative importance of the soil-forming processes and chemical reactions differ among these three horizons and vary as a function of the five soil-forming factors. As a result, soil moisture constants, air space, different soil chemicals, root distribution, and amounts of sand, silt, and clay vary among the major horizons and from one soil to the next. For example, the Cardington soil in Fig. 3.11 is a well-drained soil which supports a beech–maple forest of *Fagus grandifolia* and *Acer saccharum*. The sites of the Bennington and Marengo soils are more gently-sloping leading to imperfect and poor drainage. The Bennington soil occurs at the margin of swampy depressions where the forest is dominated by *Fagus grandifolia*, while the Marengo soil represents the most poorly drained situations and supports a swamp forest, a mixture of tree species that can tolerate poor drainage.

Textural differences among the three soil profiles are a result of movement of materials such as clay from A to B, and other soil-forming processes. Clay reaches its maximum percent in the Cardington soil at a depth of 20 inches (51 cm), while the maximum accumulation of clay in the Marengo soil is less. Furthermore, the zone of clay accumulation in the B horizon is deeper. As in Fig. 3.10 the soil moisture constants in Fig. 3.11 generally increase with an increase in clay content. The highest porosity is found in the well-drained Cardington soil and the least in the poorly drained Marengo. Large numbers of roots occur in all A horizons, but they extend to the greatest depth in the well-drained Cardington. Most of the roots in the Cardington and Bennington soils are those of

Fagus grandifolia, whereas in the Marengo they are those of swamp forest species which are more tolerant than *Fagus* of high levels of moisture and poor aeration.

In general there is a decline in porosity and numbers of roots in a soil with increasing depth and with decreasing drainage. Kochenderfer (1973) reports that in north-central West Virginia, 77-89% of all observed root endings were found in the upper 0·6 m of soil. The number of roots was greatest in coarse soil with good aeration and decreased as the soil texture became finer. Roots are distributed more superficially in poorly-aerated soils, in heavy clays, and where a dense subsoil excludes soil air and causes the water table to be high (Kramer, 1969). If air is displaced from the larger noncapillary pores by an excess of moisture for an extended period of time, root growth and water absorption may be hindered by a deficiency of oxygen. However, if the soil is porous, and the excess moisture percolates to lower soil levels, air can move into the vacated noncapillary pores behind the moving water. Frequent wetting and drying and temperature fluctuation ventilates the air spaces and facilitates the exchange of oxygen and carbon dioxide between the soil and the atmosphere so that soil oxygen does not become limiting to the growth of roots.

Shallow-rooted trees on poorly drained soils may exhaust soil moisture more readily than trees on well-drained soils which are deeply rooted (Fritts, 1958; Huntington, 1914). This occurs because the total root surface and the volume of water available to a shallow-rooted tree is less than that available to a deeply rooted tree, even though the site may be classified as "wet" (Fritts, 1958; Fritts and Holowaychuck, 1959). Also, evaporation at the soil surface can remove a larger proportion of the water available to a shallow-rooted tree than to a deeply rooted one. Thus, if other factors are equal, trees with shallow root systems are more likely to have variable ring widths than trees with deep root systems.

On steep slopes erosion can remove large volumes of soil, so that the development of horizons cannot keep pace with the removal of soil. Such soils show less pronounced profile differentiation, and often the soils on steep slopes are dominated more by the texture of the original parent material than by characteristics arising from soil-forming factors. Other soil characteristics that can affect available soil moisture, distribution of roots, and soil productivity could be enumerated; but they are less dynamic, vary little from one year to the next, and have little influence on year-to-year ring-width variability.

VII. Absorption of Water

Most of the water absorbed by a tree enters through the roots. The rates
for absorption are partly dependent upon the water potential within the
plant which is generated by the transpiration of water from the leaves
(Fig. 3.12). However, the uptake of moisture is also influenced by (1) the
absorbing surface area of the roots, (2) the resistance to movement of
water from the soil to the roots, and (3) the water potential gradient
which decreases with decreasing available moisture in the soil
surrounding the roots.

Figure 3.13 is a drawing of the tissues through which water must pass in
moving from the soil into the xylem of the young root. The area of the
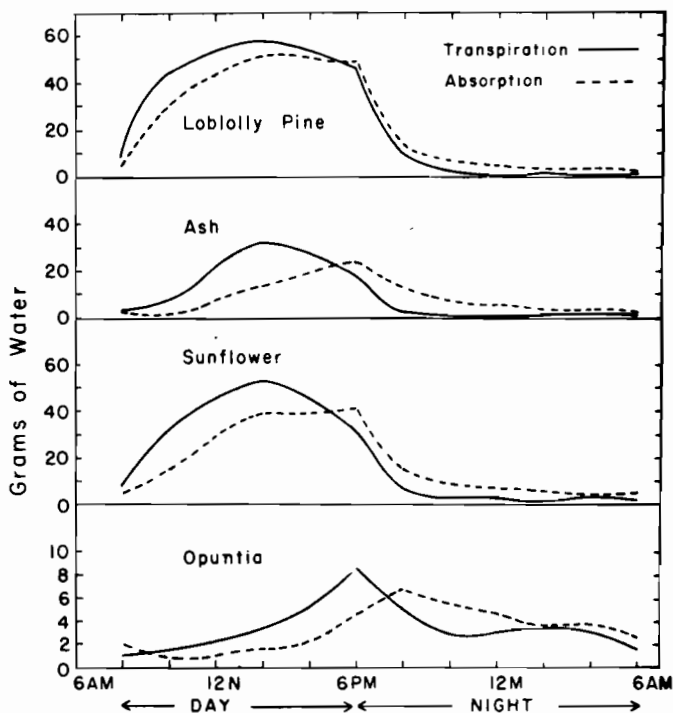
FIG. 3.12. Average rates of absorption and transpiration of four plant taxa throughout
the day. Rates of absorption change in proportion to rates of transpiration but lag behind
transpiration during the day. The tensions increase and shrinkage occurs in the xylem
until the two curves cross, at which time stem swelling will begin. Plants were mounted on
a rotating table in a greenhouse. (Redrawn from Kramer, 1937)
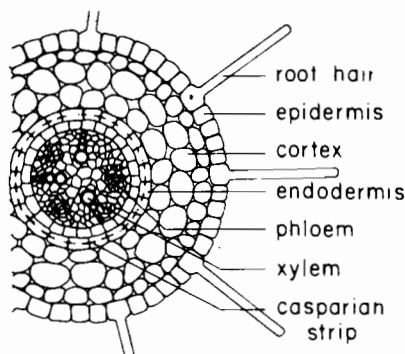
FIG. 3.13. Cross section of a young root showing tissues through which water must pass as it moves from the soil to the xylem in the root. (Drawing by M. Huggins)

absorbing surface of a root is enhanced by projections from the epidermal cells called root hairs or by fungi that may be associated with the root. Water may diffuse into root cells along this root-soil interface and can move through the cortex either along the cellulose cell walls or through the protoplasm and vacuoles. However, a layer called the *endodermis* lies inside the cortex but outside the vascular tissue of xylem and phloem, which has radially and horizontally oriented walls that are impregnated with suberin forming a band referred to as the *casparian strip* (Fig. 3.13). Water cannot diffuse through the suberin of the casparian strip, so it can move through the endodermal tissue only by diffusing into the protoplasm and through the membranes of the endodermal cells. Thus, the endodermis acts as a partial barrier through which water can diffuse only by osmosis. If transpiration is slow and the osmotic potential (Equation 3.1) is low, the root can generate a positive turgor pressure because the endodermis blocks all movement along the cell wall. When transpiration is rapid the water potential gradient steepens, the positive pressure disappears and a negative pressure begins to develop.

As roots mature, the epidermis is ruptured and destroyed by the activity of a cork cambium which develops from the outer part of the cortex. The growth of the cork cells, which are also impregnated with suberin, increases resistance to diffusion of water, but it does not render the mature roots completely impermeable to water (Kramer and Kozlowski, 1960).

Most trees have roots which not only extend well beyond the spread of the branches but which can also penetrate deeply into the soil and into fissures and cracks among rocks. The roots are most dense in soil layers

where both oxygen and soil moisture are abundant, because these factors favor high physiological activity and root growth (Kramer, 1969). A tree with a growing crown is able to maintain adequate water absorption only by continual branching, rebranching, and extension of young, unsuberized root tips into moist soil. Thus, rapid absorption of water by a root system depends in part upon the total extent and in part on the continual growth of roots. If root systems were to completely cease growing by extension, the soil mass occupied by the existing roots could become so depleted of available water that the trees would suffer from serious lack of water, particularly if transpiration were high (Kramer and Kozlowski, 1960).

As was mentioned earlier in the chapter, water absorption is dependent upon the water potential gradients both in the soil and in the plant, that is, the more the available soil moisture, the steeper the free energy gradient of the water around the root and the faster the movement of water into the root. Any salts or substances dissolved in the soil solution can reduce the free energy gradient and affect the movement of water into the roots. However, salts are rarely sufficiently concentrated in the soil solution to become a major factor limiting to tree growth. Low soil temperatures may also decrease the permeability of roots to water by increasing the viscosity of water and by reducing capillary movement Since the condition, rate of growth, and extent of roots also affect water absorption, any factor that retards root elongation such as low oxygen availability, varying amounts of growth regulators, and little available food will correspondingly decrease the area of contact between the young roots and soil water and thereby cause water absorption to decrease (Kramer and Kozlowski, 1960).

VIII. Internal Water Relations of Trees

The water in a plant forms a continuous hydrostatic system (MacDougal, 1924). As water molecules diffuse out of the cells of the leaf, additional water molecules take their place. Usually the absorption of water in th roots lags behind water loss, so that the volume of water in the xylen decreases, the cells shrink slightly, and the water becomes subjected to increasing tensions without breaking the continuity of the water within the stem. If the water potential in the xylem becomes markedly less than the water potential of the cortex of the root, water may diffuse out of the cortex faster than it enters,in which case the turgor of the cortical tissues would decline, and tensions that were first confined to the xylem would extend to the surface of the root. As a result of these tensions, water is pulled by mass flow not only through the xylem but also from the

epidermis through the outer portions of the root (Kramer and Kozlowski, 1960; Meyer *et al.*, 1973).

The continuity of the water status in a tree is maintained because there are exceedingly strong cohesive forces among water molecules confined in the cells, and strong adhesive forces between the water and the cell walls. If one of these water columns breaks, it contracts like a released rubber band, and the cell or segment of the water-conducting system no longer functions (Kramer and Kozlowski, 1960; Plumb and Bridgman, 1972). However, the water columns apparently remain continuous in a sufficiently large number of cells so that resistance to movement of water from the roots to the leaves is not in itself variable enough to produce significant variation in water stress.

Frequently the amount of water absorbed during the day lags behind the water lost from the leaves even in plants growing in moist soil (Fig. 3.12; MacDougal, 1924). As the pressure becomes increasingly negative, the adhesive and cohesive forces of water exert a greater pull on the xylem cells, which is transmitted throughout the hydrostatic system causing further reduction in cell volumes through the plant. Such volume changes in the stem have already been described in Chapter 2 (see Figs. 2.12, 2.14, 2.15).

The rate of water absorption increases during the day until the rate of water uptake equals the rate of water loss, at which time no further shrinkage in volume of the plant occurs. Cessation of shrinkage occurs in the early afternoon if the soil is moist and transpiration low. However, if the soil is dry and transpiration high, the actual rate of water absorption may continue to lag behind transpiration until sunset, when stomates close completely and cause transpiration rates to markedly decline. Water then begins to enter the roots faster than it is lost, the volumes of cells in the stem begin to increase, and the stem swells.

Detailed studies of a 110-year-old *Pinus ponderosa* in Arizona (Brown, 1968; Budelsky, 1969; and Drew *et al.*, 1972), show how the hourly changes in stem size are associated with the natural water relations, transpiration rate, variations in solar radiation, temperature, and the exchange of carbon dioxide (Figs. 3.14 and 3.15). An air-conditioned, transparent, polyethylene tent was placed over the tree during six separate 48-hour periods through a single growing season, as shown by the six *t*'s marked on Fig. 2.15 (Fritts, 1966).

Figure 2.15 shows the general growth of the tree and Fig. 2.21 portrays the environmental regime of the site. April 15 was the approximate beginning date of growth in 1966. On that day buds opened, cambial activity began, and soil moisture was relatively high (Fig. 2.21). On April 15 (Fig. 3.14) transpiration rates continued to rise until around noon as

the water potential gradients between the leaves and the atmosphere increased. Water absorption apparently lagged behind water loss and the volume of the stem decreased. Clouds that formed from 1:00 p.m. to 2:00 p.m. reduced water potential gradients and caused transpiration to decline. This decrease in water loss was accompanied by a declining rate of cell shrinkage, especially in the upper portions of the stem. Clear weather returned at 2:30 p.m., transpiration began to increase again, and the basal portions of the stem showed accelerated shrinkage. Shadows were cast by neighboring trees after 3:00 p.m., light levels and air and
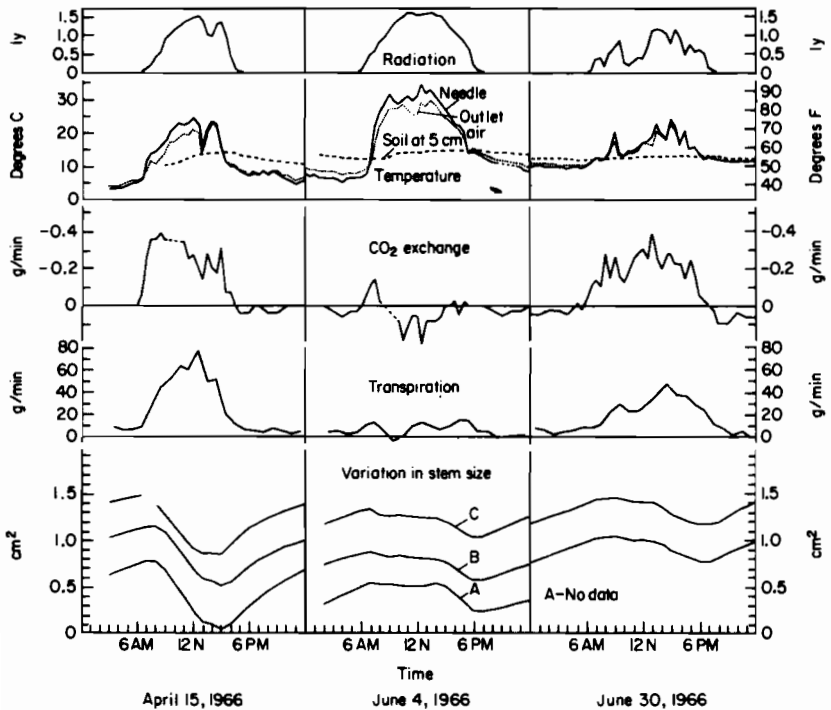
FIG. 3.14. Variation in stem size compared with variation in solar radiation, temperature, carbon dioxide exchange, and transpiration for an entire tree of *Pinus ponderosa* on a semiarid site in southern Arizona. Measurements are for three days of drought prior to the onset of the summer rains. A shower between June 4 and June 30 replenished some soil moisture, and greater cloud cover on June 30 decreased the severity of the drought. The tree was enclosed within an air-conditioned tent. (See periods marked with *t* in Fig. 2.15.) Dendrographs measured stem size at the base (A), middle (B), and upper (C) portions of the tree bole.

needle temperatures began to decline, transpiration decreased, water absorption exceeded water loss, and swelling in the stem commenced. The most rapid swelling occurred in the evening, when transpiration was low but water potential gradients between the plant and soil were steep. As pressure potentials and the turgor of cells in the tree increased throughout the night, water potential gradients between the roots and soil diminished and the rate of water absorption and the amount of stem swelling diminished.

By June 4, soil moisture was low and water deficits had begun to inhibit enlargement of growing cells in the stem (Fig. 2.15). Air temperatures had risen (Fig. 3.14) and water potential gradients between the leaf and air were undoubtedly steep. However, water content of cells was probably relatively low and leaf resistances were high, so when
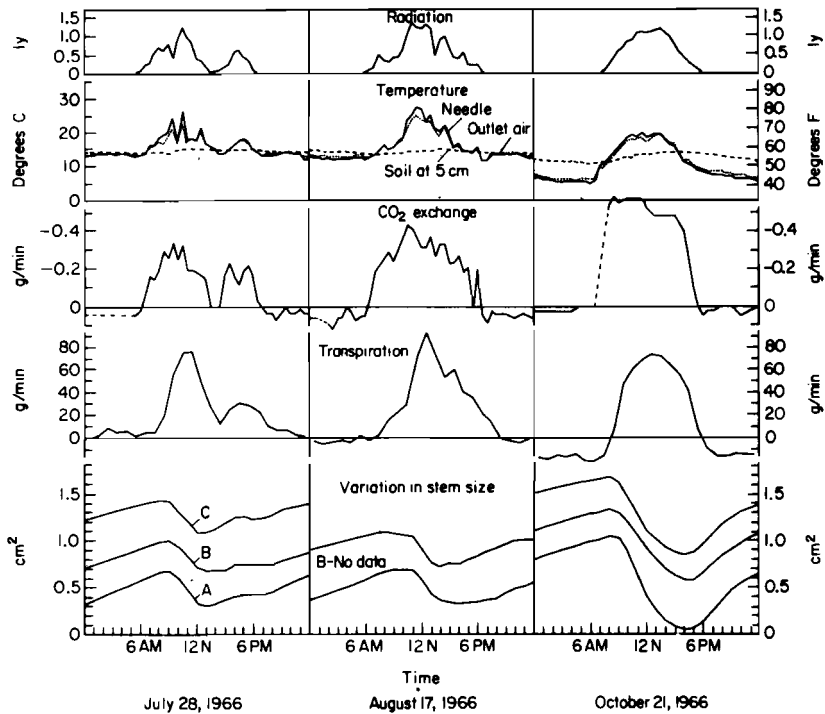
FIG. 3.15. Variations in stem size compared with variation in solar radiation, temperature, carbon dioxide exchange, and transpiration for an entire tree of *Pinus ponderosa* on a semiarid site in southern Arizona. Measurements are for three days after the onset of summer rains. Instrumentation was the same as for Fig. 3.14.

transpiration commenced after 6:00 a.m., its rate was markedly lower than on April 15 (Fig. 3.14). Dendrographs recorded an initial decrease in stem size, needle temperature soon became excessive, and the stomates (not monitored on this day) apparently closed. Even though water potential gradients outside the leaves became very steep, a high internal resistance, probably from stomatal closure, caused transpiration rates to remain low. This low rate of transpiration approximated the rate of water absorption from 8:00 a.m. through 3:00 p.m., so that the water balance and size of cells in the stem (as measured by the dendrographs) remained relatively unchanged. Stomates probably reopened around 3:00 p.m. as needle and air temperatures declined. The rate of transpiration exceeded the rate of water absorption, and the size of the stem decreased until 6:00 p.m., when low light levels caused stomates to close again.

Measurements for three summer days, June 30, July 28, and August 17, are shown in Figs 3.14 and 3.15. The weather was partly cloudy during all three days, a common condition for southeastern Arizona during the summer season. Showers associated with the periods of cloudy weather replenished soil moisture, water was absorbed more rapidly by the roots, and water potentials in the plant increased (Fig. 2.15). Stomates apparently remained open during the day, except possibly for the most cloudy weather; the internal resistance to transpiration within the needles was low, and even though the water potential gradients between the needles and air were less than in June, daytime rates of transpiration were high (Figs 3.14, 3.15). Transpiration greatly exceeded water absorption during the cloudless portions of the day and the stems exhibited a marked decline in size. As clouds built up late in the morning, the water potential of the air increased, and light levels became sufficiently low to cause stomatal closure, which in turn caused transpiration rates to decline. The water lost by the tree became less than the water absorbed by the roots, and the stem began to swell.

The rains of summer ceased prior to October 21 and soil moisture began to decline (Fig. 2.21). Measurements on October 21 (Fig. 3.15) show that transpiration increased rapidly after sunrise and continued at a high rate throughout the day so that the water loss exceeded water absorption and stems shrank rapidly throughout most of the day. The measurements of transpiration during the night exhibit negative values, implying that there was more water in the air entering than leaving the enclosure around the tree, and suggesting that some water vapor in the air was absorbed directly by the tree. However, the *dewpoint* of the air was below the temperature of the tree, so that the air water potential appeared to be lower than the water potential of the leaves. Even though no error could be detected in the measurements or in the design of the

enclosure, our present knowledge of water relations offers no suitable explanation for the apparent absorption of moisture by this tree, and the possibility of negative transpiration must remain an open question.

IX. Moisture Stress and Tree Form

Competition for water among the various plant tissues is a major factor in tree development and form. Those tissues that develop the lowest water potentials obtain water at the expense of those having high water potentials (Kramer and Kozlowski, 1960). Young leaves often obtain water at the expense of older leaves; shaded leaves may become dry and die before leaves in full sun because they cannot develop sufficiently low water potentials; and growing tissues usually obtain water at the expense of other tissues. For example, stem tips may continue to elongate and the

FIG. 3.16. Long-lived spike-topped trees of *Pinus longaeva* which contain rings that vary greatly in width and which correlate highly with variations in climate. (Courtesy of C. W. Ferguson)

cambium may remain active at a time when other tissues are shrinking (Fritts *et al.*, 1965c; Budelsky, 1969).

The height to which water must be lifted in a tall tree can also affect the tensions that are developed in various tissues and competition for water within the tree. The top branches of a tall tree may be subjected more frequently to high water stress than are other parts of the same tree. Therefore the apices of many old trees often grow very slowly, and in extreme cases the tops die while lower branches may continue to grow. With time, the conical crown of a young tree becomes spherical as the tree matures, and then it becomes distinctly flattened at the top as it reaches advanced age. Damage to a root system as well as drought can result in dieback of the tops. As erosional processes remove soil from around an aging tree, roots may become exposed and die, causing a greater reduction in water absorption and increased water stress. The dead terminal branches may remain intact for many years, giving rise to the feature referred to as a *spike top*, an important characteristic useful in locating extremely old, dry-site trees (Figs 1.12 and 3.16).

X. Soil Factors Affecting Root Growth, Ring-width Sensitivity, and Longevity

Sensitivity, as defined in Chapter 1, is the amount of relative variability in width from one ring to the next. Often the longest, most homogeneous, and most sensitive series of annual rings are from old trees growing on cliff faces, talus slopes, and rocky sites where there is little soil space for the growth of roots. The soil is relatively coarse textured and can include humus mixed with partially weathered parent material lodged in crevices and among large broken rock fragments.

The roots of a young tree growing on such a site gradually extend throughout the available soil mass. As the root volume increases, the amount of water available to the tree increases, allowing for increases in the growth of stems and leaves. When the roots have fully permeated the available soil mass, however, further increases in the volume of the roots cannot occur. Any growth of new leaves and branches which increases the transpiring surfaces will result in increased competition for water among the existing tissues of the tree. As competition increases extreme conditions of water stress will develop in those branches that are least vigorous, excessively exposed, or shaded, and they will die. The mass of living shoots is pruned and maintained in proportion to the absorbing surface of the roots, especially during years of extreme water stress.

Unless there is an enlargement of the available soil environment, little increase in growth rate is possible. Except for the variability in ring width

that occurs from one year to the next in proportion to amount of moisture available to the tree, no major change in stem size and in foliage or root mass occurs because of the limited space in the environment. The volume of the annual wood increment remains relatively constant so that there may be a slow decline in maximum ring width associated with the increasing circumference of the cambial sheath around the stem. Partial dieback of the cambium may occur in very old trees so that eventually only a strip of bark connects the living crown with the living roots (Figs 1.12, 3.16). Such individuals can live for several centuries or, in certain species, for several thousand years, exhibiting variability in ring widths that is highly correlated with variations in precipitation and temperature, without exhibiting any marked changes in the foliage, the roots, and in the mean growth rate (Fig. 1.12).

The crevice which supports an old tree may retain an extremely small proportion of any precipitation that falls. Large amounts of water may be lost to runoff, especially during intense summer storms or during winter storms which are prolonged, and only the small amount that is retained in the crevice can become available to the plant. Rocks often serve as collecting basins, and moisture is channeled into or away from certain sites. In addition, only a small volume of the crevice soil may be exposed to direct evaporation at the soil surface, so most of the available water that is trapped by the soil is subsequently absorbed by deeply penetrating roots. Since the total amount of available soil moisture is small, it becomes depleted over a relatively short period of time. The water potential of the plant decreases relatively rapidly between rains as the wilting point is approached, and water stress usually persists until soil moisture is replenished. The water table is commonly too deep to supply significant amounts of moisture to roots, but local areas of soil moisture seepage can sometimes provide a small but reliable moisture supply enabling the tree to survive. High mortality may be observed in those young trees whose roots are unable to penetrate to a more or less reliable moisture supply.

On crevice sites in semiarid western North America, water stress limits the growth of trees for longer periods of time than on sites with deeper or better developed soils (Fig. 3.17). As a result of these limiting conditions, ring widths from crevice-site trees are not only more variable from one year to the next, but they are on the average narrower and may be more highly correlated with variations in the number of precipitation days throughout the year than with the total precipitation amounts.

The tree growing on a crevice site may be a valuable study tree since the crevice environment can lead to longevity, high year-to-year ring-width variability, and little interdependence of ring widths upon conditions in prior years. This occurs because the crown and the xylem

FIG. 3.17. A crevice site *Pinus edulis* from Nothern Arizona in which the most exposed and least vigorous branches have died as a result of extreme water stress. Note the stunted and contorted shape of the tree and the large amount of exposed rock in the site.

increment cannot increase substantially over a period of several years of unusually high precipitation because the excess precipitation drains from the operational environment.

Trees on more optimum growth sites, on the other hand, are better able to use the high precipitation. Their crown can expand in height and aerial extent in the "luxury" of a favorable environment and there is a marked increase in ring width corresponding to the crown increment. However, a subsequent drought may be highly detrimental because the increase in transpirational area of the crown causes the tree to be more subjected to water stress. A several-year dry spell following years of high moisture can cause a large reduction in the crown area, the rings for several years can become very narrow (and sometimes absent), and in extreme cases death of the tree can result.

Since the crevice site tree will have much less moisture available to it during a wet period, the area of its crown, the xylem increment, and the

tree vigor do not respond to the favorable climate as much as they did in the optimum site tree. During the subsequent drought the ring may become narrow without being associated with a large reduction in crown area and a decrease in growth potential that persists for several years as occurs in the optimum site trees.

XI. Uptake of Mineral Salts

Salts dissolved in the soil water or on the surface of the soil particles may also move into the roots, be transported through the tree, and be utilized in processes affecting growth. Molecules and ions of salt, like water, often move by diffusion along gradients of decreasing free energy. Factors affecting the free energy gradient, such as permeability of the root and root growth, therefore, can affect the uptake of salts. Salts may be accumulated by the plant against a free energy gradient, however, through expenditure of metabolic energy. This accumulation is called *active absorption*. The mechanism by which the accumulation occurs is not completely understood, but one popular theory involves a carrier. This carrier becomes bound to the mineral salt, and the combination can move across membranes which are impermeable to the salt alone (Kramer and Kozlowski, 1960).

Individual cells can accumulate mineral salts in concentrations considerably higher than those occurring in the environment. The process is selective so the concentration of certain ions is controlled independently of the concentration of others. Since active absorption is influenced markedly by the physiological activity of the roots, factors such as low soil oxygen, low temperature, and low amounts of food and growth-promoting substances can also limit the absorption of salt.

Mineral salts are absorbed at the soil-root surface by an exchange of ions between the root and the soil. The root produces ions of H^+ and HCO_3^- and these ions are exchanged for mineral ions such as Ca^{2+}, K^+, and Fe^{3+}. Exchange may also occur between the root and minerals in water solution both outside and inside the root.

As is the case for many other soil factors, the absorption of salts rarely varies sufficiently from year to year to be important to the relative variations in ring width. However, changes in the mineral cycles of the soil, which may result from changes in the soil or from pollution of the environment, may alter the mineral content of plants. When other factors are not limiting, the availability of minerals can be the most limiting one and may influence ring characteristics such as the maximum ring width. There is growing interest in the possibility that microelements or isotopes in the air, dissolved in rain water or carried as dust, might be absorbed by

the tree through the leaves or roots and utilized in the structure of the ring. For example, carbon-14 from the rings has been shown to have varied markedly from one decade to the next over the past 10,000 years (Olsson, 1970), and certain stable isotopes of hydrogen, oxygen, and carbon, resulting from differences in sources of atmospheric moisture, could conceivably vary in measurable concentrations from ring to ring.

It has been suggested by some workers (Jonsson and Sundberg, 1972) that acidity of rain water due to present-day industrial pollution of the air may, over a period of time, alter soil factors which affect forest growth. If this occurs, and if it becomes a world-wide phenomenon, trees which are now limited by climatic factors may become more limited by changes in acidity and pollutants. This could influence calibration of ring width with climatic factors and limit future applications of tree rings to problems of climate.

XII. Translocation

The long-distance movement of organic and inorganic solutes from one part of the plant to another is referred to as *translocation*. The term is not ordinarily applied to the diffusion of solutes from cell to cell, but it does include the movement of mineral salts dissolved in water which usually are transported upward from the roots to the leaves through the xylem. The salts may then be translocated out of leaves through the phloem and become distributed among various tissues of the plant. Organic substances are generally translocated through the phloem. Some salts absorbed from the soil, such as those of nitrogen, phosphorus, or sulfur, can react with organic substances that have been translocated to the roots. The salts which are then a part of the organic compounds are translocated out of the root through the phloem (Kramer and Kozlowski, 1960). However, the pathway for upward translocation of mineral salts, more specifically ions dissolved in water, is usually the xylem. High rates of transpiration, high concentrations of mineral salts in the soil, and favorable aeration of the soil favor rapid translocation of ions through the xylem.

Translocation through the phloem, unlike translocation in the xylem, may be bidirectional, that is, different substances may be translocated in opposite directions simultaneously. Translocation in phloem can occur at substantial rates through the living sieve cells which are metabolically active (**Fig.** 2.1). Lateral movement of organic molecules in the stem occurs in the radially oriented and living rays.

Several hypotheses have been proposed to explain the mechanism of translocation in the phloem, but no one hypotheses is entirely satisfactory

(Kramer and Kozlowski, 1960). The hypotheses involve simple diffusion, movement along the protoplasmic interfaces of the phloem, active streaming of the protoplasm throughout the elongated sieve tubes contained in the phloem, and mass movement developed by the water potential gradient throughout the plant.

Downward translocation of organic molecules from large branches occurs in a vertical direction in straight-grained wood so that the substances are used by the cambial tissues and roots directly below them. Often trees exhibit spiral grain and translocation occurs in a spiral direction. Annual rings formed by cambia in the path of the translocation stream from a heavily foliated branch or from the crown often are wider than those not in the path. Changes in the growth and shape of the crown which are due to changes in competition or exposure of the tree can alter the translocation of organic substances down the stem and can cause corresponding changes in ring widths.

The variability in translocation of food and growth substances from irregularly shaped crowns of aging *Juniperus osteosperma* (Fig. 3.18), *Pinus longaeva, Pinus flexilis,* and *Artemisia tridentata* may be partly responsible for the asymmetric growth of stems, partial dieback of the cambium, and the formation of thin strips of live bark that connect the live tops with the live roots (Fig. 3.18). If the strip of cambium continues to grow for many years, it will produce flattened slab-shaped stem form. Sometimes the wood grain is twisted and the strips of living bark frequently spiral around the stem of such strip-barked trees (Wright and Mooney, 1965; Ferguson, 1964, 1968; Fritts, 1969).

Injury of the bark may destroy the phloem. If a segment of bark completely encircling the stem dies, transpiration of organic food to the roots will be blocked. If the injury is permanent, the stem and roots below the injury die after all food reserves are exhausted. If injury is not permanent or a portion of the bark remains intact, a reorientation of the conducting tissue occurs and new xylem and phloem are formed around the wound, which function effectively in both upward and downward translocation (Kramer and Kozlowski, 1960; Meyer *et al.,* 1973). Serious injury of the stem by fire can kill as much as 90 per cent of the bark circumference in some trees without causing a noticeable reduction in growth in the stem below the injury. However, severe fire injury can reduce ring-width growth (Jemison, 1944) or induce anomalous growth in the injured area. Fungi, insects, and bark-eating animals can also injure the bark and effectively girdle the stem of a tree. Some diseases infect phloem cells and thereby interfere with food conduction in the tree.

Natural root grafts may establish connections between root systems of adjacent trees (Graham and Bormann, 1966; Eis, 1970; Stone, 1974), and

FIG. 3.18. A gnarled crevice site *Juniperus osteosperma* from Northern Arizona in which the leaf surface has been limited by the small soil volume available to the roots. Dieback in the branches causes partial die-back of the cambium so that only narrow strips of living bark remain intact along the branches, main stems, and roots of the tree.

sizeable quantities of food and other substances may be translocated from one tree to another of the same species through such grafts. A group of stumps in a dense forest may be connected so effectively through root grafts that the root systems will enable the stump to survive on carbohydrates supplied by neighboring standing trees (Kramer and Kozlowski, 1960). LaMarche and Wallace (1972) report on a *Sequoia sempervirens* stump in which the rings continued to form after the tree was cut, with no major change in mean width. This indicated there was substantial translocation through roots grafted to neighboring trees and that translocation through such grafts must have been substantial even before the tree was cut.

Young sprouts from roots of grafted seedlings grow more rapidly than the nongrafted neighbors, since they can obtain carbohydrates from the mother tree (Laufersweiler, 1955). It is likely that the translocation of food through root grafts is an important factor in the survival and growth

of some suppressed subcanopy trees (Graham and Bormann, 1966). The effect of root grafting and subsequent translocation from neighboring trees on a ring-width chronology has not been ascertained. It is possible that root grafting would have little effect on the climatic information in rings because all neighboring trees would be essentially responding to the same variation in macroclimate. However, root grafting could conceivably reduce some of the differences in ring-width response among trees because each tree would be utilizing the same common root system and drawing upon a communal source of moisture.

The movement of organic solutes over long distances throughout the plant is basically controlled by factors affecting diffusion of substances into and out of the translocation stream as well as by the physiological activity of the phloem. Food seems to move toward regions of high metabolic activity, and certain growth regulators may at least partly control the direction of translocation because of their effects on the physiological activity of various tissues in the plant. Kramer and Kozlowski (1960) point out that changes in temperature may affect certain metabolic processes and influence the rate of transport in phloem. Oxygen is also necessary for high metabolic activity, and presumably poor soil aeration may hinder or prevent translocation of organic substances through some roots.

Studies on translocation rates and times of peak movement show the following results. Huber et al. (1937) reported that maximum rates of translocation in oak stems follow the daytime peak of net photosynthesis in the crown. Maximum rates occurred in the early evening first near the stem top and last at the base, while minimum rates occurred in early morning. The movement of carbohydrates out of leaves is reportedly more rapid during the day than night (Meyer et al., 1973), since during daytime photosynthesis is producing high concentrations of carbohydrates in the leaves. Zimmermann (1969) reports translocation rates for sugar in stems of *Fraxinus americana* of approximately 30–70 cm per hour. Lateral transport of organic molecules in the stem may occur more slowly than vertical transport due to smaller free energy gradients in that direction.

According to Wardlaw (1968) it is probable that the effect of environmental factors on actual conduction of foods and other organic substances is of minor importance in determining ring widths as well as their pattern and distribution within the stem. The environmental factors are more likely to critically limit the food-making or food-using processes directly than the rate of food movement. The various processes and limiting factors affecting them are described in the following chapter.

Basic Physiological Processes: Food Synthesis and Assimilation of Cell Constituents

I. Introduction

The life activity of a plant is dependent upon a continual source of energy which is usually derived from food. When the plant is actively growing, large amounts of food must be available, not only as a source of energy, but also as a source of raw materials from which the new tissues are built. It has been shown in previous chapters that the various growth processes

throughout the tree occur at different rates which can vary from one minute to the next, one month to the next, and from year to year throughout the operational history of the plant. The availability of foods can have a variety of effects on plant growth, depending upon which growth processes are involved, their rate of activity at the particular time of year, and age of the plant.

Chapter 3 describes those processes involved in the movement of materials into and out of the plant and among its living cells. This chapter will deal with the most important biochemical processes involved in (1) the making of organic compounds classed as foods, (2) the release of energy within living cells, and (3) the synthesis of complex organic and inorganic substances which become living protoplasm, nonliving cell parts, and other substances that are necessary for life and growth.

Near the end of the chapter, consideration is given to some of the preconditioning systems within the plant which influence the relative activity of processes which in turn affect growth. Finally, the seasonal variations in climate are described as a function of elevation and are related to variations in the physiological activity of the plant.

II. Photosynthesis and Respiration

Photosynthesis, sometimes referred to as *carbon assimilation*, is the process by which sugar (glucose) is manufactured from carbon dioxide and water by the chlorophyll-containing tissues (chlorenchyma) in the presence of light, with oxygen being formed as a by-product. Light energy is absorbed by the chlorophyll-containing plastids called *chloroplasts* and converted to chemical energy in the glucose molecule. The resultant glucose manufactured in the process is sometimes referred to as *photosynthate*.

The simplest chemical equation for photosynthesis may be written as follows:

$$6\,CO_2 + 6\,H_2O \xrightarrow[\substack{\text{chlorophyll} \\ \text{(in living cells)}}]{\text{673 kg-cal light energy}} C_6H_{12}O_6 + 6\,O_2\uparrow \qquad (4.1)$$
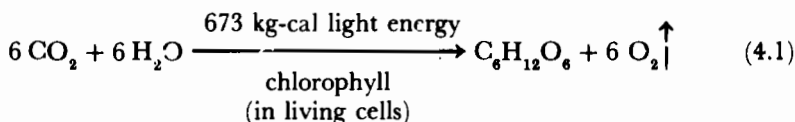
Actually the process is a highly complex one where the carbon from carbon dioxide becomes a part of a number of intermediate substances before glucose is formed (Meyer *et al.*, 1973). There are two basic steps involved, the first requiring light and the second involving chemical reactions which depend upon favorable temperatures but not light. It is

satisfactory for our purposes, however, to regard the process as a single reaction in which glucose ($C_6H_{12}O_6$) and oxygen are the end products.

In higher plants two different chlorophylls (identified as chlorophylls *a* and *b*) may be involved in photosynthesis. Basically, each chlorophyll molecule is built from carbohydrates and salts of nitrogen and magnesium. Salts of iron are also essential to certain biochemical reactions that are involved in the chlorophyll synthesis (Meyer *et al.*, 1973). Photosynthesis is an important process because the glucose molecule, or chemically altered fragments of it, form the building blocks from which all other organic substances are made.

The energy that is stored in the glucose molecules can be released by a series of biochemical reactions, referred to collectively as *respiration*. Part of this energy is lost as heat, but the remainder is transferred to high energy molecules called *adenosine triphospate* (ATP). The energy is stored as ATP molecules until it is utilized directly by energy-using processes occurring in the cell. The simplest chemical equation for respiration may be written as follows:

$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O\ +\ 673\ \text{kg-cal energy} \qquad (4.2)$$
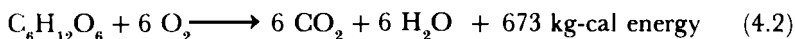
Such respiration which utilizes oxygen and glucose and releases carbon dioxide, water, and energy is *aerobic respiration*. The glucose molecule is chemically altered and this substance is split into smaller fragments. Some of these fragments, in turn, form basic structural units for the synthesis of the various foods and other cell-building substances. Respiration results in a loss of dry weight and occurs continuously in all living cells, both during the day and night. Respiration may be extremely slow in dormant seeds and dormant plants, while it is most rapid in the active meristems, including the cambium, growing shoots, root tips, young leaves, and growing fruits.

If atmospheric oxygen is absent, *anaerobic respiration* which does not require free oxygen can occur in cells of certain species. Anaerobic respiration can occur in roots when soils are poorly aerated and in tissues where diffusion of oxygen is restricted by impermeable structures such as the seed coat (Kramer and Kozlowski, 1960). Unlike aerobic respiration described above, anaerobic respiration releases only a portion of the energy chemically bound in the sugar molecule. Various chemicals such as aldehydes and alcohols are by-products, and if these substances accumulate, they may become sufficiently concentrated to be toxic to the tissues in which they are formed (Kramer and Kozlowski, 1960). When oxygen is available but in limited supply, both aerobic and anaerobic respiration may occur.

III. Synthesis of Foods and Assimilation

If one is to properly model and analyze ring-width growth as a function of climatic factors, it is important that he be aware of the role of glucose in the making of foods and other substances which are necessary for growth and development (Fritts, 1971). The following section describes the three basic classes of organic materials that are synthesized from glucose, and their functions in the growth of the plant. The term *food*, as used in this text, refers only to organic molecules classed as carbohydrates, fats, and proteins which contain chemically bound energy. Mineral salts which may be essential for growth are technically not foods, because they are not utilized as an important energy source. The best-known carbohydrate foods include sugars and starches, to be distinguished from carbohydrate cell constituents such as cellulose and lignin, which are synthesized from food but cannot be utilized again as a food or energy source. Sugars such as glucose are utilized in respiration as well as in the synthesis of the other two food classes, fats and proteins. Any glucose that is not so utilized may accumulate or be converted to starch or some other type of reserve food.

Fats and fat-like substances are present in every living cell. They are important constituents of protoplasm and may accumulate in large quantities in storage tissues or may form the waxes, such as cutin or suberin, that are commonly deposited in the cell walls of the endodermis, epidermis, and cork.

Proteins also are important constituents of protoplasm, and in some cases they can serve as food storage material as in seeds. In addition, most enzymes which catalyze the chemical reactions within cells are proteins. Protein molecules are comprised of long chains of amino acids, and the chemical characteristics of each protein are determined by the order of the amino acids along the chain.

The biochemical reactions involved in the synthesis of foods from glucose are extremely complex. These reactions basically involve two types of chemical processes. The first, referred to as a *condensation-hydrolysis reaction* represents a change in solubility of reactants in water but involves little change in energy.

$$\text{glucose} \xrightleftharpoons[\text{hydrolysis}]{\text{condensation}} \text{starch} + \text{water} \qquad (4.3)$$

$$\text{(amylase)}$$
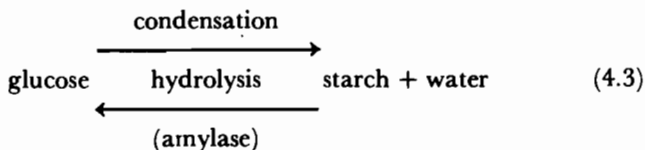
When *condensation* occurs molecules of soluble substances such as glucose

combine with one another to form an insoluble and chemically more complex substance such as starch. *Hydrolysis* is in a sense the reverse of condensation in that relatively complex insoluble substances are converted to smaller soluble ones as occurs in *digestion*. Both types of reactions are catalyzed by enzymes produced by the plant, but the direction and rate of the reaction may be controlled by a combination of the specific enzymes, the concentrations of reactants, acidity of the solution, and other conditions within the plant. The presence of the enzyme *amylase* is required for both the synthesis of starch from glucose and the reverse reaction, hydrolysis, which converts starch back to glucose.

The rates of these particular condensation–hydrolysis reactions are markedly influenced by the rates of production, consumption, and translocation of glucose throughout the tissues of the plant. Under daylight, when photosynthesis is rapid, much of the glucose that is produced by the leaves diffuses out of the green cells of the leaves and is translocated to areas of the tree where glucose concentrations are lower. The glucose then can be utilized for growth or can accumulate in the living cells. The accumulation of glucose drives the condensation reaction (to the right in Equation 4.3) which converts glucose to starch. During the first hours of darkness, when photosynthesis has ceased but respiration continues, glucose becomes most evenly distributed around the plant, and its concentration declines until the reaction is forced in the opposite direction initiating hydrolysis. By early morning starch is being digested back to glucose.

The significance of the condensation–hydrolysis reaction is that starch, unlike sugar, is insoluble in water, and its presence in a cell has no effect upon the water potential. Changes in the rates and direction of condensation and hydrolysis, therefore, affect the amounts of dissolved substances in cells, influence the cell–water relationships, and as a result play an important role in many processes such as the opening and closing of the stomates, translocation, and growth.

The second basic type of biochemical reaction in a plant is *oxidation-reduction*, which involves an energy exchange in the reactants. The energy is usually derived from ATP. The molecule which gains energy is said to be *reduced* during the reaction, and the molecule which loses energy is *oxidized*.

Figure 4.1 diagrams the interrelationships among the basic food-making processes. Arrows in the vertical direction represent oxidation-reduction reactions, while arrows in the horizontal direction represent condensation-hydrolysis reactions. The synthesis of many foods involves both types of reactions. For example, in the synthesis of fats,

carbohydrates are first reduced in oxidation-reduction reactions to form glycerol and high energy-containing fatty acids, and then fats are synthesized by condensation of glycerol and three fatty acids. Because fatty acids contain considerably more chemically bound energy than the carbohydrates, they are more efficient food storage molecules than carbohydrates. Before the insoluble fats can be utilized in processes such as respiration and the manufacture of cell parts, they must be hydrolized to the more soluble fatty acids and glycerol.
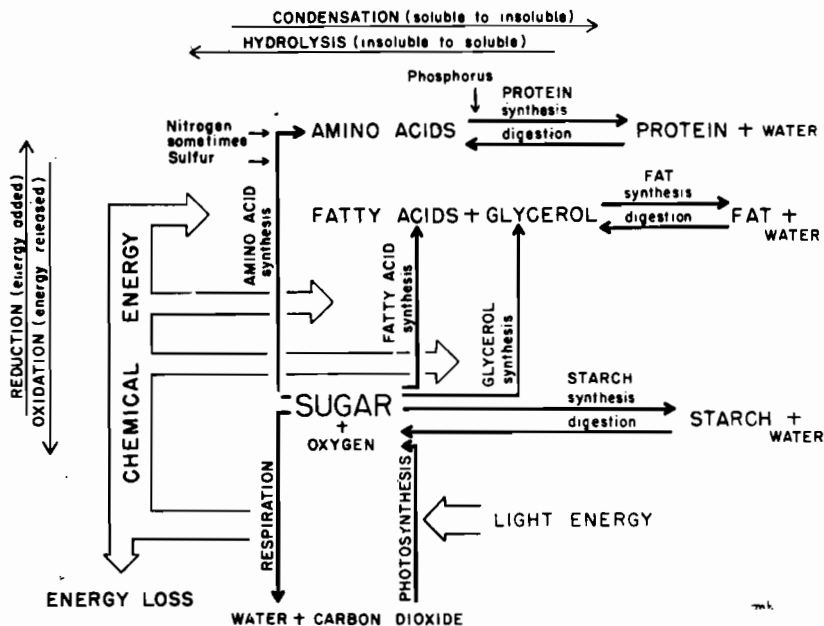
FIG. 4.1. Diagram representing the basic processes of food synthesis in green plants. The downward pointing arrow represents an oxidation reaction in which energy is released, and the upward arrow represents a reduction reaction in which energy is added. Horizontal arrows to the right represent condensation and to the left, hydrolysis. Organic substances on the left are soluble, those on the right are insoluble. Light energy is utilized in photosynthesis, as shown by the input arrows at lower right. Respiration releases this energy which was stored in the sugar (glucose) molecule. The energy is either released or transferred to reduction reactions, such as glycerol synthesis, fatty acid synthesis, and amino acid synthesis (arrow marked CHEMICAL ENERGY, on left). By means of condensation amino acids are converted to insoluble proteins, fatty acids to fat, and glucose to insoluble carbohydrates, such as starch. Insoluble substances are converted to soluble substances in the process of digestion. All reactions require specific enzymes. Nitrogen, phosphorus, and sulfur are necessary for the formation of certain amino acids and proteins. (Drawing by M. Huggins)

Amino acid synthesis (Fig. 4.1) involves reduction of certain mineral salts as well as changes in organic molecules. For example, reduced nitrogen and sometimes sulfur are combined with carbon compounds derived from carbohydrates. The synthesis of the soluble amino acids requires expenditure of chemical energy. The amino acids can then be linked to one another by a series of complex condensation reactions to form insoluble protein molecules.

The term *assimilation* is used in this book as an extension of food synthesis. In its simplest aspects, assimilation may be considered to be the utilization of carbohydrates, fats, and proteins to synthesize the protoplasm, cell walls, and numerous other substances making up the enzyme systems, pigments, and structures of plants. Assimilation involves the same sort of reactions involved in food synthesis, except that the end products become functional constituents of a cell. Assimilation requires the energy released by respiration, it utilizes soluble foods and minerals, and it depends upon numerous enzyme systems found in living cells. All the parts of a growth ring are essentially produced by assimilation, which may in turn be dependent upon any factors that limit photosynthesis, respiration, synthesis of food, and the general level of metabolism in the plant.

IV. Measurement of Photosynthesis and Respiration

Since the processes of photosynthesis and respiration involve a number of biochemical reactions and both processes can occur simultaneously, it is not an easy task to obtain accurate measurements of their respective rates. Both processes affect the amount of glucose in the plant and the exchange of carbon dioxide and oxygen between the atmosphere and the plant. At night respiration can be measured directly from the changes in carbon dioxide, oxygen, and dry weight, since photosynthesis does not occur in the dark. In the presence of light during the day, changes in the same variables provide a measure of the net effect of photosynthesis minus respiration, which is referred to as *net photosynthesis*. *Gross photosynthesis* is the total amount of glucose formed without regard to its consumption in other processes. It can be estimated by assuming that daytime respiration rates equal nighttime respiration rates and then adding the estimated daytime respiration to the net photosynthesis measurement. It has been found in recent years that such calculations may underestimate gross photosynthesis, because in certain plants respiration in light is more rapid than respiration in the dark (Ray, 1972; Decker, 1957).

Many estimates of photosynthesis and respiration involve measurements of carbon dioxide as it increases or decreases in an

airstream passed over the plant material. The rates of the processes are expressed as grams of carbon dioxide utilized or lost per gram of dry weight of the plant. Other approaches utilize measurements of the amounts of oxygen absorbed, or changes in dry weight. For a general discussion of various techniques for measuring these processes, see Kramer and Kozlowski (1960) and Meyer et al. (1973).

V. Factors Affecting Photosynthesis and Respiration

Since all foods and cell constituents are derived from glucose molecules, tree growth can be markedly affected by conditions influencing photosynthesis and respiration rates. Both external factors and internal conditions of the tree affect the rates of these two processes. The important environmental factors involved are light, temperature, moisture, available gases, and soil fertility. The internal conditions include such things as physiological state of the tissues, the condition of the stomates, accumulation or availability of foods such as glucose, and any structural modification of functional plant tissues resulting from prior growth, increasing tree age, and injury of some plant part.

A. Light

Light is an important factor in photosynthesis, because it is the ultimate source of energy that can be utilized in the making of glucose. At low intensities, light is usually the most limiting factor, and the photosynthetic rates vary directly as a function of light intensity. At high light intensities, however, a further increase in intensity may not increase the rate of photosynthesis, because chloroplasts may be "light saturated" and some other factor becomes most limiting to the process (Fig. 4.2). Often clouds can reduce light intensities sufficiently during midday to cause photosynthetic rates to be low. (See Figs. 3.14 and 3.15 for June 30, July 28, and August 17, 1966.)

The length of the daylight period can affect the length of the photosynthetically active period. This may be an important factor for the growth and survival of trees at high latitudes where the growing season is short, because days are long and photosynthesis occurs at high rates almost continually throughout cloudless periods in summer (Tranquillini, 1964a).

All leaves or needles within a tree crown are not equally exposed to light. Those on the east side become light-saturated early in the morning, while those on the west may be light-saturated by late afternoon. Leaves in the lower crown may rarely reach light saturation, due to shading, and

as a result there is a tendency for net photosynthesis, as measured for the entire tree, to increase to some extent with any increase of light intensity. As a result, the maximum rate of photosynthesis for a single leaf occurs at lower light intensities than the maximum for the entire crown of the tree.

The intensities at which light saturation occurs may vary because of differences in structure and optical density of leaves. Leaves that have grown in full sun are generally thicker .and darker green than leaves grown in the shade (Kramer and Kozlowski, 1960). These thick leaves absorb light more efficiently and become light-saturated at higher intensities than leaves grown in shade. Photosynthesis is also reported to utilize certain frequencies of light more efficiently than others (Gates, 1965). However, the various light frequencies in a moderately dense forest are probably not sufficiently altered from those of full sunlight to affect photosynthesis to any substantial extent (Kramer and Kozlowski, 1960).

As a tree grows and the upper crown extends over and shades the lower leaves, photosynthesis in the most shaded branches can b 'come so limited that they produce less food than they consume. These lower branches will eventually lose their vigor and die (Kramer and Kozlowski, 1960). Since a significant amount of food reserves can become consumed by these
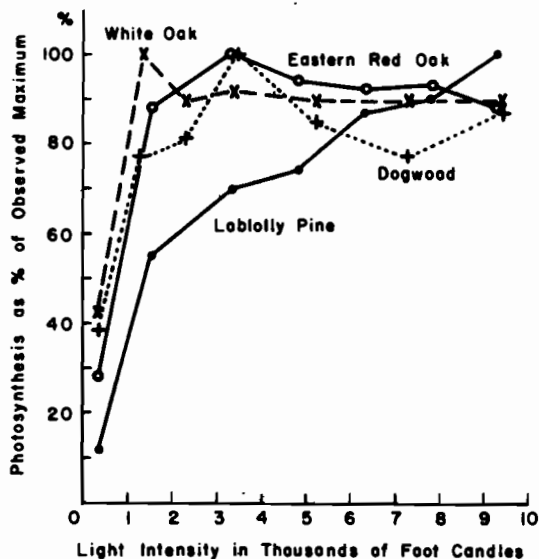
FIG. 4.2. The rates of gross photosynthesis occurring in tree seedlings for one-hour periods at various light intensities. Values are expressed as percentages of maximum observed rates. Temperature was maintained at approximately 30°C. (Redrawn from Kramer and Decker, 1944)

lower branches, it is possible that their death in a stress year can actually increase the overall accumulation of food in the tree during the following years.

Different species require different minimal light intensities to carry on photosynthesis and are said to differ in their tolerances to light. Seedlings of species which require high light intensities can become established in a site only after disturbance and opening of the canopy or in early successional stages when there is sufficient light to carry on the photosynthesis necessary for growth. The more shade-tolerant trees can establish themselves at any time, though they usually become established later in the successional sequence (Daubenmire, 1959).

There are two distinct groups of biochemical respiration reactions, one of which is called *photorespiration* and involves light (Ray 1972). Those plants which carry on photorespiration are referred to as C-3 plants; those which carry on respiration unaffected by light are called C-4 plants. Even though light does not affect respiration itself in C-4 plants, it can have indirect effects on the reaction because it enters the energy budget and affects plant temperature (see Chapter 5). Light can also influence photosynthesis, which in turn increases the amount of oxidizable substances available for respiration; light can influence chemical reactions involving the state of food reserves; and, as mentioned earlier, light can also influence stomatal opening and the exchange of gases involved in respiration. Brown (1968) reports high rates of net carbon dioxide production indicating high rates of respiration in *Pinus ponderosa* under high light levels during the day, which he attributes to high daytime temperatures of the needles due to heating by the sun.

B. Temperature

Photosynthesis and respiration occur over a wide range of temperatures, and temperature can affect each of the processes differently. Temperature also may affect conditions and processes such as dormancy, meristematic activity, reproduction, and growth, all of which interact with and modify respiration and the net photosynthesis of the plant.

The temperature minimum for net photosynthesis generally lies between $-2°$ and $-5°C$ (Tranquillini, 1964a), while respiration has been measured at temperatures as low as $-12°C$ (Freeland, 1944). Brown (1968) reports that he could not identify measurable exchanges in carbon dioxide from needles of *Pinus ponderosa* below temperatures ranging from $-2°$ to $-4°C$. The persistence of low temperatures can prevent significant amounts of respiration and photosynthesis from
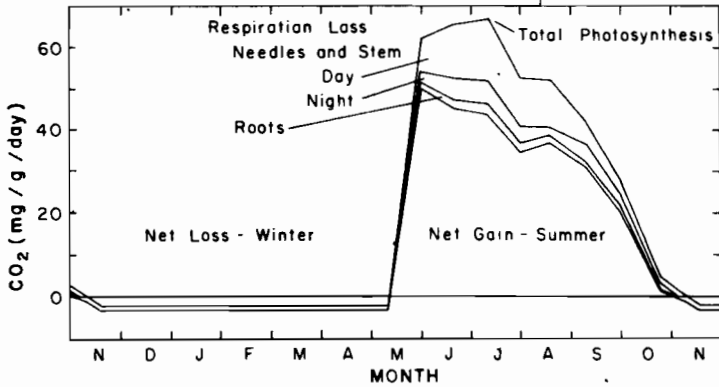
FIG. 4.3. The carbon dioxide balance throughout the year for young pines at tree line. The top line represents the total daily carbon dioxide used in gross photosynthesis. The area between the top and second highest line represents the carbon dioxide loss during the day due to needle and stem respiration. The area between the second and third highest lines represents loss of carbon dioxide due to respiration in the needles at night, and the area between the third fourth highest lines represents loss of carbon dioxide in the roots. The area between the lowest line and zero represents the daily net gain in carbon within the plant. During the winter little photosynthesis occurs and there is a net loss of carbon dioxide due to respiration of the plant. (From Tranquillini, 1964b)

occurring in conifers during long periods throughout the winter (Fig. 4.3; Tranquillini, 1964a, b). However, during brief periods of elevated temperatures within a long cold period respiration may increase much more rapidly than photosynthesis so that there is a loss of stored foods (Tranquillini, 1964a). Photosynthesis can also occur during winter in the twigs of deciduous trees (Perry, 1971).

Wintertime respiration of the high elevation *Pinus longaeva* in California, is reported to remain at the summer rate. Schulze *et al.* (1967) estimate that for *Pinus longaeva* at least half the summer season is needed to manufacture enough carbohydrate to equal that consumed during the brief warm periods in a normal winter. The probability of a negative net photosynthesis balance occurring throughout a year would increase with elevation and latitude, because the photosynthetic season becomes shorter and the inactive winter period longer. To a certain degree, the location of alpine and arctic tree lines may be influenced by the balance between winter respiration and summer net photosynthesis. Summer photosynthesis above the tree line may be reduced to such an extent that there is not enough food surplus to compensate for the loss due to respiration during the long winter (Tranquillini, 1964b).

When daytime temperatures are below 0°C during clear winter

weather, high elevation conifers have been shown to be especially sensisitive to high radiation and to suffer considerable loss of chlorophyll, causing the foliage to turn yellow (Tranquillini, 1964a). In late winter, respiration in the yellow-colored foliage utilizes sizeable amounts of stored carbohydrates at a time when the absence of chlorophyll prevents photosynthesis from occurring. Normal photosynthesis resumes in spring after chlorophyll is resynthesized in response to warm weather. If shoots of *Pinus cembra* that are in subfreezing temperatures are brought to +10°C in midwinter, about three days are required before net photosynthesis can be measured (Tranquillini, 1964b). If the shoots are placed in a warm temperature toward the end of winter, however, net photosynthesis can be measured immediately, although the rates are markedly lower than those that occur in the summer (Fig. 4.3). Tranquillini reports further that differences between the photosynthetic capacity of trees in the high mountains and those in the valleys are due primarily to differences in the frequency of severe frost which can destroy and thus deactivate chlorophyll in the leaves.

On warm sites such as those at low elevations or on south-facing exposures, there may be little deactivation of chlorophyll during winter. For example, Brown (1968) found little reduction in wintertime photosynthetic capacity and no decrease in chlorophyll content for *Pinus ponderosa* near its lower forest limits in southern Arizona. He did, however, find daytime release of carbon dioxide following winter nights when the trunk of the tree was frozen (Fig. 4.4). In these instances, carbon dioxide was released during the morning until noon when the tree had thawed and photosynthesis began. Carbon dioxide was absorbed during the afternoon until light became limiting at the end of the day (Fig. 4.4). When nighttime freezing of the trunk was less extreme, less carbon dioxide was lost by the branches and net photosynthesis reached maximum rates earlier in the day. In contrast, no carbon dioxide was lost during winter days which followed warm nights when the stems did not freeze. Under these conditions, net photosynthesis began at sunrise and continued at a high rate throughout the day except for periods when light, temperature, or moisture became limiting to the process (Fig. 4.4).

High temperatures can be limiting to both photosynthesis and respiration. In general, gross photosynthesis increases rapidly with increases in temperatures in the 0° to 15°C temperature range (Fig. 4.5). At higher temperatures there may be little change in the photosynthetic rate. Respiration, on the other hand, increases at a less rapid rate in the lower temperature range (Fig. 4.5). Respiration in many plants increases 2·0 to 2·5 times for each 10°C rise in temperature within the 10° to 30°C range (Meyer *et al.*, 1973). The optimum temperature for net
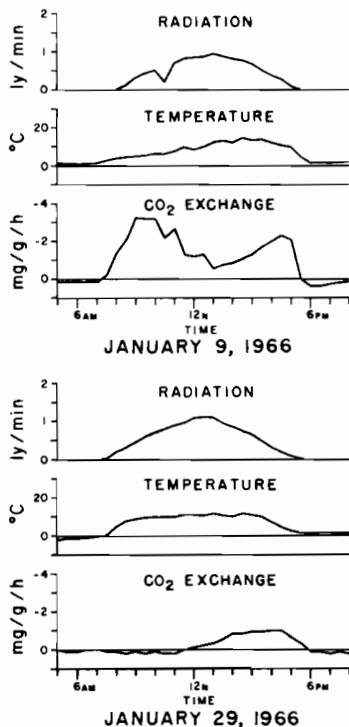
FIG. 4.4. Net carbon dioxide exchange from a branch of an arid-site *Pinus ponderosa* during two winter days. January 9 was preceded by a relatively warm night when no freezing occurred within the main stem of the tree, while January 29 was preceded by a cold night when freezing caused marked shrinkage in the tissues of the main stem. (Redrawn from Brown, 1968)

photosynthesis of temperate-region plants lies between 15° and 30°C. As temperatures increase above the optimum, net photosynthesis declines, because the rate of respiration increases faster than the rate of gross photosynthesis. Eventually more food may be consumed than is manufactured, and if the conditions persist, death due to starvation can result. The thermal death point of most living plant cells is between 50° to 60°C. Death due to extreme heat is caused by the coagulation of protein components in the protoplasm (Meyer *et al.*, 1973). Optimum temperatures for net photosynthesis may also vary among different species, throughout the season, and from site to site, depending upon prior light intensities, moisture availability, and factors which precondition the tree. Optimal temperatures for net photosynthesis in tropical and subtropical species often lie between 25° and 30°C, and in
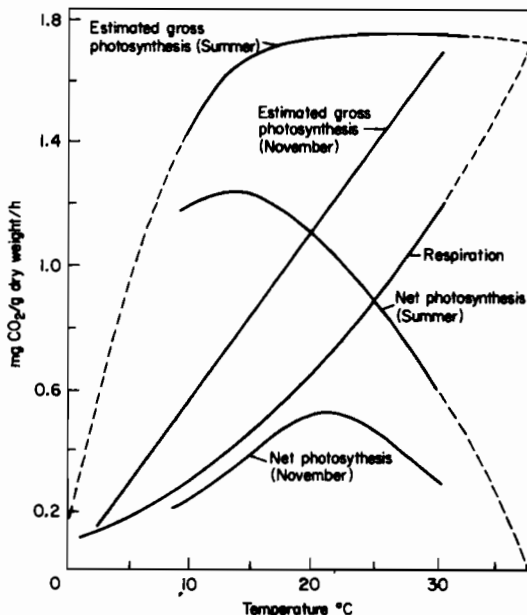
FIG. 4.5. The apparent relationship among temperature and estimated gross photosynthesis, net photosynthesis, and respiration in *Pinus longaeva* during summer and the month of November. Dashed lines represent extrapolated data, and respiration is assumed to occur at the same relative rates throughout the day and throughout the year. (Redrawn from data presented by Mooney *et al.*, 1966, and Schulze *et al.*, 1967)

species of the cooler temperate latitudes they may lie between 15° and 20°C. At the upper tree line, however, the optimal temperature may be 2° or 3° lower than 15°C (Tranquillini, 1964a).

The specific relationship among temperature, estimated gross photosynthesis, net photosynthesis, and respiration in *Pinus longaeva* for summer and fall months obtained by Mooney and his colleagues is summarized in Fig. 4.5. The rate of gross photosynthesis in summer appears to rise rapidly from temperatures near freezing to 15°C, but further increases in temperature are not accompanied by marked changes in gross photosynthesis. On the other hand, respiration, as inferred from measurements made in the dark, increases exponentially as a function of temperature between 0° and 30°C. The maximum rate of net photosynthesis measured in summer for high elevation *Pinus longaeva* occurs around temperatures of 15°C. Young plants grown under greenhouse conditions, however, exhibit lower rates of net photosynthesis

at 10°C and higher rates at temperatures of 20° and 30°C (Mooney *et al.*, 1966). Seedlings measured in the field during November exhibit low rates of net photosynthesis with optimum values occurring around 20°C (Fig. 4.5; Schulze *et al.*, 1967).

High respiration rates due to high temperatures of nongreen tissues, such as those in the stem and root, may result in deleterious conditions within the plant. For example, soils that are compact and waterlogged may reach critical temperatures in summer. Oxygen can be depleted by aerobic respiration of soil microorganisms to such an extent that continued metabolic activity and life can be continued only by anaerobic respiration in the roots. Thus, prolonged flooding in the summer months can be injurious to the deeper roots, but if there is a series of wet and dry cycles or if flooding occurs during the colder winter period, respiration may not exhaust the available soil oxygen sufficiently to cause death or a reduction in the growth rates of roots.

C. Water

Slatyer (1967) defines two main modes of action of water deficits on photosynthesis: (a) the indirect effect of water deficits on stomatal closure and reduced diffusion of carbon dioxide into the leaf, and (b) the direct effect of water deficits on the biochemical reactions involved in photosynthesis. Slatyer goes on to point out that photosynthesis is dependent on four main groups of processes all of which can be affected by water stress: (1) diffusive processes associated with the supply of carbon dioxide to photosynthetic sites, (2) photochemical processes associated with the utilization of light energy, (3) chemical processes associated with the chemical reduction of carbon dioxide, and (4) transport processes affecting the translocation of photosynthate away from the production sites. In general, the rates of net photosynthesis can begin to decline when the water potential is one to three bars below zero and continues to decline in a more or less linear manner as cell turgidity decreases. The carbon dioxide exchange between the leaf and air reverses from a negative to a positive flux as respiration exceeds photosynthesis.

The opening and closing of stomates is a mechanism that regulates the water balance and maintains a favorable water balance within the plant. As mentioned in Chapter 3, when the guard cells surrounding a stomate increase in size, they arch and the stomate opens. The processes involved in this opening are relatively complex. It will suffice for this discussion to point out that the guard cells are the only cells of the leaf epidermis that contain chloroplasts. Photosynthesis commences when the guard cells are illuminated in the morning and carbon dioxide concentrations in the cell sap are reduced below night concentrations. Since carbon dioxide forms a

weak acid in water, the cell becomes less acid as carbon dioxide is removed. This shift in acidity forces starch in the cell to be hydrolyzed to glucose. The increase in glucose lowers the osmotic potential of the cell, osmosis occurs, and water diffuses from the neighboring nongreen cells. The associated increase in pressure potential and swelling of the adjacent guard cells causes the stomates to open. In the evening, the reverse conditions occur and cause stomates to close.

It was mentioned in Chapter 3 that when the stomates close, leaf resistance to the diffusion of water vapor increases and the rate of transpiration declines. Although the diffusion of carbon dioxide may also be reduced, stomatal closure can be expected to influence water vapor transport to a greater extent than the carbon dioxide flux because of differences in the sizes of the two kinds of molecules (Slatyer, 1967). As water stress is imposed, factors other than low concentrations of carbon dioxide appear to become progressively more limiting to net photosynthesis.

Water deficits can affect respiration rates and thus produce changes in net photosynthesis. If water stress is imposed suddenly, an increase in respiration rate may be observed first, but after a period of time a reduction in respiration rate occurs, representing a sort of physiological adjustment. If stress is imposed gradually, however, no initial increase occurs and the rate of respiration gradually declines.

Wright and Mooney (1965) subjected three 20- to 40-year-old trees of *Pinus longaeva* to various soil moisture levels and measured net photosynthesis and respiration. Fig. 4.6 shows only a slight observable reduction of net photosynthesis and respiration while soil moisture levels were higher than −15 bars, the approximate water potential of wilting point. Severe reduction in net photosynthesis occurred at water potentials lower than wilting point.

Slatyer (1967) describes the effects of water deficits resulting from the drying of soil on the diurnal variations of metabolic processes. A base level of stress is imposed by declining water potential in the soil. Superimposed upon this is the water stress due to the diurnal lag of water absorption behind transpiration. Initially, metabolic processes are suppressed only during the afternoon period of maximum water deficit, but this period will become longer each day. Stomatal closure at this time can retard the transpiration, causing leaf temperatures to rise above the temperatures of the surrounding air. The elevated leaf temperatures can, in turn, cause increased respiration and reduced net photosynthesis. In addition, closed stomates can conceivably reduce photosynthesis by reducing the diffusion of carbon dioxide into the leaves. Finally, net photosynthesis may be affected adversely by reduction in turgor of the chlorenchyma.
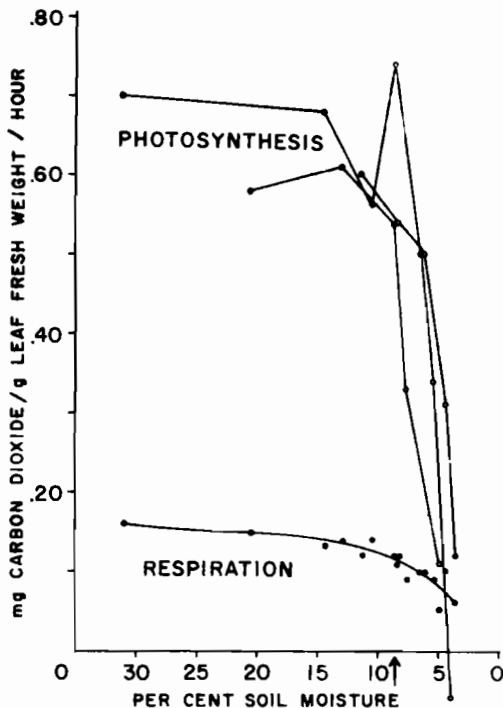
FIG. 4.6. Net photosynthesis and nighttime respiration of *Pinus longaeva* as a function of soil moisture. Lines connect rates of net photosynthesis for individual plants. The line for respiration is the mean for the three plants. Arrow designates soil moisture percentage at wilting point where soil water potentials are approximately –15 bars. (From Wright and Mooney, 1965)

The effects of soil moisture on photosynthesis have been studied by Brown (1968) for *Pinus ponderosa* in Arizona. As soil moisture decreased from April through June (see Fig. 3.14), rates of net photosynthesis declined and periods of net carbon dioxide production during the day increased in frequency and duration. Whenever replenishment of soil moisture occurred, water potentials increased and rates of net photosynthesis increased so that the net carbon dioxide flux became more negative (carbon dioxide was absorbed by the leaves) during the day as long as light intensities were adequate.

Figures 4.7 and 4.8 show measurements of carbon dioxide exchange from branches of *Pinus ponderosa* in a transparent enclosure during six days of different environmental regimes; three represent days when soil
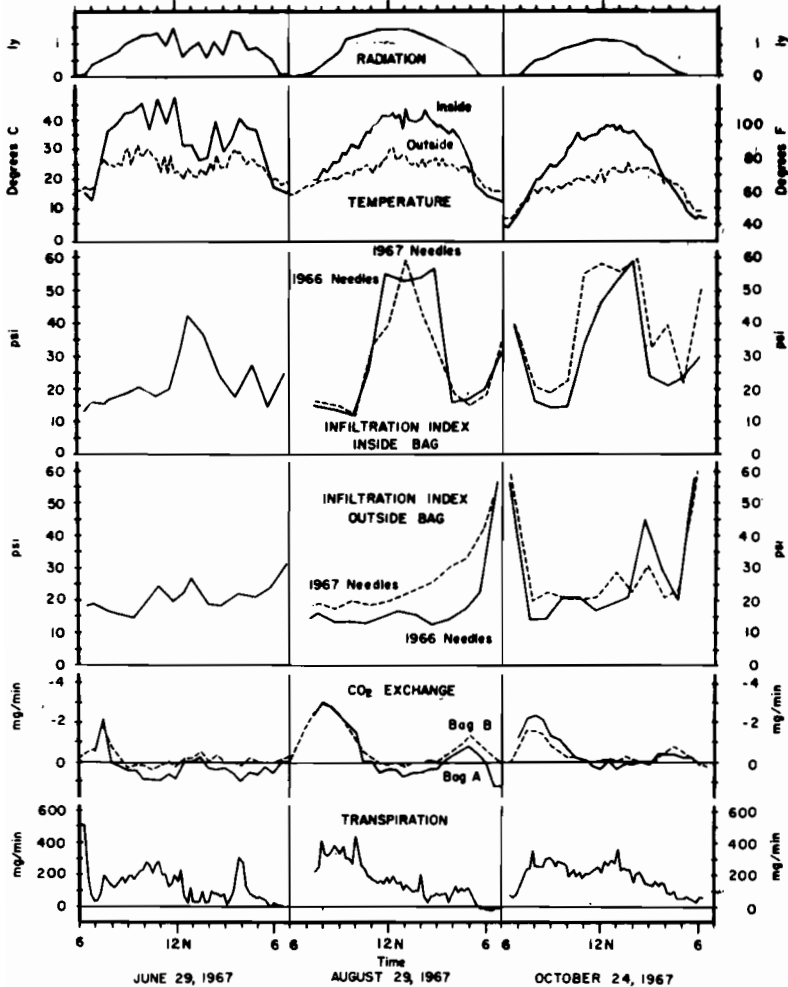
FIG. 4.7. Measurements of solar radiation and temperature, an index to stomatal size, carbon dioxide exchange, and transpiration as measured from one- and two-year-old needles on branches of *Pinus ponderosa* enclosed and unenclosed in a polyethylene bag during three days of apparent water stress. Carbon dioxide exchange is negative when photosynthesis exceeds the rate of respiration and positive when the relative rates of the two processes are reversed. Transpiration represents water lost from branches in the enclosure. Radiation is measured in langley units; the stomatal size is expressed as pounds of pressure per square inch required for infiltration; and carbon dioxide exchange and transpiration are expressed as milligrams per minute. Stomates are closed at pressures of 60 psi. As stomates open, the infiltration pressures become lower.
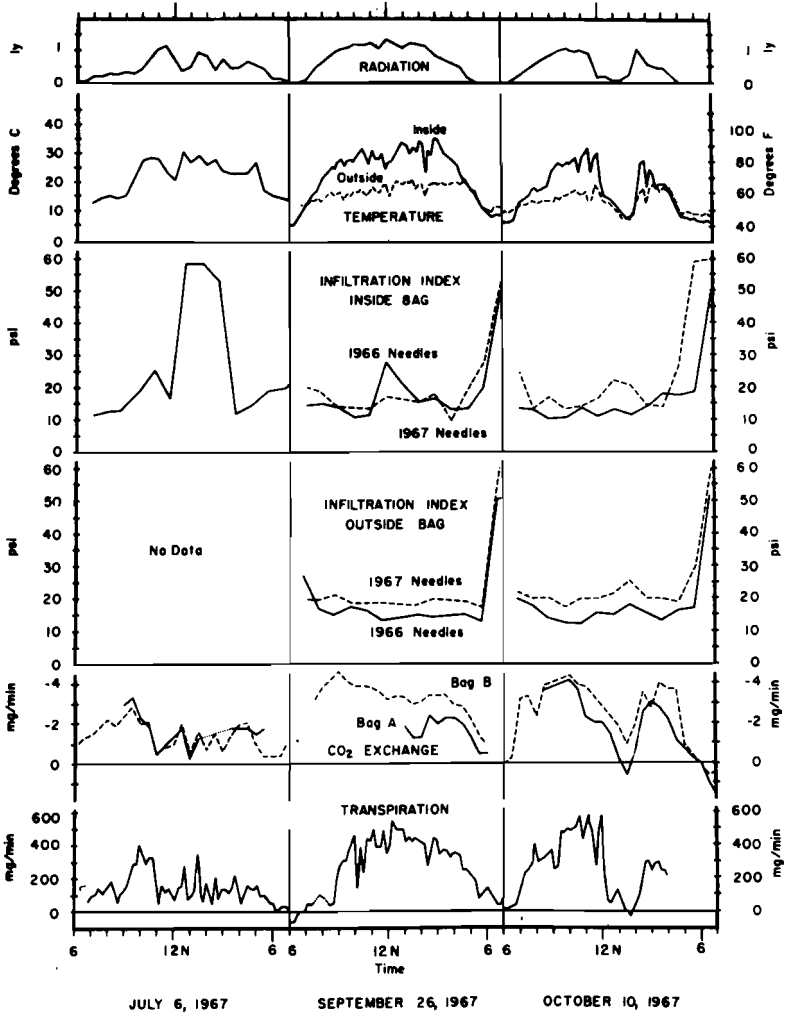
FIG. 4.8. Same as Fig. 4.7 except measurements are for three days of no apparent water stress.

moisture was low and three when soil moisture was ample. The rates of respiration, the amounts of solar radiation, temperatures, and relative size of stomates measured by infiltration techniques are also shown (see Chapter 3) (Drew *et al.*, 1972). During the midday period of the driest

and hottest days, stomates closed within the polyethylene enclosure, but stomates on unenclosed needles remained relatively open. Since complete stomatal closure has also been observed for branches in the open during dry, warm summer days (Drew, 1967; Drew *et al.*, 1972), it may be inferred that conditions within the bag truly represent natural conditions resulting from drought, although in the particular instance shown, the enclosure became warmer than the outside air, which accentuated stress and raised respiration rates. Under dry conditions illustrated by Fig. 4.7, about two hours after net photosynthesis commenced, its rate began to decline with increasing radiation and air temperatures, while stomates remained open and transpiration was relatively high. Needle temperatures that were above $25°C$ (the optimum for net photosynthesis) were often recorded, and water stress was increasing as indicated by declining stem size (see Fig. 3.14). Typically stomatal closure occurs when respiration approximates gross photosynthesis and there is no net carbon dioxide exchange between the foliage and the surrounding atmosphere. In this example from an arid-site *Pinus ponderosa*, the maintenance of open stomates until the carbon dioxide flux reaches zero suggests that high temperature and high water stress, rather than low carbon dioxide, must have caused the declining rates of photosynthesis to occur.

When soil moisture was high, such as on September 26 and October 10 (Fig. 4.6), stomates remained open, needle temperatures were lower, and rates of both transpiration and net photosynthesis remained high, except during cloudy weather which both lowered light intensities and reduced needle temperatures (Brown, 1968).

Slatyer (1967) states that as stress becomes severe and water potentials approach the permanent wilting point, the effect throughout the day of the diurnal water deficit will become less important (as in Fig. 3.14, June 4, 1966). Stomates will close for most of the day and only small amounts of water diffuse through the cuticular surfaces of the leaves. Daytime temperatures of leaves can rise well above air temperature, and net photosynthesis, cell division, and overall plant growth are likely to decline.

D. Components of the Atmosphere

Photosynthesis in trees with adequate water and light is often limited by low concentrations of carbon dioxide. In such cases the rate of photosynthesis can be increased simply by raising carbon dioxide concentrations in the surrounding air. Carbon dioxide in an actively photosynthesizing forest canopy is most limiting early in the afternoon

when it reaches its lowest concentration. Carbon dioxide is more likely to limit photosynthesis in trees at high elevations than at low elevations, because the pressure of gases decreases with increasing elevation, and the rate of diffusion declines (Gale, 1972; Kramer and Kozlowski, 1960).

Ordinarily, oxygen is not limiting to tissues in organs above the ground. However, as was discussed in the last chapter, the oxygen concentrations in soils may decline to less than 10%, which is sufficiently low to limit respiration and root growth in species not well adapted to wet soils. It is sometimes suggested that in poorly aerated soils carbon dioxide accumulates to toxic levels, but a deficiency of oxygen rather than excess carbon dioxide appears to be the more important factor.

Sometimes gases other than those normally present in the atmosphere become limiting due to their toxic effects upon plants. For example, industrial sulfur dioxide or ozone may adversely affect plants. Most species of plants are injured by exposures of only one hour to an atmosphere containing as little as one part in a million of certain toxic gases (Meyer et al., 1973).

E. Physiological Factors

A number of conditions related to age and physiological activity can influence respiration and photosynthesis. Respiration occurs in all living cells, but the rates are considerably higher in younger tissues than in older tissues because the former usually contain a greater number of growing cells. Rates of respiration of maturing cells are inversely correlated with the increasing vacuole size and with increasing proportion in the amount of cell wall material to the amount of protoplasm. High respiration rates in the stem are confined largely to the apical and cambial meristems and adjacent young tissues. In apical meristems, respiration may decrease abruptly in August when the buds become dormant and increase abruptly in the spring at the time of bud break (Kramer and Kozlowski, 1960).

Photosynthetic rates generally increase with increasing age of leaves or needles up to a level representing leaf maturity, and then they decline (Freeland, 1952; Kramer and Kozlowski, 1960). Mooney et al. (1966) measured photosynthesis in needles of *Pinus longaeva* at the end of a growing season and found that the needles formed in the course of the summer were somewhat less efficient than the older needles. This may be a result of mutual shading among the five needles of the young fascicle, for they remain in a tight bundle until some time after the autumn of their first year. Mooney et al. (1966) report that the photosynthetic rates in

needles from one to five years in age were markedly similar. Fritts (1969) reports that in some trees of *Pinus longaeva* needles are green and appear capable of photosynthesis for 15 to 30 years.

In many other species the photosynthetic efficiency drops rapidly and needle numbers decrease with increasing needle age greater than one year. O'Neil (1962) reports that there is little reduction in growth of *Pinus banksiana* when two- or three-year-old foliage has been removed from the trees, which suggests that the photosynthesis in the two- and three-year-old needles is inefficient. When the one-year-old foliage is removed, however, there is a marked reduction in shoot and diameter growth, as well as a high mortality of apical buds. Silver (1962) states that 90% of the total foliage produced in a given year by *Pseudotsuga menziesii* is lost at the end of five years. The percentages of foliage usually lost at ages one to five years are 28%, 23%, 17%, 13%, and 10%, respectively in this evergreen species.

Photosynthetic efficiency sometimes diminishes with increasing age of trees, regardless of needle age. Results of Wright and Mooney (1965) show that old trees of *Pinus longaeva* have lower ratios of photosynthesis to respiration at temperatures of 10°, 20°, and 30°C than do younger trees. According to Möller *et al.* (1954), about 46% of the food produced by photosynthesis is used in respiration of eight-year-old *Fagus silvatica*, while at 25 years, respiration consumes only 40% of the photosynthate. However, with increasing age thereafter, the percentage of photosynthate consumed by respiration increases to about 50% in 95 years. This change is a function of the ratio between the amount of respiring tissue and the amount of photosynthesizing tissue. Young trees generally have a higher ratio of photosynthetic surface to respiring tissue than older trees (Kramer and Kozlowski, 1960).

The actual accumulation of glucose in the leaves, particularly during the latter part of the daylight period, can become limiting to photosynthesis. Sweet and Wareing (1966) report that growth in *Pinus radiata* appears to affect photosynthesis directly by reducing the amount of photosynthate that can accumulate. Therefore the young, fast-growing seedling may have a more efficient system than a dormant or old tree simply because there is less accumulation of photosynthate in the leaves and concentrations of glucose are less likely to become the most limiting factor to photosynthesis.

Möller *et al.* (1954) present evidence that a decrease in net dry-matter produced by aging stands is caused partly by a decreased rate of photosynthesis in the leaves and partly by a small increase in respiration accompanied by a greater loss of dry weight in roots, branches, and twigs (Fig. 4.9).
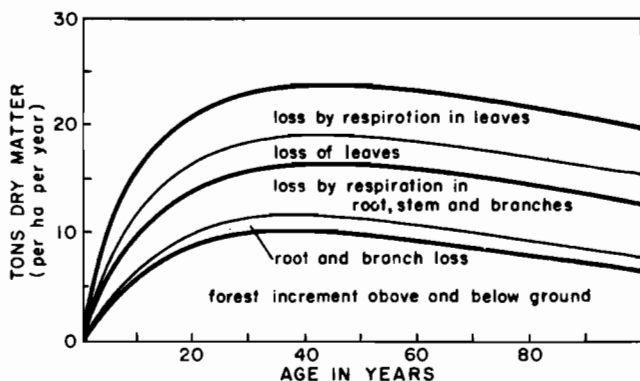
FIG. 4.9. Dry matter production in *Fagus silvatica* plotted as a function of tree age. The upper heavy line is dry matter production representing gross photosynthesis; the middle heavy line is net production translocated to other organs by the leaves; the heavy line at the bottom represents the annual accumulation of dry matter both above and below ground. The area between the upper and middle heavy lines represents the loss of dry matter through respiration in leaves and through shedding of leaves, while the area between the middle and lower heavy line represents the loss of dry matter by respiration and loss of roots and branches. (From Möller *et al.*, 1954)

Mooney (1972) points out that the differences in light sensitivities of respiration in C-3 and C-4 plants may help explain distribution and behavior of certain plants. In general, C-4 plants which cannot carry on photorespiration are less severely affected by extremely high temperatures and seem to occur more frequently in hot, bright, and dry environments. The C-3 plants occur in cooler habitats or are active in the cooler seasons of the year. While differences in these two types of metabolic pathways could account for differences in ring-width and climatic relationships, all trees so far used in dendroclimatology appear to be the C-4 type.

VI. The Annual Net Photosynthetic Regime
for a *Pinus Ponderosa* on a Semiarid Site

It will be shown in Chapter 5 that the ring widths in warm and arid-site trees are statistically related to climatic conditions during a nine- to ten-month period prior to growth, as well as to the three to four months of the

growing season from April through July. These statistical relationships can result from limiting effects of climate . on the annual net photosynthetic regime of the plant. Some of the biological evidence for this effect is described below.

The carbon dioxide exchange for branches of *Pinus ponderosa* enclosed in a ventilated polyethylene bag was monitored during several years of contrasting climate (Brown, 1968). The enclosure was mounted on branches of a tree growing in an extremely arid site in southern Arizona at 8,500 ft (2591 m). The carbon dioxide in the enclosure, along with a number of other environmental variables affecting the trees, were monitored from May, 1964, through October, 1967. An important part of the study involved the application of energy balance equations (Chapter 5) to assess the environmental conditions that were affected by the particular carbon dioxide measuring technique being applied. For example, it was shown by Brown (1968) that the polyethylene enclosure actually reduced the heat load, but that needle temperatures during the day inside the enclosure were frequently higher than needle temperatures outside the enclosure, because of differences in air movement. The enclosed tissue was continually subjected to very low wind velocities (approximately $0 \cdot 1$ mph, or $0 \cdot 045$ m/sec), while the unenclosed portions of the tree crown were commonly exposed to higher wind velocities.

During summer days when transpiration rates were low and the branch was subjected to high solar radiation, air temperatures in the enclosure were sometimes $10°C$, and in exceptional cases $20°C$, higher than temperatures on the outside (see Figs 4.7 and 4.8). Air temperatures within the enclosure at night were from $2°$ to $7°C$ below temperatures of the outside air, depending upon wind conditions (Brown, 1968). It was concluded from this analysis that the measuring technique used in the study did somewhat modify the actual temperature environment by essentially excluding the influence of wind. The modification remained within the natural limits of the plant, however, and simply caused a bias toward warmer-than-average temperatures. Since none of the years of study was extreme, the particular conclusions drawn about the patterns of carbon dioxide exchange are considered valid and comparable to natural conditions in extremely warm and dry years which climatic records indicate have occurred in the past.

Figure 4.10 is a plot of climate and carbon dioxide exchange of the enclosed branches expressed as three-day averages throughout two years. Precipitation and temperature during the winter of 1964–1965 were near the average of the five previous years. The frequent occurrence of a carbon dioxide uptake during the warmer winter days indicated net photosynthesis could occur almost any time when temperatures were

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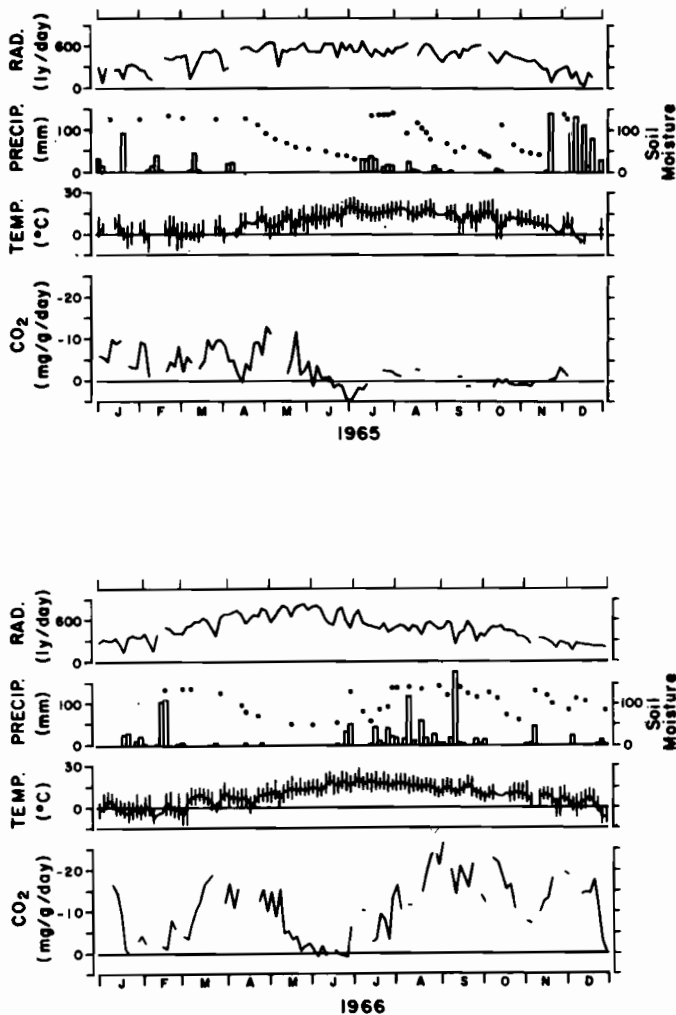
FIG. 4.10. The climate and carbon dioxide exchange during 1965 and 1966 for a branch from an arid-site *Pinus ponderosa* in southern Arizona. In 1965 less precipitation fell, soil moisture was lower, and the amount of net photosynthesis was more limited by moisture deficits than in 1966. The radiation, temperature, and carbon dioxide exchange are shown as three-day averages. Precipitation is the total for the three-day period, and the soil moisture values (shown as dots) are corrected dial readings from nine Colman soil-moisture units. The vertical bars indicate the range of temperatures during each three-day interval. (Redrawn from Brown, 1968)

near or above freezing. However, net photosynthesis ceased whenever daytime temperatures were less than $-2°C$, and it was low during days following nighttime freezing of the stem (see Fig. 4.4). Net photosynthesis generally increased with increasing temperature above freezing.

Soil moisture began to decline in April of 1965, after the snow had melted. Air temperatures for the months of March, May, and June were $1°$ to $2°C$ below the five-year average for these months, and during March the rate of net photosynthesis varied directly as a function of temperature and light intensity. However, later in the season as soil moisture was depleted and air temperatures rose, high water stress and excessively high needle temperatures became more limiting and caused the rates of net photosynthesis to decline. During the warmest and driest periods, daytime respiration exceeded gross photosynthesis, and carbon dioxide was released from the enclosed branch. Fig. 4.10 shows that the mean carbon dioxide exchange for the entire 24-hour period was positive for many days in June. As drought and air temperatures increased in June, dendrograph records, stomatal infiltration pressure, and relative turgidity measurements indicate that water stress increased throughout the tree. For example, infiltration rates (Drew *et al.*, 1972) showed that stomates closed during midday in unenclosed portions of the tree, while those within the enclosure often closed at an earlier hour. Days of high temperature resulted in little net gain of photosynthates. Growth at the base of the stem, which began in April (see Chapter 2), must have utilized primarily stored foods because there was little net accumulation of photosynthate in the leaves.

Precipitation during July and August of 1965 was below the five-year average for those months. Virtually no precipitation occurred from September until late November, and the occasional rains replenished moisture only in the upper levels of the soil. Even though net photosynthesis was not monitored continually due to equipment failure, sufficient data were collected to show that net photosynthesis for the dry autumn of 1965 was markedly lower than the following year, when there was more moisture in the soil.

A storm in November, 1965, was followed by a cold winter with snow persisting for several months (Fig. 4.10). Where data are available for the winter of 1966 and when day temperatures were below $-2°C$, little or no net photosynthesis occurred. When day temperatures were above freezing, net photosynthesis occurred at higher rates than in 1965, probably because of the deep snow and its effect on insulating the soil and recharging soil moisture reserves. Net photosynthesis was rapid in March and April because soil moisture was abundant and air temperatures did not greatly exceed the optimum for the process. Growth started early in

April (see Chapter 2), and in May and June net photosynthesis of the enclosed branch declined with rising needle temperatures. Air temperatures in June, 1966, were $3 \cdot 3°C$ warmer than in June of 1965, but net photosynthesis was more rapid, apparently as a result of the greater soil moisture supply and higher transpiration rates which maintained lower temperatures in the leaves.

The 1966 summer rains started late in June, which was earlier than the previous year, and precipitation in both August and September was high. Consequently, the average rate of net photosynthesis was markedly greater than during the previous summer. High net photosynthesis continued until late in October, when soil moisture began to decline. A storm in November replenished soil moisture, and high rates of net photosynthesis were measured until daytime temperatures dropped below $-2°C$ near the end of the year.

In summary, the rates of net photosynthesis were lower during 1965 than in 1966, as it was a year of average winter precipitation and below average summer precipitation. In contrast, the higher net photosynthesis in 1966 occurred because of high precipitation during both the winter and summer periods. Even though air temperatures were higher during June of 1966, net photosynthesis was higher than in the prior year because of greater soil moisture reserves.

Brown's measurements indicate that low-elevation, arid-site conifers, unlike those at high elevations described by Tranquillini (1964b), Mooney *et al.* (1966), and Schulze *et al.* (1967), can carry on net photosynthesis almost any time in the year if leaf temperatures during the day are not $-2°C$ or below. At low elevations low air temperatures are less often limiting to photosynthesis during the winter than at high elevations, but soil moisture in winter is more likely to be insufficient and internal water stress is more likely to occur.

VII. Some Implications of these Physiological Measurements

Measurements of net photosynthesis, respiration, and transpiration in arid-site conifers confirm that these processes vary sufficiently during the autumn, winter, and spring periods to have a substantial effect upon food reserves and subsequent ring growth. To be more specific high soil moisture and low air temperatures (except for those below $-2°C$) are shown to favor rapid net photosynthesis and production of glucose and derived stored foods, which are then available for growth in the spring. Moisture recharge of the soil which occurs during the autumn and winter can favor high photosynthesis the following spring when temperatures

are favorable and growth begins. High growth, however, may not always accompany high winter temperatures if moisture is the most limiting factor, because the potentially favorable effects of high winter temperatures are counteracted by the unfavorable effects of high temperatures on transpiration and depletion of soil moisture reserves. In such arid sites, the amount of net photosynthesis is proportional to the amount of water which is available and is transpired whether the transpiration occurs in winter or is delayed until the spring (Budelsky, 1969).

Trees in colder sites, on north-facing slopes, or at higher elevations and latitudes may have more moisture available in the soil than those on arid sites, so that the increased moisture loss due to high transpiration during warmer periods in winter may not substantially affect the moisture available later in the year. In such cases, high temperatures in winter and early spring can favor rapid net photosynthesis and increased physiological activity, which could lead to either early initiation of cambial activity, or rapid growth, and favor the formation of a wide ring.

The measurements of net photosynthesis, respiration, and transpiration during the growing season also indicate that these processes can exert an immediate effect on growth occurring at the same time by their effect on water relations, food reserves, and the making of growth-controlling substances derived from them. However, during a brief period early in the growing season low temperatures may become limiting to growth directly unless moisture stress is severe and more limiting. If so, high temperature accelerates transpiration, and water stress may limit growth and alter growth-regulating processes.

Temperatures during late spring and summer may at times exceed the optimum for net photosynthesis and perhaps for other growth-controlling processes. If water is also scarce, the deleterious effects of high temperature can be accentuated by the increased water stress. In the most arid sites high temperatures accompanied by high water stress may be the primary limiting factors during summer, except during cloudy weather and for periods during and after a rainfall when temperatures are lower and water stress is not as great.

As the cambial activity slows down during midsummer the unfavorable effects of high temperature and low moisture begin to impinge more on the accumulation of stored foods than on the current growth, which in turn will affect the growth of the following year. When ring growth in August or September ceases, any limiting temperature and moisture conditions which affect processes and food reserves cannot affect growth until it is resumed in the following spring. Sometimes environmental conditions which hasten the cessation of growth during

late summer may have the reverse effect upon the growth the next year, for photosynthate which would have been used for building cell parts is shunted into stored food reserves which are then available for more growth the following year.

During a warm and relatively dry summer season at high elevations, high latitudes, or on cool sites, prolonged water stress accompanied by excessively high temperatures may be rare, though they can cause a decrease in the rate of net photosynthesis and affect growth if water is in limited supply (Hari and Luukkanen, 1973). As on warmer and more arid sites, with the passage of time the effect of climatic factors on the ring that is being formed declines as the growth processes subside, while the effects on the width of the next year's ring increases through this control of food production, accumulation of stored food, and other conditions important to growth in the following spring.

In early autumn temperatures in cool high-elevation sites are not only lower but they may reach critically low levels and become directly limiting to processes long before they are low enough to be critical in warmer low-elevation sites. Thus, at high elevations and latitudes temperature rather than moisture is best correlated with the width of the following year's ring.

During the winter, high elevation or high latitude conifers may be deeply frozen so that the chlorophyll is deactivated. Periods of unusually warm weather may thaw out the tops, produce extreme water stress, favor excessive respiration, and hence bring about depletions of food reserves. This can lead to an inverse correlation of winter temperatures with food reserves and with the width of the subsequent season's ring.

VIII. The Distribution of Foods and Interactions with Growth

The relative distribution and consumption of food varies among the structures and organs of the tree and from one season to the next. The areas of the circles and squares in Fig. 4.11 illustrate the average amounts of glucose that can become involved in the various tissues of a typical middle-aged deciduous forest tree. Approximately 10% of the total glucose produced in leaves is consumed by leaf respiration. The remainder becomes stored or is involved in assimilation of other parts of the tree, with the aerial parts utilizing 81% and the roots utilizing 9%. Within the aerial parts of a tree, each year's growth of new leaves utilizes approximately 36%, the bole 36%, and the branches 8%. Fruit production utilizes about 1% of the total glucose. Allocation to the

various structures in the diagram includes the glucose consumed in respiration as well as the portion that is converted to the structure of each tree part.
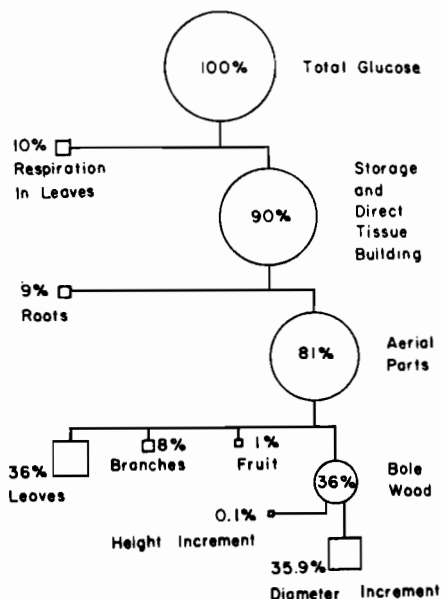
FIG. 4.11. Diagram showing the disposition throughout the tree of glucose made in the leaves. Ten percent of the glucose is consumed by respiration in the leaves and the remaining 90% goes to storage and tissue building. Of this 90%, 81% goes to tissues in aerial parts and 9% is used for growth of roots. The aerial distribution includes 36% which is used in growth of leaves, 8% for branches, 1% for fruit, and 36% for bole diameter growth. The squares represent ultimate dispositions and the circles intermediate allocations. (Modified and redrawn from Baker, 1950)

Figure 4.9 is actually another representation of the same phenomenon plotted as a function of tree age and expressed as respiration loss. It shows that up to two-thirds of the dry matter production is eventually consumed by respiration in the various organs of the tree. The remaining one-third represents the increase in dry matter in the above-ground and below-ground portions of the tree.

The processes of photosynthesis, respiration, and assimilation vary throughout the season and affect food accumulation and depletion throughout the tree. Respiration and assimilation occur continuously in living tissues but are most rapid during the most active period of growth. Photosynthesis can be active as long as there is light, moderate

temperatures, sufficient moisture in the plant tissue, and green leaves. Ordinarily photosynthesis occurs at sufficiently high rates to replenish stored foods used by respiration and assimilation. At night, however, when respiration and assimilation are especially high, or during periods of low photosynthetic activity, more food may be consumed than is produced by photosynthesis and a net decrease in reserve foods may result. If the food consumption continues faster than food manufacture, the supplies become exhausted and the tree dies. In years of drought, the stored foods may become low and become the most limiting process to cambial activity, especially during the *grand period of growth* (see Chapter 2).

The reserve of food may be used at different times and by different plant tissues, depending upon various conditions in the tree. The crown in an arid-site tree is likely to utilize most of the photosynthates produced during the growing season, with the result that relatively small amounts may be translocated to the lower stem and roots during the period of active crown growth. As a result, cambial activity in the roots and in the lower stem may occur largely at the expense of stored foods accumulated during the prior dormant season. The low correlation between ring width at the stem base of arid-site trees and the climate of the growing season and the high correlation with the climate of the prior autumn, winter, and spring is consistent with such a dependency of the cambium on food reserves derived from photosynthesis in the prior autumn, winter, and spring.

As a tree ages, the efficiency of photosynthesis may decline, and a lack of food available from photosynthesis may become increasingly critical to growth in the lower stem and roots. At the same time, the circumference at the cambium continues to increase and the available foods must be distributed to a larger growing area. The ratio of roots to shoots may decline; less water may be absorbed, with water loss more often exceeding water supply and branches suffering repeated drying, resulting in narrower growth rings with more variable widths. As these conditions become more limiting, the tree becomes weaker, so that disease or a year of extreme climate is more likely to cause destruction and death of the tree.

In aging *Pinus longaeva* and *Pinus flexilis* the amount of roots relative to the amount of shoots referred to as the *root/shoot ratio*, is essentially constant. But as the stem grows, the cambial tissue becomes distributed around a larger and larger circumference until those portions farthest from food, hormone, and water sources die. In very old individuals, the portion of living bark may be reduced to a narrow strip which connects a small group of living branches with the few remaining living roots (Fig.

4.12, also see Figs. 1.12 and 3.18). The total living tissue remains relatively constant and the ratio of food-producing and food-consuming tissues are kept in balance by the gradual change from "full-bark" to "stripped-bark" trees. Sometimes the width of the strip will increase and decrease to some extent with changes occurring in the crown and roots; but in *Pinus longaeva* the average width of the annual rings in these "stripped-bark" trees may remain remarkably constant even though the arc of the strip may change (Ferguson, 1968; Fritts, 1969).
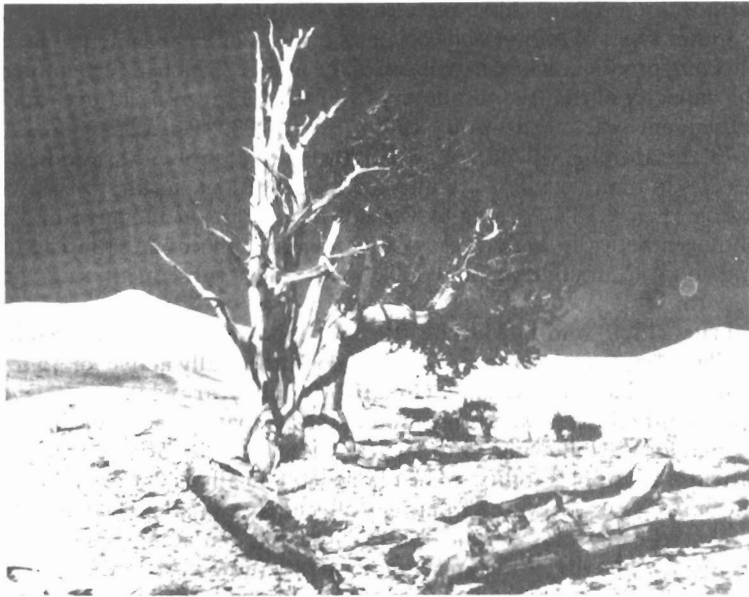
FIG. 4.12. *Pinus longaeva* may live to great ages. As the tree reaches old age, a portion of the cambium dies, leaving a strip of bark which connects the flagged top with the live roots. After the strip is formed the average ring width ceases to change with increasing tree age. (Courtesy of James Harsha and Valmore LaMarche)

Various growing regions of the plant, including root and stem tips, cambia, fruits, and seeds, compete for food and other growth substances. The success of the growing regions in competition seems to vary with their age and stage of development. The apical branch of a conifer seems to have competitive advantage over the side branches. Young leaves may compete for and receive substances that originate in older leaves. After the young leaves mature, they lose some of the competitive advantage and begin to lose substances to the areas of the plant that are still growing

(Rangenekar and Forward, 1973). Flowers, fruits, and seeds often obtain food at the expense of roots and other vegetative structures. Competition for food in *Fagus silvatica* between growing fruit and the cambia may cause narrow rings to form during years of especially abundant fruit set (Holmsgaard, 1962). Changes in the translocation of food substances and in the vigor of the crown can influence the availability of food and other growth substances to the cambium at the stem base and cause the climatic information recorded in the ring widths and cell structures to change in a systematic pattern throughout the life history of the tree (Chapter 2). For further discussion of this topic also see Chapter 5.

Other types of interactions occur as a result of environmental factors affecting production and expansion of the foliage, which in turn influence the capacity of the tree to photosynthesize at a given light level during subsequent years (Fritts *et al.*, 1965c; Fritts, 1969; Garrett and Zahner, 1973; LaMarche, 1974a). The lengths and possibly the numbers of needles in many conifers are affected by conditions during the growing season (Fig. 4.13). As long as the needles persist on the stem and are photosynthetically active, they can influence photosynthetic capacity and food accumulation, and hence can affect subsequent ring-width growth.

Fritts (1969) and LaMarche (1974a) report that needles are retained by *Pinus longaeva* and appear to be photosynthetically active for 15 to 30 years, so that an extreme climate of one year which affects the photosynthetic area and food production in that species can influence growth for the following 15 to 30 years. However, for arid-site trees this provides a type of stability to the photosynthetically active area, because one or two years of severe climate can affect only a small percentage of the total needle mass. LaMarche (1974a) observed that at higher elevations, however, when the spring and summer temperatures are low for a period of 10 to 15 years they can reduce the photosynthetic area substantially and cause a marked reduction in ring width. Furthermore, recovery may take 10 to 15 additional years of near-average spring and summer temperatures because the needles that were affected are held for such a long time on the trees.

Other conifers on stress sites show similar effects of climate on needle number and size, but they retain their needles for only a few years. One or two years of extreme climate can have a marked effect on the needle mass in these species, which results in a marked change in growth lagging one, two or three years behind the occurrence of the climate. Such differences in needle retention, as well as defoliation, changes in root mass, and fluctuations in fruit set, can result in variations in size and other characteristics of tree rings (see Chapter 6).
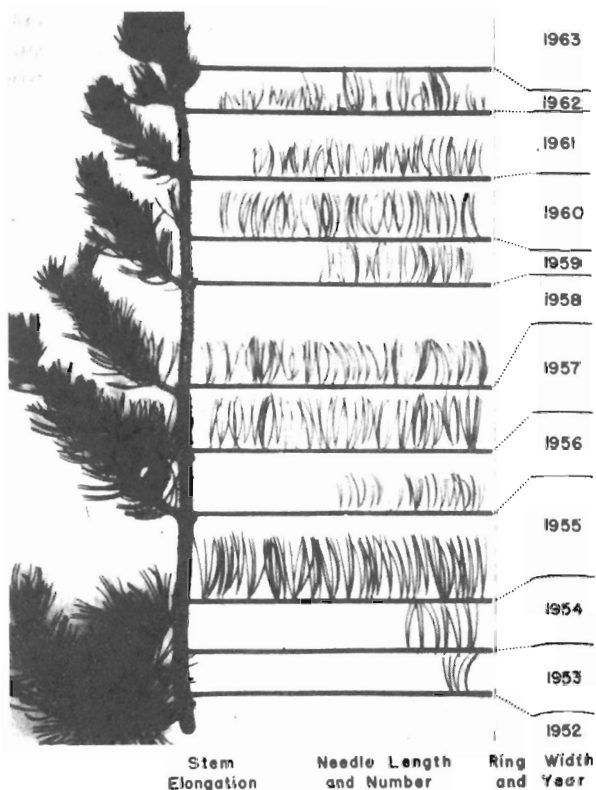
FIG. 4.13. Needle lengths and numbers, stem elongation, as well as ring widths of arid-site *Pinus edulis* may vary from one year to the next depending upon controlling factors of the environment. The needles which persist up to 10 years for this species and for longer intervals for other species can affect photosynthetic capacity, food accumulation, and the ring width. The needles shown have been stripped from the corresponding segment of the main stem and arranged to display the variation in numbers and length. The heavy horizontal lines mark the positions of the apical buds for each year and the distances between them correspond to the amount of shoot growth. The distance between the arcs drawn on the right is proportional to the area of the rings on the section cut from the stem base shown in the figure for 1952. (From Fritts *et al.*, 1965c)

IX. Essential Mineral Salts

The term *nutrient* used in a botanical context refers to mineral salts which are essential in small amounts for the normal growth and survival of the plant. As has been mentioned earlier, these nutrients should not be

considered true foods because they are not significant sources of energy. Their actual functions within plants are varied. Nitrogen, sulfur, and phosphorus are components of amino acids and protein; nitrogen and magnesium are components of chlorophyll; and iron, while not a part of the chlorophyll molecule, is necessary for chlorophyll synthesis. Other elements, including potassium, calcium, boron, manganese, zinc, copper, molybdenum, and chlorine can also influence rates of important processes in trees. In addition, mineral salts influence water potentials within plant cells, and the balance of the various ions affects membrane permeability.

Soil minerals also may control the distribution of some tree species. Wright and Mooney (1965) report that *Pinus longaeva* is relatively more tolerant of low phosphorus levels in soils than some of its competitors and suggest that this tolerance may explain the greater abundance of *Pinus longaeva* on phosphorus-deficient dolomitic soils in the White Mountains of California.

The limiting effect of mineral deficiencies is most apparent when other environmental factors are not limiting. If a particular mineral such as phosphorus is deficient enough to influence growth processes, it will restrict the capacity of a tree to respond during years when climatic factors are favorable for growth. For example, Fritts (1969) noted that water deficits in *Pinus longaeva* growing on dolomitic soils account for the variations in width for rings which are below the average size, but when ample water is available the rings are all about the same width. It is conceivable that the uniformity in size of the larger *Pinus longaeva* rings could be due to nutrient deficiency (perhaps phosphorus) setting the upper limit to ring width.

Naturally occurring minerals are of limited importance in dendroclimatology, however, because they tend to be constant from year to year and therefore do not cause variations in ring widths. On the other hand, substances arising from environmental pollution or other disturbances may affect soil minerals and produce systemic changes in availability of minerals, which in turn may result in changes in growth (Jonsson and Sundberg, 1972). Certain elements reaching high concentration in polluted habitats can have direct toxic effects on the trees of the area in terms of cell structure and ring width (Vinš, 1965).

X. Growth-Regulating Substances

Plant *growth regulators*, or *hormones*, are organic compounds produced in small amounts which promote, inhibit, or qualitatively modify growth. The better known growth regulators include *auxins*, compounds which

are responsible for cell enlargement; *antiauxins*, compounds that inhibit action of auxins; *kinins*, substances which promote cell division; *gibberellins*, compounds affecting stem elongation; and *inhibitors*, substances that reduce or stop growth and induce dormancy. For details on kinds of substances that act as growth regulators see Leopold (1964) and Giertych (1964).

If water, temperature, and food supplies are not limiting, tracheid diameter may be governed primarily by concentrations of certain hormones produced elsewhere in the tree. There is general agreement among plant physiologists that auxins are the hormones most important to the enlargement of cells, and that they are produced in the stem apices and are transported normally in a basipetal direction to the tissues in the stem (Giertych, 1964). Those factors limiting vegetative growth of the crown, therefore, can affect the auxins reaching the cambial regions and influence tracheid size (Larson, 1964). For example, the very rapid rate of the first flush of apical growth in spring produces a large quantity of auxin which migrates down the stem and stimulates production of large earlywood cells throughout the cambial regions in the stems and roots. As the season progresses, the rate of shoot elongation declines until shoot growth finally ceases. This causes auxin synthesis to decline, tracheid enlargement to be less rapid, and small, thick-walled latewood cells to be produced.

Larson (1962) proposes that auxin synthesis and transport in conifers account for the varying rates of growth and cell enlargement along the main axis of the stem. Therefore, both the width and structure of rings can be highly related to vigor of apical growth, auxin synthesis and transport, and the proximity of the cambium to the auxin source. This would help explain the presence of thin-walled tracheids making up low density latewood sometimes called *juvenile wood*, formed in the upper stems nearest the auxin source. With increasing distance from the stem apex, tracheid size decreases, latewood cells are smaller and thicker-walled, and there is an increasing difference in density between earlywood and latewood.

Digby and Wareing (1966b) note that the method of spread of cambial activity in spring among nonconiferous trees is different in ring-porous and diffuse-porous species. They show that in diffuse-porous trees (in which earlywood and latewood vessels are similar in size) growth promoters such as auxin are produced first by the swelling apical buds and later by tissues at the base of the tree as the gradient concentration of the growth regulator migrates down the stem. In ring-porous trees (those with large vessels in the earlywood), a gradient of auxin is not apparent in the stem at all. Rather, it is believed by some that an auxin precursor is

present throughout the stem in early spring which is converted to auxin at all levels just before the buds swell. Since the auxin is in the same concentration throughout the stem, cambial activity in ring-porous species is initiated simultaneously throughout the stem.

The transition from the large cells of earlywood to the small cells of latewood in ring-porous species may be related to a decline in auxin level resulting from cessation of apical growth in the crown or simply to the completion of pore enlargement and the beginning of active division of the cambium (Phipps, 1967). However, Digby and Wareing (1966b) show that after cessation of shoot growth the mature leaves of ring-porous species continue to produce enough auxin to maintain continued cambial activity and the formation of the latewood.

Westing (1968) points out that various aspects of xylem differentiation, such as radial enlargement, longitudinal enlargement, wall thickening, and lignification are under separate, more or less independent, hormone controls. Wodzicki (1964) presents evidence that growth substances found in cortical tissues of *Larix decidua* influence the thickening of tracheid cells independent from the effect of auxins. Digby and Wareing (1966a) show that the relative levels of both auxin and gibberellin may be important in determining whether the cambium differentiates xylem or phloem.

Giertych (1964) states that some of these features of growth may be governed by a balance between growth promoters and inhibitors rather than by the concentration of any one growth-controlling substance. For example, the breaking of bud dormancy may be associated both with a decline in inhibitors and an increase of promoters, which in turn initiate cambial activity.

In the case of certain trees, such as *Quercus robur*, which have two phases of shoot growth during a season, one in April and May and the other in August separated by a rest period, the dormancy of summer is temporarily characterized by moderately high concentrations of growth inhibitors in the buds. This temporary dormancy can be broken by temperature alteration or by certain chemical treatments. The more permanent dormancy of autumn is accompanied by higher concentrations of inhibitors and is not broken easily until the following spring.

Larson (1962) points out that in *Pinus resinosa* false rings invariably result from second flushes of shoot growth which produce auxin and stimulate a change in the cambium from production of latewood to production of earlywood. The stimulus is of limited intensity and reaches the stem base only under exceptionally favorable conditions. Thus, the occurrence of false rings near the growing tips of the stem without false

rings at the base of the stem (see Fig. 2.23) may be attributed to variations in auxin gradients within the tree (Fritts *et al.*, 1965a). Westing (1968) ,states that the production of compression wood in an inclined gymnosperm stem may be attributed to lateral redistribution or asymmetric production of a growth-regulating substance, a growth inhibitor, or an auxin-destroying enzyme.

Larson (1962) also proposes that differences in earlywood and latewood in trees with large crowns grown in the open and those with small crowns grown under more restricted conditions may be attributed to variations in the production of growth regulators resulting from differences in crown vigor. The absence of certain rings at the stem base of suppressed trees or of those trees growing in a very unfavorable climate may result from reduced activity in the shoot and an auxin stimulus which is too weak to initiate cambial activity by the time it reaches the stem base. Giertych (1964) reports that effects of day length on flowering and other phenomena may be observed by a change in concentrations of growth regulators before there is any visible change in growth.

Future studies will undoubtedly reveal many other ways environmental factors can affect the production or movement of growth regulators, which in turn affect growth. It is possible that the delayed effect of autumn and winter climate on growth in the following spring could result from an interaction between climate and the formation of some growth regulator. The anatomical changes in ring structure associated with its position along the stem, tree age, and crown vigor are undoubtedly related to production, movement, and distribution of growth regulators as well as the amounts of available foods.

Considerable differences exist in points of view regarding the relative importance of growth regulators, internal water stress, and food to cambial growth. All three factors are undoubtedly interrelated and important. Each may be of primary significance in certain situations, species, and sites, and all growth models should recognize that any one or a combination of these factors may become limiting under certain circumstances to ring-width growth.

XI. Physiological Preconditioning and Correlating Systems

The growth of a tree is, of course, directly influenced by its prevailing environment, but often there are many lingering effects on current growth from previous environmental conditions, as was suggested in Fig. 1.10. *Physiological preconditioning* is the induction of internal metabolic conditions which eventually influence the growth or biochemical

reactions of a tree during a later stage in its life history. Such conditions may be variable and complex. For example, Lowry (1966) noted meteorological factors over a 27-month period that appeared to precondition *Pseudotsuga menziesii* and influence its cone crop. Climatic conditions were important during periods of activity such as the differentiation of buds, the formation of pollen, and fruit set.

Several examples of the effects of physiological preconditioning on ring growth have been described in earlier sections. Some of these are: (1) the accumulation and storage of food and other substances by arid-site conifers during the dormant period; (2) the production of root and shoot masses and variation in the root-shoot ratio; (3) the changes that occur with increasing tree age and size which can influence efficiency and rates of various processes; (4) the production of growth-controlling substances within the tree; and (5) the deactivation of chlorophyll and loss of photosynthetic capacity in conifers during the winter when temperatures are low. Additional examples of physiological preconditioning which possibly affect the formation of xylem rings are the influences of photoperiod, the induction and breaking of dormancy, the development of drought resistance and frost hardiness, and the presence of frost rings and fire scars resulting from injury to tissues of the tree.

A. Photoperiod

Changes in length of exposure to light (*photoperiod*) may influence both vegetative and reproductive phases of plant growth. Shoot growth, radial growth, breaking of dormancy, leaf abscission, frost resistance, seed germination, and flowering are processes known to be influenced by length of day. The growth of woody species so far investigated with respect to day length responds to short days by growth inhibition and to long days by growth promotion.

Photoperiod does not vary from year to year and therefore does not directly produce variable features in successively formed rings. The response to photoperiod can, however, be important as a genetically controlled factor that prevents unusually early bud break during a warm winter or the flushing of buds late in the season, which would produce young tissue susceptible to injury from frost. Although the genetic factors are constant for a given plant and cannot produce variable ring width from year to year, genetic factors do vary from plant to plant and are probably responsible for different photoperiodic responses among individual trees and among different populations or races, which result in differences in the date of bud break, in the duration and rate of cambial activity, and in the time of dormancy in autumn. Day length is most likely

a significant factor in tree growth at high latitudes, also, where large differences in daylight occur seasonally and the length of the summer is short. As was discussed earlier, the very long summer days permit photosynthesis to proceed at high rates. For further discussion of photoperiod as a possible factor in tree growth see Downs (1962) and Kramer and Kozlowski (1960).

B. Dormancy

Trees do not grow continually, no matter how favorable the environment, but rather periods of active growth will alternate with periods of inactivity and dormancy. Tropical species in a continuously favorable environment may make several growth flushes during the year (Kramer and Kozlowski, 1960). In some temperate trees that at times produce multiple rings, growth can occur in two or three periods, separated by brief intervals of dormancy. Dormancy of this type is classified as *temporary*, as it lasts a few days or a few weeks. Growth may begin again spontaneously or it may be stimulated by a change in the environment. Dormancy which occurs for periods of many weeks or months is classified as *permanent*. In temperate regions, permanent dormancy usually cannot be broken until plants have been exposed to low temperatures for one or two months, normally during winter months. While temporary or permanent dormancy can be induced by environmental factors, it can be caused by internal conditions (Kramer and Kozlowski, 1960). For instance, the tree itself may bring about the conditions for dormancy by producing an inhibitor or by exhausting some substance essential for growth. The age of tissues also seems to affect the rate and degree of entrance into the period of rest (Levitt, 1956). For a more detailed description of these types of phenomena see Samish (1954).

Dormancy may be viewed as a type of "safety factor" which has evolved through the death of all individuals of a population that failed to become dormant and did not survive in a given climate. Dormancy is important for dendroclimatic consideration because it is a natural factor that modulates the response of growth to the environment at particular phenological stages of the tree. Climatic factors in the autumn may affect conditions which hasten or increase the depth of dormancy, while others may govern the rate and timing of the breaking of dormancy in the spring. When dormancy is broken, climate may directly affect the production of growth-regulating substances and influence the various growth processes, as well as affect net photosynthesis, accumulation of food, and water relations of the tree. During the dormant period when climate cannot affect growth directly, it can affect subsequent growth

through its influence on soil moisture, photosynthesis, and food accumulation, or other processes that are still active in the plant. A variety of effects of this nature delayed for one or more years may be seen in many statistical results of tree ring–climatic relationships and are a part of the models developed in Chapters 5, 7, and 9.

C. Drought Resistance

Different species can vary in their ability to withstand drought, and individuals of the same species can also vary depending upon conditions which have preconditioned the plant. There are four basic strategies or adaptations which enable plants to survive conditions of drought: (1) escaping the drought; (2) evading the drought; (3) enduring the drought; and (4) resisting the drought (Parker, 1968). Examples of drought-escaping plants are the annuals which survive the dry period as dormant seeds. Drought evaders are able to economize on water use by structural or other modifications such as thick cutin or dense hairs on the leaf which allow them to evade internal water stress. Drought-enduring plants, rather than conserving water by some permanent feature, may lose their leaves, modify their root structure, or change in some other way that enables them to survive during periods of drought. On the other hand drought resistors possess certain physiological adaptations that allow their tissues to continue life processes under the stress of drought. Drought resistance in trees involves primarily the latter two types.

Most workers view drought resistance as a characteristic largely under genetic control and hence not a phenomenon that can change from one year to the next. For example, *Juniperus virginiana* and *J. communis* are apparently more resistant to desiccation than many common species of *Pinus, Picea, Abies,* and certain broad-leaved species of trees (Parker, 1968). Hence, these two species of *Juniperus* can survive at lower elevations and on drier sites than the other less well-adapted plants.

Certain conditions of particular plant tissues may cause physiological changes or structural modifications which can affect a tree's ability to grow or survive through periods of drought or water stress (Parker, 1968). The extent and conditions of root systems can modify water absorption or water loss. For example, trees in the sun which undergo high photosynthesis can develop larger root systems than those in the shade. The roots of the Mediterranean tree *Pinus halepensis* cease growth in times of drought, the outer root cortex turns brown and collapses, and a heavy suberin layer develops which retards dehydration of the roots and enables the species to better withstand drought (Parker, 1968).

Leaves developing in the sun or those in the upper portion of a tree

crown may withstand more desiccation than those in the shade or those formed in the less vigorously growing areas of the crown, because the former may have a thicker cutin on their leaves, the osmotic potentials in the plant may be lower because of higher concentration of sugar and other dissolved substances in the cells, or their stomates may be able to exert a stronger control over water loss. Similarly, vigorously growing trees in open habitats can often survive more severe drought than those in the shade of a dense forest canopy, or a period of unusually sunny and cool weather may enable a tree to develop physiological conditions, enabling them to better withstand conditions of water stress.

In general, if water stress increases slowly in a drought-resistant plant, the physiological conditions in its tissues are more likely to keep pace with and compensate for the water stress. However, if the onset of water stress is sudden, a reaction may occur during which time water may be withdrawn from the plant tissue and adverse effects on various processes may be evident. With the passing of time a period of restitution may follow in which the cells become better able to develop the necessary water potentials so that water diffuses back into some of the desiccated tissues of the plant. Very often drought appears to be more damaging if it is preceded by a long wet period of vigorous growth than if it is preceded by conditions of more reduced growth and occasional periods of water stress.

The ability of *Pinus ponderosa* and *P. edulis* to continue growth during the dry period before the summer rains as described in Chapter 2 may represent a type of drought resistance which could in part result from some preconditioning of the plant. Some of the statistical correlation of temperature and precipitation in one year or season with the growth of the following spring could well arise from preconditioning leading to improved drought resistance of the tissues within the plant.

D. Frost Hardiness

If temperatures remain unusually warm late in the autumn, an abrupt onset of cold weather may injure many temperate trees; but if temperatures decline in a more gradual manner, hardiness or resistance to frost injury develops. A period of unseasonably warm weather in winter can decrease frost hardiness, but a return to colder temperatures will usually reestablish it. In the early spring if the weather turns unseasonably warm, some trees may lose their frost hardiness, thereby becoming more susceptible to freezing injury. Plants that had survived the most extreme freeze during midwinter may be killed or injured by very slight freezing in the spring after dormancy has been broken (Levitt, 1956).

.Low soil moisture, high levels of light, and a scarcity of certain minerals may interact with low temperature to increase frost hardiness (Levitt, 1956). For example, *Pinus longaeva* at its upper tree line in the White Mountains of California does not form the contorted and stunted *krummholz* form, as it does in climates of the Mt. Washington area, Nevada, and the Rocky Mountains where summer drought is lacking. LaMarche and Mooney (1972) believe that drought conditions, which always occur during the growing season in the White Mountains but not n the krummholz sites, make the trees frost hardy so that winter conditions do not dry the foliage and kill the branches. This preconditioning by drought may be one reason why the dry-site trees maintain full stature right up to their high elevation limits. Because of the effects of frost hardiness (and possibly drought resistance), dry and cold conditions late in autumn or early in the spring may have a favorable effect upon subsequent growth, because it assures that any subsequent low temperatures or dry conditions cannot damage the foliage of the tree. Thus, if they acted in the above manner, both low moisture and low temperature during these periods, prior to winter dormancy would be expected to be correlated with wide rings.

If frost hardiness or drought resistance is lacking and the foliage is killed, large variations in the remaining living tissue may occur from one year to the next. Small differences in relief and wind exposure may control the amounts of living tissue that remain at the end of winter, and there is often little or no synchronization in ring widths or crossdating from tree to tree or from branch to branch in the same tree. The coupling of growth with climatic factors becomes insufficient to provide meaningful analysis of past climate from the contorted upper tree line trees. However, by analyzing rings of these contorted krummholz trees, interesting studies may be made on age and movement by vegetative propagation. The interested reader can refer to Levitt (1956) and Parker (1968) for a detailed discussion of frost and drought resistance in woody plants.

E. Frost Rings

Freezing is harmless to tissues that are frost hardy, because crystallization of water is restricted to the intercellular spaces. When freezing occurs very rapidly or the tissues are not hardened, ice may form in the cytoplasm or vacuole of living cells (Meyer *et al.*, 1973) or ice may crush young growing cells. The active cambium in branches is especially susceptible to injury when temperatures drop below freezing. Such injury produces distorted xylem tissue that is referred to as a *frost ring* (Fig. 4.14).
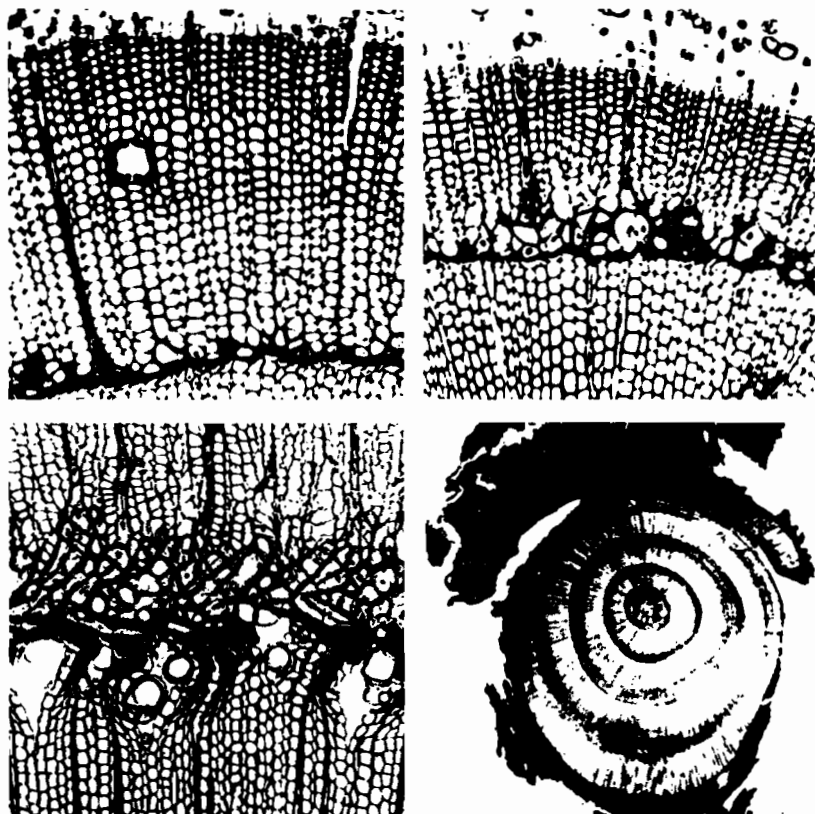
FIG. 4.14. Transverse sections of tree stems showing frost damage. The distinct dark line within the ring is a layer of crushed cells. Deformed and incompletely lignified tracheids often lie inside the crushed cells, while parenchyma and abnormal tracheids can lie outside. These abnormal cells form lines of weakness which may cause the wood to break, and ruptures may occur in the stem (see lower right photo). The upper sections are *Picea glauca* (from Glerum and Farrar, 1966), and the lower are *Pseudotsuga menziesii* (left) and *Larix decidua* (right). (From Day and Peace, 1934, courtesy of Oxford University Press)

Mature tracheids become crumpled and the cells that are undifferentiated at the time of the freeze become crushed (Glock, 1951). Rays are commonly offset at the line of injury. In the case of a severe frost, the cambium and therefore the tree may be killed outright. For injured but surviving trees, the first regenerated cells are enlarged and deformed, but successively formed cells gradually assume normal size and form. The effects of a severe frost may also seriously defoliate the tree and weaken

stems. Glock (1951) reports that mechanical breakage and mortality of branches and trees may occur for several years following a severe frost.

Glock (1951) and LaMarche (1970) associate an injury along the inner portion of a ring with frosts occurring in spring after initiation of cambial activity. Frost injury near the outer boundary of the ring is associated with a freeze late in the growing season before the cambium becomes dormant. Frost rings are less frequently found in the larger stems than in the small branches, probably because of the insulation of the thick bark, the late initiation of cambial activity, and the early growth cessation in portions which are distant from the growing stem apex. Thus, frost rings may be less frequent in older portions of stem, but this does not necessarily imply that frosts were less severe at that height on the tree or in more recent years. Thus, it follows that one must sample trees of comparable size and age to compare the absence or presence of frosts during the period of growth. Glock successfully uses frost rings to label and study growth layers in species such as *Cupressus arizonica* that form several distinct rings in a year. Frost rings can be important markers which aid in the dating of trees of high elevation or high latitude environments (LaMarche, 1970; LaMarche and Fritts, 1971b).

F. Fire Scars

High temperatures resulting from fire can defoliate a tree and kill buds and living tissue exposed to the heat (Jemison, 1944). J. Parker (1971) reports that trees are more resistant to heating in winter and least resistant in summer as indicated by the rate of respiration after exposure to one to ten minutes' heating at 57°C. *Juniperus virginiana* possesses an ability to withstand both extreme heating and low moisture levels. The thick bark of species such as *Pinus ponderosa* often insulates the large trees from injurious effects of small ground fires. Fig. 4.15 is an especially interesting example of a fire scar in *Pinus sylvestris*. A fire apparently killed all of the cambium except for two small areas, where growth rate accelerated after injury and the new tissue expanded around the stem. Eighteen years after the fire, the bark had fully encircled the original scarred stem.

Fire injury may cause a marked reduction in the total growth of a stem if a substantial part of the foliage is destroyed, but in the area of wounding, the ring may be anomalously large. Fire may destroy competition in a stand of trees, remove the shade, release minerals, and make more soil area available to the roots. Thus, after a forest fire, rings of some trees become wider, the ring-width variations are virtually unrelated to climate, and there is often very little year-to-year width

variability common to all trees of a stand. What ring-width variability exists is mostly due to local site factors, which often vary slowly through time so that there are long periods of several years with enhanced or sometimes reduced growth. As time passes, the rings become narrower (or wider) and the year-to-year variability shared by all trees increases as climatic factors once again become increasingly limiting to ring width.
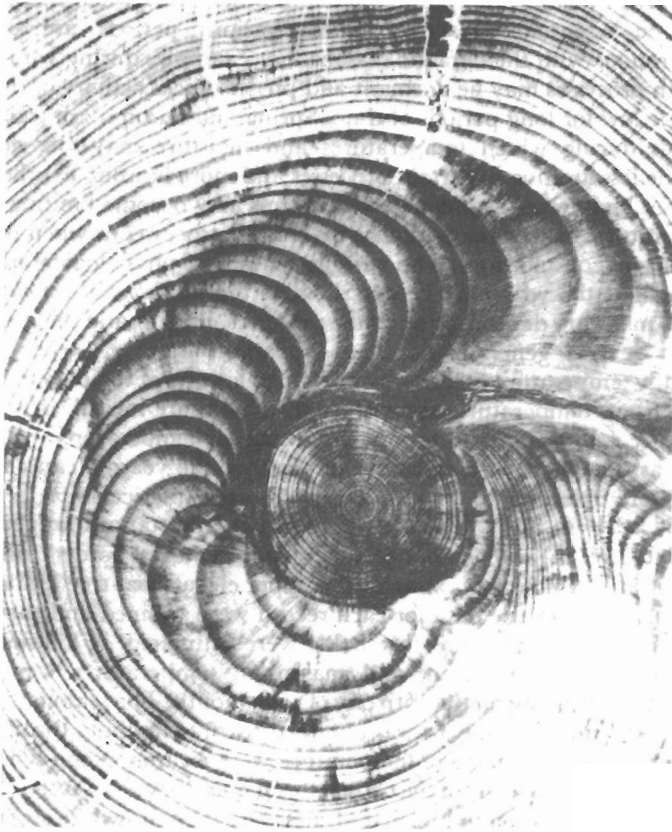
FIG. 4.15. A cross section of a stem of *Pinus sylvestris* which was severely damaged by fire when the tree was about 25 years old. The cambium remained alive at two locations. Rapid growth occurred after the fire, and in 18 years the new growth encircled and buried the scarred stem. (Specimen courtesy of Jon Pilcher, photo by James Harsha)

XII. Changes in the Physiological Seasons with Varying Elevation of the Tree Sites

The physiological processes affecting tree rings and their most important climatic controls have been described in the preceding pages. It can be seen from the discussion that there are certain periods of time within the year when climatic factors are generally favorable to a process, other times when factors are limiting, and still other times when the process may be essentially inactive. These various periods are usually synchronous with the climatic seasons. For example, during winter the growth processes may be dormant and physiological activity of the tree may be low for long periods of time. Spring and autumn are transition periods during which temperatures and moisture may change and become less limiting to certain processes and more limiting to others. In summer high temperature, and water stress may become limiting when temperatures exceed the optimum for certain processes or when there is insufficient soil moisture. The varying periods of physiological activity throughout the year may be described as the *physiological seasons*. The season may vary depending upon the processes, the site, and the species of plant. Several generalizations are apparent, however, when mean monthly temperature regimes are examined for sites of various elevations and certain temperature or moisture thresholds are identified.

Figure 4.16 is a plot of several thresholds for temperature and water stress as they vary with elevation throughout the year. Mean climatic data were obtained for various western North American sites between latitudes 34° to 38°N. The elevations of climatic stations ranged from 5,500 ft (1677 m), which approximates the lower forest border, to 10,400 ft (3171 m), which approximates the upper elevational tree limits. The monthly temperature data for each record were scanned and the mean data for five temperature thresholds were estimated as follows: The monthly minimum, mean, and maximum temperatures were each plotted as occurring on the 15th day of each month. The seasonal regime for each of the three means was obtained by drawing lines through the plotted points. The plots of temperature were examined and whenever the lines intersected any of the chosen thresholds, they were entered at the appropriate elevation in Fig. 4.16. Lines were then drawn through these points for dates when (1) the mean maximum temperatures intersected 0°C, (2) the mean temperature intersected 0°C, (3) the mean minimum temperature intersected 0°C, (4) the mean maximum temperatures intersected 25°C, and (5) the mean maximum temperatures intersected 30°C.

These particular temperature thresholds are in part arbitrary, for they do not represent the results of any particular physiological study. The rationale for their use is as follows:

(1) When maximum air temperatures remain below 0°C it can be assumed that the trees in general are physiologically inactive. Chlorophyll in coniferous trees probably has been deactivated and the only processes of importance are respiration and transpiration, which may occur for short intervals of time when temperatures rise
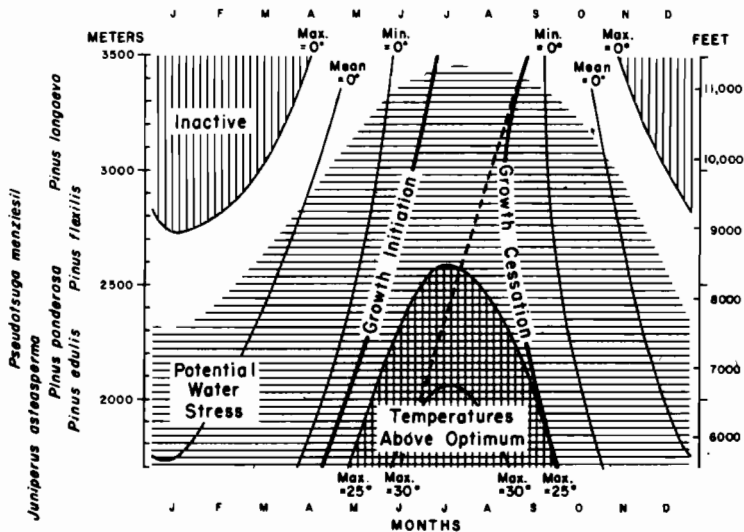
FIG. 4.16. Diagrammatic representation of elevations and approximate dates when maximum, mean, and minimum air temperatures are at 0°C; when maximum temperatures are at 25°C and 30°C; and when the growing period begins and ends. The elevations and times when water stress is most likely to be limiting are shaded with horizontal lines. The vertical lines indicate the photosynthetically inactive period when maximum temperatures are generally below 0°C. The area shaded with both horizontal and vertical lines indicates the dates and elevations when maximum temperatures are on the average above 25°C. The heavy dashed line designates the earliest date that growth would be expected to cease because of severe water stress. The approximate elevational ranges of certain trees are indicated on the left margin. Data are from latitudes 34°–38°N in western North America and are based in part upon LaMarche and Mooney (1972), Erdman et al. (1969), Fritts (1969), Fritts et al. (1965c), and U.S. National Weather Service. (Drawing by M. Huggins).

above freezing. The plot in Fig. 4.16 shows that temperatures are below this threshold for substantial periods of time only at high elevation sites.

(2) When mean maximum temperatures are above 0°C but the mean temperatures remain below this value, certain processes may occur during the daytime period. Chlorophyll regeneration may begin during warm periods when night temperatures are not extremely low, and net photosynthesis can occur during the warmest intervals. Temperatures are likely to be directly correlated with the accumulation of photosynthates, but they are not high enough to cause serious water stress except in habitats that are exceptionally arid.

(3) As mean air temperatures rise above 0°C but minimum temperatures are below that value, daytime temperatures are frequently above freezing and processes such as net photosynthesis can occur at substantial rates. Nighttime temperatures are low and there is little consumption of food by nighttime respiration. If moisture is adequate, periods with higher than normal temperatures are associated with high productivity and accumulation of foods. Except for extremely high elevations, internal water stress may occur at midday if soil moisture supply is inadequate. It is possible that this increasing water stress can counteract the favorable effects of the moderate temperatures on processes such as net photosynthesis.

(4) When mean minimum temperatures remain above 0°C but the maximum temperatures are lower than 25°C, the physiological activity is highest and many of the growth processes may be initiated. Temperature is rarely limiting except for unusually cold or warm days. Moisture reserves can become low in dry years, however, and water stress can become limiting.

(5) At low elevations maximum temperatures during the summer season may rise above 25°C and sometimes above 30°C. These temperatures are above the optimum for many processes, especially net photosynthesis, and during years of low precipitation the inhibiting effects of heightened temperatures are accentuated. As the temperatures begin to decline in late summer, the thresholds are passed in reverse order, and the processes reverse in like manner. However, growth may cease well before temperatures become limiting to the process. If moisture is available, net photosynthesis can occur rapidly and foods can accumulate. As temperatures approach 0°C most growth processes cease, and winter hardening may occur while net photosynthesis remains active. When maximum temperatures fall below 0°C chlorophyll may be deactivated,

photosynthesis then ceases, and the winter inactive period commences. Different species, of course, vary in their tolerance to various temperatures and degrees of water stress, and the microenvironmental conditions can accentuate or counteract the particular climatic effects.

On the left margin of Fig. 4.16, each species name spans its approximate elevational range. When these ranges are compared to the diagram of physiological seasons, several features become evident. The physiologically inactive period is long in duration throughout the range of *Pinus longaeva*, but relatively short for other species, except at high elevations, and cold exposures. For most arid-site species the average maximum temperatures in winter are above freezing.

Mean temperatures in winter reach 0°C levels at all elevations considered in the diagram. At the high elevational tree line, mean temperatures average freezing or below for more than half the year, while for the lower forest border temperatures as low as 0°C may last for no more than a few weeks to a few months. During April minimum temperatures at low elevations can rise above 0°C and growth may commence, but at tree line this threshold is not attained until June or early July. The period of above-optimum temperatures occurs during midsummer only for species at low elevations, where the effects of high temperatures are likely to be most severe if water is unavailable and the plants are subjected to water stress. In winter water stress is generally restricted to sites below 7500 ft (2287 m). In summer water stress can occur at all elevations, although it is rare at the upper elevational tree line.

It can also be noted from the diagram that the growing season at low elevations is potentially longer than at high ones. However, early cessation due to water stress and elevated plant temperatures can occur there as early as June, and is less likely to occur with increasing elevation. Above 9,800 ft (2988 m) the length of the growing season does not vary substantially, although both the dates of growth initiation and cessation occur later with increasing elevation.

Figure 4.16 represents changes associated only with elevation, but modifying factors of the site such as exposure, slope, and soil characteristics may further modify the microclimate and affect the timing of the physiological seasons. The marked differences in the elevational ranges of the listed species and the wide variations in the physiological seasons suggest that there will be a variety of ways that climatic factors can affect the plant processes. Since the processes interact to negate or accentuate each other's effect, it is reasonable to expect that the net effect on growth will vary not only among the different species but also among

the various macro- and microenvironments of the sites. The following chapter deals with the important factors of the macroclimate and the environment as they may influence growth-controlling processes which affect ring width; and it describes some models which express the most important growth–climatic relationships.

Chapter 5

The Climate–Growth System

I. Introduction

It was pointed out in Chapter 1 that an important and basic step in dendroclimatological research is modeling the climate–growth system. The biological portions of the system have been described in Chapters 2, 3, and 4. It is now necessary to consider how the biological system is linked to climate, how the variables of the site may affect the linkages, and how the essential structure and components of the system may be modeled to assist in the identification of the important dendroclimatological components. As mentioned in Chapter 1 such modeling can be accomplished by means of word diagrams, logical

statements, mathematical equations, or other analytical schemes which portray the important linkages between the initial causal phenomena, which in this case include variables of climate and site, and the resultant end product, which is ring width.

This chapter begins with a description of the two major components of the climatic portion of the system, the energy and water balances which link the macroclimate to the operational environment of the plant. Consideration is given to site factors such as topography, substrate, and elevation, as well as to the biotic and other factors which can modify or nullify certain components of these energy and water balances and thereby alter, complicate, or obscure the tree growth–climate relationship

The discussion of the climate–tree growth system as a whole begins with a model of those factors or conditions that can become operationally limiting to cambial growth. This rather simple word diagram is then expanded and generalized to a more comprehensive one including a variety of processes occurring throughout the tree, as well as those occurring in the cambial region, which are in turn linked with two physical factors of the macroclimate, temperatures and precipitation. The possibility for both direct and inversely correlated relationships between growth and these two physical factors is accounted for by the model. It also allows for those variations that may be attributed to changes in the season, differences in the microsites, and differences among tree species.

II. The Energy and Water Balances

The amount of energy and water that a plant utilizes depends upon the amounts that are available to it and the portions which are absorbed and lost. Availability of both energy and water is very much dependent upon the conditions of both the atmosphere and the site in which the plant is growing, and the relative importance of these conditions can be best portrayed by mathematical equations. The inflow, outflow, sources, and sinks, and transformations of energy are referred to collectively as the *energy balance,* while similar components for water are referred to as the *water balance.* All energy and water balance equations are based upon conservation of energy and matter, which is to say that any change occurring within a system will affect that system's overall balance and be associated with a corresponding addition or loss of energy or water. The energy balance for a column of atmosphere and a soil is described by Sellers (1965) as

$$G = (Q + q)(1 - a) + I\downarrow - I\uparrow - H - LE + F_i - F_o \qquad (5.1)$$

where G is the net transfer or flux of heat (energy) into or out of the system; Q is the direct solar radiation incident on the exposed surface of the soil; q is the diffuse solar radiation reflected, or scattered from atmospheric dust and clouds incident on the same surface; a is the *albedo* (reflectivity) of the earth's surface; $I\!\downarrow$ is the absorption of longwave or infrared radiation from the atmosphere into the ground at the surface; $I\!\uparrow$ is the loss of longwave radiation from the soil surface to the atmosphere; H is the *sensible heat* exchange between the soil and air; LE is the heat loss by evaporation where L is the *latent heat* of vaporization (cooling by evaporation of 590 cal/g) and E the amount of moisture evaporated; F_i is the horizontal transfer of heat from surrounding soil; F_o is the horizontal transfer of heat to the surrounding soil.

The first five items govern the flux or transfer of incoming radiant energy that is delivered to a given soil surface. The next three items, $I\!\uparrow$, H, LE, govern the dissipation of this energy back to the atmosphere and space after it has been absorbed, and the last two items deal with small amounts of energy that are transferred laterally into or out of the column of soil.

This energy balance equation is an approximate one, but in general it applies over any time period from seconds to many years where the relative importance of items can vary as a function of the weather, the latitudinal and elevational location of the site, its exposure and slope, and other characteristics such as soil color, water content, and the amount of plant cover. Components other than those included in the equation are usually small and can be neglected (Sellers, 1965).

The water balance for a column of soil can be portrayed in a similar fashion,

$$g = r + D + f_i - E - f_o \tag{5.2}$$

where g is the net rate of change in moisture content in a column of soil; r is the moisture added by precipitation; D is the moisture added by condensation of dew; f_i is the horizontal flux of moisture into the column of soil; E is the loss of moisture from the soil by *evapotranspiration*; f_o is the horizontal and downward flux of moisture out of the column of soil.

Usually dew formation is negligible (Sellers, 1965). The water balance is tied to the energy balance through the term E, because large amounts of energy are dissipated by evaporation from the soil and plants.

A soil moisture accounting system, such as the one developed by Thornthwaite and Mather (1955, 1957) utilizes daily precipitation, mean daily air temperature, and potential radiation as the moisture and energy input, and considers moisture storage along with the depletion of moisture from evaporation (E) and run off (f_o). Thornthwaite and

Mather's accounting system was used to compute total available and lower-layer available soil moisture in Fig. 2.21 and evapotranspiration deficits shown in Fig. 2.24. Such accounting systems are thought to be useful in that they convert weather data into new variables that hopefully simulate growth-influencing environmental conditions (Zahner and Stage, 1966). Palmer (1965) uses a water balance approach to convert temperature and precipitation data to an index of drought. This index is relatively well correlated with variations in ring width (Julian and Fritts, 1968) and is a climatically derived factor that may be calibrated with and reconstructed from ring-width indices.

Large discrepancies arise, however, between actual and calculated moisture conditions for arid sites. These discrepancies have two possible causes: First, the use of mean temperature may not be appropriate, for it does not take into account the extreme diurnal range of temperatures that occurs on arid sites, nor does it take into account the radiational heat load as it affects the daytime energy balance of the plants. Second, the run off from the high-intensity storms that occur during summer is not adequately considered by the water-accounting procedure.
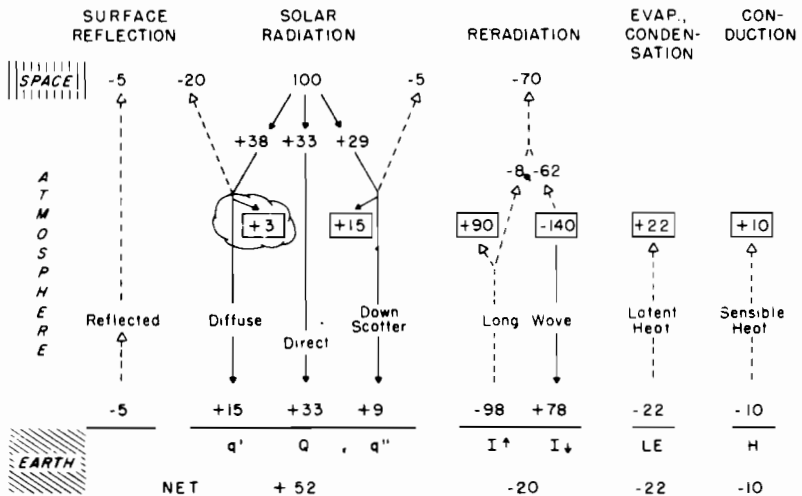
FIG. 5.1. The mean annual energy balance of the earth–atmosphere system for the Northern Hemisphere. The 100 units are equivalent to 0·485 cal/cm²/minute, which is based on a solar constant of 1·946 cal/cm²/min. Downward fluxes are indicated by solid lines and arrows, outward fluxes by dashed lines and open arrows. Symbols refer to Equation 5.1. (After Gates, 1962, as modified by Sellers, personal communication) (Drawing by M. Huggins)

Gates (1967) discusses the water balance equation and describes an aerodynamic method which he believes is more suitable for accurate estimation of the water balance. The method has not been applied to dendroclimatic work because insufficient data are available for a statistical comparison with annual ring widths.

Figure 5.1 shows the components of mean annual energy balance starting with 100 units per minute of incoming solar radiation at the top of the atmosphere. An average of 38 units are affected by clouds, and of these 38 units, clouds reflect 20 units back into space, absorb 3 units, and transmit 15 units to the ground surface. Other atmospheric substances deal with 29 units, reflecting 5 back to space, absorbing 15 in the atmosphere, and scattering 9 downward. Direct solar radiation accounts for 33 of the 100 units which are added to the diffuse radiation and down scatter, making a total of 57 units reaching the earth's surface, 5 of which are reflected back to space.

The surface of the earth radiates heat very much like a black body. The other columns in Fig. 5.1 indicate that 98 units are reradiated outward from the ground surface, 22 units are transferred as latent heat by evaporation and condensation, and 10 units as sensible heat. The total amount of energy transferred from all sources to the atmosphere is 140, as shown by summing the positive numbers inside the boxes. A total of 78 units of these 140 are reradiated back to the earth while 62 units, plus the 8 units reradiated directly from the earth are lost to space. This energy is the longwave infrared radiation included in the term, 1, in Equation 5.1, and it occurs day or night, summer or winter, sunny or overcast.

The condition of the atmosphere is always changing and the components of the energy balance may vary somewhat in response to yearly or decadal changes as well as shorter-term fluctuations. For example, the net rate of exchange in heat, G (Equation 5.1), may be altered by changes in the energy received from the sun, Q, by changes in atmospheric carbon dioxide, dust, or pollutants which intercept some of the energy. Snow cover may alter the albedo, a, causing a significant portion of the incoming radiation to be reflected back to space, and it may reduce the sensible heat transfer between the atmosphere and the ground. Oceans may absorb large quantities of heat during the periods of warming and may dissipate the energy during periods of cooling, so that they contribute to long-term variations in climate.

Such long-term variations in the energy balance can result in changes in weather and climate that produce correlated variations in ring widths for certain trees and sites. In such cases the appropriate variations in the earth's energy and water balance can be calibrated with and inferred from past variations in the ring widths. The reconstruction of sea surface

H

temperatures (Douglas, 1973) and of the levels of Lake Athabasca (Stockton and Fritts, 1973) are good examples of reconstructing elements of the energy and water balance by tree-ring analysis.

Every living organism is exposed to and lives in this stream of energy expressed by the energy balance equation. The temperature of an organism is a function of how rapidly it absorbs and dissipates the energy it receives, as well as any additional energy resulting from metabolism. Its temperature will fluctuate as the hourly, daily, seasonal, and long-term variations in the energy balance cause changes in the organism's operational environment.

As for all organisms, plants are coupled to the energy and water balances depending upon certain properties and characteristics they may possess (Gates, 1968a, b). As mentioned in Chapter 1, sometimes the coupling is tight and the plant absorbs and dissipates energy or moisture readily, or the coupling is loose so that plant temperature and moisture may lag substantially behind those of the surrounding environment. The coupling factor related to the energy balance is referred to as *absorptivity* and may depend upon the composition of the plant surface, spectral quality and geometry of radiation on the plant surface, and perhaps time (Gates, 1968a, b).

The plant is coupled to air temperature across a boundary layer of adhering air surrounding the organism, and variations in the depth of this boundary layer may influence the rate of energy exchange between the organism and the atmosphere. The depth of the boundary layer depends upon wind speed, the temperature gradient between the plant's surface and the air, and the size, shape, and orientation of the plant's surface.

The boundary layer surrounding the plant along with the epidermis also offers resistance to transpiration, which is the most important coupling factor for exchange of moisture between a plant surface and the atmosphere. The details of transpiration as it relates to the water balance have already been described in Chapter 3.

Gates (1962) expresses the energy balance for plants in a form similar to the energy balance at the soil surface in Equation 5.1:

$$G_o = Q_s - (a+t) \, Q_s + \varepsilon R - LE - H_t - H_a \pm s - P + M \qquad (5.3)$$

where G_o is the net transfer or flux of heat (energy) between the atmosphere and the plant; Q is the solar radiation on the plant surface; a is the reflectivity or albedo of the plant; t is the *transmissivity*, or the ability to transmit the energy through the plant; ε is the *emissivity* of the plant, its power to emit the radiation from the surface which often is less than that of a black body; R is the thermal longwave radiation flux from the ground, atmosphere, and objects surrounding the plant; LE is the heat

lost by evaporation from the plant; H_g is the transfer of sensible heat by conduction from the plant to the ground; H_a is the transfer of sensible heat by conduction and convection from the plant to the air; s is a term for storage of energy by heating or cooling of the plant mass over short periods of time; P is the energy used by the plant for photosynthesis; M is the heat released from the plant by respiration.

It can be seen from the above equation and prior discussion of the energy balance that the environmental factors which are most relevant to the energy transfer process of the aerial parts of a plant are sunlight and skylight; thermal radiation from the ground, atmosphere, and nearby objects; air temperature; wind; availability of water for transpiration; and water vapor in the air. If the energy absorbed is greater than or less than energy lost, plant temperatures will rise above or decline below the temperatures of the ambient air.

Evaporative cooling by transpiration is usually sufficiently rapid for well-watered plants to maintain the plant temperatures near or below air temperatures if the absorbed energy does not greatly exceed the energy dissipated by convection and reradiation. However, under high heat loads during the day, especially when water stress occurs, the energy absorbed by exposed leaves usually exceeds the energy that is dissipated, and aerial portions of plants can rise to temperatures in excess of 10° to 20°C above those of the surrounding air (see Fig. 3.6). Wind increases convection and helps to maintain plant temperatures near those of the ambient air, but wind may have detrimental effects in that it removes the vapor boundary layer and increases the rate of water loss to the surrounding atmosphere (see Fig. 3.7).

The brief description of the energy and water balance as outlined here is included to call attention to the many factors other than air temperature and precipitation which affect the actual temperature and water status of a plant. Unfortunately, detailed data are often unavailable for most components of the energy budget for a sufficient number of years to be calibrated with variations in tree rings. However, correct interpretation of statistical correlation of ring width with mean monthly temperature and precipitation involving trees at various elevations, on various exposures, and in various climatic regions requires an understanding of the differences in microclimates that can result from differences in the energy and water balances.

III. Site Factors which can Modify the Energy Balance

Many physical phenomena are not a specific part of the operational environments because they do not directly impinge upon the organisms'

physiological processes. However, such phenomena may have indirect effects on plant processes because they play an important role in the development of a particular site. For example, the topography and soil are the result of geological, physical, and biological processes operating through past geological ages creating the land mass supporting the site. The plant community on a site is a result of past plant migrations, and the establishment, growth, reproduction, and death of individuals on the site. The death of a tree frequently results in more light and moisture available to neighboring trees while the growth of a neighbor may increase competition for water and light. These factors are important to the operational environment in that they create features that modify the energy and water balances.

A. Topography

Topography is one of the most important factors of the site which affects the energy and water balance by controlling the incident
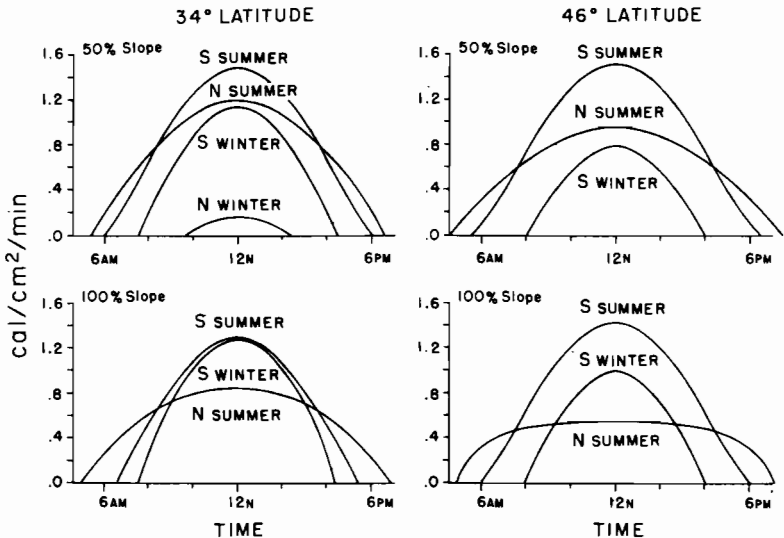
FIG. 5.2. The theoretical regime of solar radiation reaching a site on a clear day for 2 slopes, 2 latitudes, 2 seasons, and 2 exposures (N = north-facing and S = south-facing) Calculations are for December 3 or January 10 (winter) and for June 1 or July 12 (summer). Sun declination from the Equator is assumed to be 22; solar constant, 1·946 cal/cm²/min; and transmission coefficient, 0·8, to account for atmospheric thickness at 22° latitudes. (Data from Fons *et al.*, 1960) (Drawing by M. Huggins)

radiation, Q, received on the site and by influencing the amount and disposition of moisture. South-facing slopes in the Northern Hemisphere on the average receive more annual solar radiation per unit area and are drier than other slopes (Haase, 1970). Fig. 5.2 shows the theoretical radiation, Q, on north- and south-facing 50% (26·57°) and 100% (45°) slopes at latitudes of 34° and 46° North (Fons *et al.*, 1960).

It is apparent from this figure that the 100% south-facing slope at 34° N latitude (the approximate latitude of southern USA) receives almost as much radiation in winter as in summer. The 50% slope at 34° latitude is the only north-facing slope shown which receives any direct radiation in winter. Because of the angle of sun and the day length in summer, both south-facing slopes at 46° latitude (northern USA) potentially receive more radiation than similar slopes at 34° latitude. In general, the north-facing slopes in summer receive as much as or more total radiation during the day than the comparable south-facing slopes in winter. The contrast in radiation between summer and winter is generally greater at a higher latitude than at a lower latitude site.

Because arid, south-facing 100% slopes at low latitudes can receive as much solar radiation in winter as in summer, winter temperatures are high and trees on such sites are more likely to remain physiologically active even during the middle of winter (Fig. 4.16). During the day, temperatures of plants in direct sunlight can rise much above those of the air; but soil temperatures can be relatively low, so that high daytime temperatures can cause transpiration to exceed water absorption, thus creating water stress and desiccation of plant tissue even when there is moisture available in the soil. As a result, net photosynthesis in such low latitude trees may be limited more by high than low temperatures in winter. Thus, at low latitudes on south-facing slopes, temperatures at any time during the year can be high enough to be detrimental to physiological conditions in trees, subsequently affecting ring-width growth the following spring. For more northerly sites, such as 46° N latitude, there is a more marked difference in the energy received during the summer and winter on 100% south-facing slopes, and elevated plant temperatures in winter are not as likely to become high enough to limit processes in the plants. This phenomenon, involving elevated temperatures on south-facing slopes, has been discussed in Chapters 3 and 4 and can be substantiated by field measurements as well as inferred from numerous statistical analyses of environmental–growth relationships described in Chapter 8 (Fritts, 1974).

Haase (1970) reports that in southern Arizona the southeast-facing slope is the most arid exposure in the summer, due to cloudless mornings. By noon or early afternoon, when radiation is potentially high on the

south- and southwest-facing sites, clouds develop which reduce net solar radiation. Erdman *et al.* (1969) measured forest environments in several sites at Mesa Verde, Colorado, and they report that a southwest-facing slope is drier than a northeast-facing slope. The rings of *Pinus edulis* at Mesa Verde substantiate these findings in that high ring-width variability, which indicates the effects of drought, is characteristic of the more arid southwest-facing exposures.

Fritts *et al.* (1965c) state that ring-width variability is greater in trees on steep, well-drained canyon walls than in trees on the mesa tops, indicating greater aridity for the canyon-wall sites. However, the extremely old *Pseudotsuga menziesii* from Mesa Verde are not only on steep slopes but the exposure is north-facing so that these trees receive little direct solar radiation in winter (Fig 5.2). As might be expected, the ring widths from these trees do not correlate as well with winter climate as do trees on south-facing exposures, probably because the north-facing trees remain frozen during the cooler winter season and are unable to respond to certain variations in the winter environment.

Fritts (1969) used ring-width variability and other statistical characteristics in *Pinus longaeva* to assess the aridity of sites on different exposures in the White Mountains of California. He found that substantial variations in ring-width characteristics were related to topographic differences. Trees on the south-facing slopes, which receive the highest incident radiation, exhibited the most ring-width variability (sensitivity) and were inferred to be on the driest sites. The trees on the west-facing, steepest, and most exposed slopes also indicated aridity by their high ring-width variability. It was suggested that in the latter case snow is removed from these exposures by the prevailing winds.

Trees on a southeast-facing slope near a protecting ridge had wide rings and low ring-width variability. Drifting snow was observed to accumulate in the lee of the ridge, adding to the moisture of the site. Thus, it could be assumed that the trees on the southeast-facing and protected slope would grow more rapidly and uniformly than those on slopes exposed to the sweep of the wind because of the additional moisture from drifting snow. Both ring characteristics and stand density indicate that growth is most favored on north-facing slopes and valleys, where snow can accumulate but the incident radiation is low and where the trees are protected from the sweep of the wind.

B. Substrate

The parent material, or soil type, may modify the environment of a site in several ways and therefore must be taken into account when modeling

or interpreting tree-growth conditions. *Pinus longaeva* in the White‑ Mountains is largely confined to dolomitic substrates. Mooney *et al.* (1962) and Wright and Mooney (1965) demonstrate that this is in part due to the lighter color of the dolomite which has a 15% to 20% greater albedo than sandstone. The greater reflectivity results in lower soil temperatures and lower evaporation rates, so that a dolomitic soil remains consistently wetter and cooler than sandstone soil when other environmental factors are equal. In addition to the above conditions, Wright and Mooney (1965) point out that there are lower levels of certain minerals on dolomite than on sandstone. *Pinus longaeva*, which is more tolerant and therefore less limited by the low mineral availability than other species, is dominant in the plant community on dolomitic soils, but occurs infrequently on sandstone and granite where it apparently cannot compete with other plants.

Fritts (1969) reports that rings of bristlecone pine are wider on granite and, to a lesser extent, on sandstone than on soils derived from dolomite. This may indicate that minerals may also be limiting to *P. longaeva* on the dolomite and may be at least in part responsible for their slow growth on dolomitic sites. Dendrochronologists have frequently noted that the oldest trees with the most datable and varied rings are often found growing on limestone or dolomitic substrates.

Erdman *et al.* (1969) and States (1968) note that trees in semiarid regions often grow best on soils with a heavy charge of rock fragments. Such soils hold less moisture per volume of soil than fine-textured soils, but the penetration of moisture is deeper and less water is lost by evaporation. As a result, more of the moisture that falls as precipitation can be utilized ·by deeply rooted trees than by shallow-rooted grasses. Run off is also less on the coarse-textured than on fine-textured soils. Erdman *et al.* (1969) note that interbedding of shale between sandstone produces seeps and springs at the contact, which serve as sources of moisture for trees. For more discussion of similar phenomena see Chapter 3.

Fritts and Holowaychuck (1959) describe soil profile differences (Fig. 3.11), and Vinš (1970) and Stockton and Fritts (1971c) describe changes in water tables which control root distribution and water relations of trees and influence their growth. Other factors of substrate, such as the amount of leaf litter, the percentage of surface covered by rock, and soil permeability, may markedly affect the operational environment of trees on particular sites. However, these soil and site factors do not change measurably from year to year and therefore are not usually factors governing the year-to-year ring-width chronology of a site.

C. Elevation and Orographic Factors

Elevation or altitude is a site factor affecting mean annual precipitation and temperature regimes (Fig. 4.16). Disregarding the influence of surface features, air temperatures decrease with increasing elevation. This decrease in temperature is referred to as the *lapse rate*. An average value for the lapse rate is 0·5°C per 100 m elevation (Geiger, 1965).

The density of the air column also decreases with altitude, so that there is less scattering and absorption of direct solar radiation by the atmosphere (Fig. 5.1). As a result, plants at high elevations are often subjected to high radiation loads and high daytime temperatures during cloudless days. At night the exposed surfaces lose heat rapidly because there is less reradiation by the atmosphere back to the earth surface, and plant temperatures can fall well below the temperatures of the air.

Mountains may serve as barriers to moisture-laden winds, so that high-elevation sites receive more precipitation than the sites at lower elevations. Since temperatures are lower in the mountains, moisture evaporates more slowly and a greater proportion of the precipitation may fall as snow. Snow in turn reflects the solar radiation and reduces that portion of energy absorbed in the site. Snow also can insulate the soil, keeping it relatively warm, and reducing the outgoing longwave radiation so that night-time temperatures in the above-ground tissues drop well below freezing.

Sites in the lee of mountain ranges usually receive significantly less precipitation than comparable sites on the windward slopes. Little moisture falls on *Pinus longaeva* sites in the White Mountains of California even though they are at high elevations, because the Sierra Nevada mountains to the west are an orographic barrier removing a large portion of the moisture from the prevailing westerly winds. Although available moisture generally increases and temperature decreases with increasing elevation in this area (Wright and Mooney, 1965; Fritts, 1969), there is less change in tree-ring characteristics associated with elevational difference than with topographic exposures of the tree sites. More details of this analysis are presented in Chapter 6.

Additional examples of elevational, orographic, or other types of physiographic factors influencing microclimate are the *foehn* or *chinook winds*, cold air drainage, temperature inversions, and mountain-valley winds (see Geiger, 1965). Any correlation between variations in macroclimates and ring widths can be influenced by the microclimates as they control the ranges of environmental factors that limit the processes in plants. As will be discussed in Chapter 8, there are many differences in the

response of ring width to climatic, factors which can be attributed to microclimatic conditions in the respective tree sites.

IV. Biotic and Other Nonclimatic Factors: Dendrochronological Examples

The location and condition of surrounding plants may influence the operational environment of a tree by casting shade, by influencing the drifting or blast of wind-carried snow, by competing for moisture or essential minerals, or by producing substances which favor or inhibit growth. Certain details of these influences have been described in Chapters 3 and 4. Because none of these factors is directly climatic in origin, the dendrochronologist needs to be able to both recognize them and remove them from tree-ring data being used for climatic analysis.

Changes in the operational environment of a tree due to the growth and senescence of neighboring trees usually occur slowly and in more or less systematic fashion. Because the resultant variations are nonclimatic in origin, they will differ from tree to tree and from site to site and they can be at least partially removed by the standardization of ring widths. For the same reason this variability from tree to tree can be used quite successfully for ecological analyses such as the assessment of stand history, site disturbance, and other ecological conditions and events. Although not the focus of this text, it is interesting to look at a few examples of studies concerning nonclimatic factors affecting the ring-width variations in trees.

There is extensive literature involving the use of ring counts to determine the age of trees following a catastrophic event, to determine the age structure of a forest, or to identify the age of a scar on a tree stem. Lawrence (1950), Lawrence and Lawrence (1961), Sigafoos and Hendricks (1961), and Alestalo (1971) have used ring counts to estimate tree age to determine the minimum length of time since a substrate surface was exposed and available for establishment of plants. These studies assume that existing trees on the site represent the original invaders after the given substrate was produced. Sigafoos and Hendricks (1969) show that age estimates may be improved by establishing the interval of time between stabilization of the substrate surface and establishment of the tree seedlings used in age determination.

Tree-ring crossdating, though more time consuming than ring counting, usually produces a more reliable determination of age because it takes into account any missing rings or double rings. Roughton (1962) and Alestalo (1971) review some of the literature which discusses the use of crossdating to obtain dates for past occurrences of fires, frost, insect

infestations, release from competition, mortality, animal use, vegetative reproduction, glacial movements, and other geomorphological changes that have left a record in the rings of trees. Vinš (1970) describes similar studies on forest environments in Czechoslovakia.

The dendrochronologist can often reconstruct the past history of many events by detailed study of stems and anomalous structure of the rings (Sigafoos, 1964; Sigafoos and Sigafoos, 1966; Potter, 1969; Alestalo, 1971; Helley and LaMarche, 1973). Landslides, floods, earthquakes, and glacial advances can bury, injure, or tilt a tree stem and may cause changes in the growth which are recorded in the rings (Lawrence, 1950; Lawrence and Lawrence, 1958b; Potter, 1969; Page, 1970; Alestalo, 1971; LaMarche and Wallace, 1972). Tilting of angiosperms can be
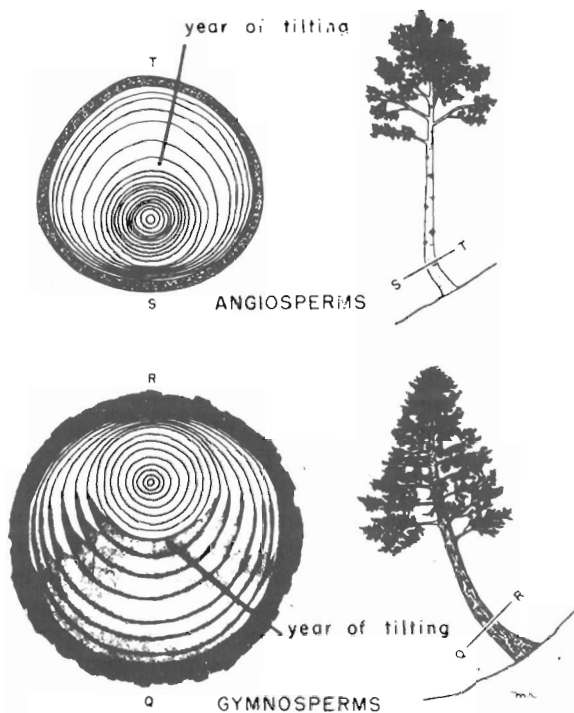
FIG. 5.3. Tilting of trees may be dated because after the year of tilting growth rings are formed asymmetrically in the stem. In angiosperms, the widest rings are formed in the stem on the upper side of the tilt, producing tension wood, while in gymnosperms the widest rings form on the lower side of the tilt, producing compression wood. (Modified from Lawrence, 1950) (Drawing by M. Huggins)

recognized by the presence of tension wood on the upward side of the tilt (Chapter 2). In gymnosperms, compression wood producing wider rings is found on the downward side of the tilt (Fig. 5.3).

Direct injury can produce scars on a tree stem, alter the ring structure, or affect crown form which itself produces a change in ring width (Alestalo, 1971). Scars at the base of trees are commonly used to reconstruct the past frequency of wildfire (Fig. 5.4) (Weaver, 1951, Erdman *et al.,* 1969; Kilgore, 1970; Billings, 1969; Heinselman, 1969, 1973). Abrupt changes in ring width have been used as evidence for snow slides (Potter, 1969), for burial of trees from deposition of rock debris or volcanic ash (Lawrence, 1950; Smiley, 1958; Sigafoos, 1964; Druce, 1966; Helley and LaMarche, 1973), for injury due to smoke pollution (Fig. 5.5) (Bakke, 1913; Clevenger, 1913; Vins, 1965, 1970), for
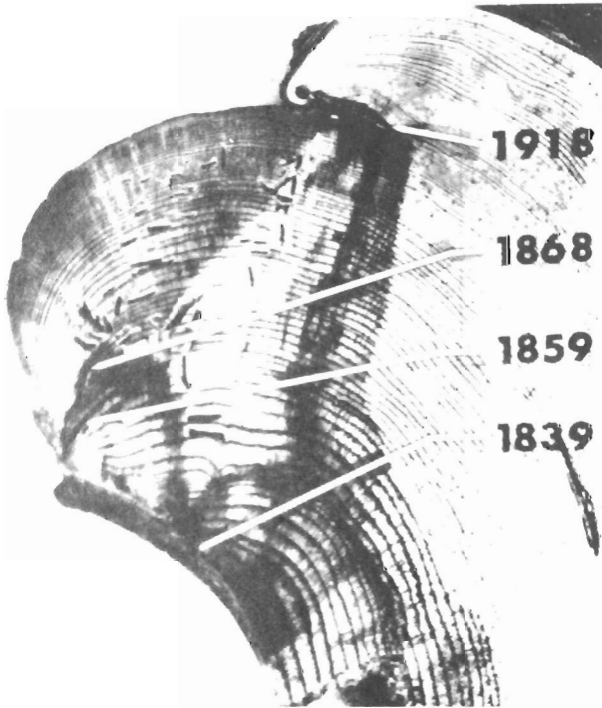
FIG. 5.4. Cross section of a tree stem showing scars from fires for 1839, 1859, 1868, and 1918. A part of the cambium has been killed and the living portion of the stem has grown over and buried some of the scarred tissue. (Specimen courtesy of David F. Aldrich and Robert W. Utrech, U.S. Forest Service)

disturbance of a site by rupturing of faults during earthquakes (Page, 1970; LaMarche and Wallace, 1972), for reduced soil aeration by rising lake levels (Antevs, 1939), and for damage by browsing herbivores (Lawrence, 1952; Vinš, 1970). Spencer (1964) reconstructed past variations in populations of the porcupine (*Erethizon epixanthum*) in Mesa Verde, Colorado, by using tree rings to date browsing scars on *Pinus edulis*.

Sometimes radiocarbon dating of ancient wood can be used to establish the relative age of a buried forest while the precise relative dating of tree-ring patterns is used to establish the histories of the individual trees. Although such relative dates are not accurately placed in time, the trees are dated accurately relative to one another, and such information can lead to considerable understanding of past geological changes and climatic events (Lawrence and Lawrence, 1958a; Munaut, 1966).
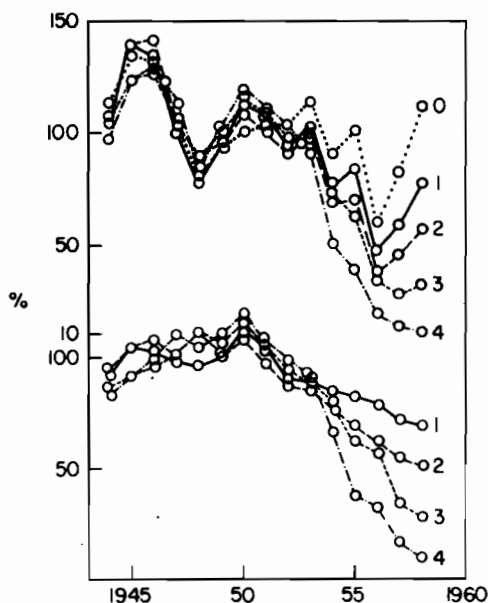
FIG. 5.5. Ring-width variation present in forest stands in Czechoslovakia subjected to various degrees of air pollution. The plot labeled 0 in the upper part of the figure represents growth indices for an untreated control stand, as compared to stands 1 to 4 representing increasing degrees of smoke pollution. The lower set of curves shows the growth of stands 1 to 4 as a percentage of the unaffected one labeled 0 at the top. (Vinš, 1965)

Koerber and Wickman (1970) discuss the use of ring-width measurements to evaluate the impact of insect defoliation on forest growth. They state that an increase in insect populations will increase defoliation of the host trees and reduce their photosynthetic capacity, which results in marked decreases in growth for a number of consecutive years following the insect attack. They also develop a model for the effect of weather factors on insect populations (Fig. 5.6) and show that the same climatic factors of low precipitation and high temperatures which are correlated with narrow tree rings also favor the growth of insect populations, increasing defoliation, and reducing further the width of tree rings.
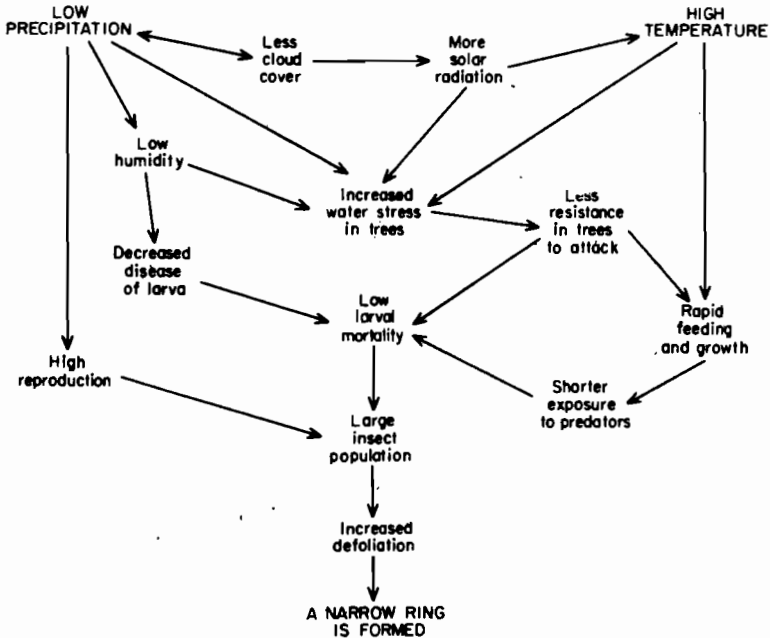
FIG. 5.6. A model of the relationships between low precipitation and high temperatures on insect populations, which decrease tree foliage and reinforce the effect of unfavorable climate on tree growth. (Redrawn from Koerber and Wickman, 1970)

V. Modeling Relationships in the Ring-Width and Climatic System

The foregoing portions of the book include descriptions of the most important plant processes affecting ring-width growth. Many of the

factors that limit these processes are shown to be linked to macroclimatic conditions through the energy and water balances. However, none of these processes and climatic linkages operates in a simple and singular manner. All are part of an ecological system in which there are almost endless numbers of interrelationships and complexities affecting the linkages between climatic factors and ring width (Billings, 1952).

However, the system can be simplified and described by developing models, which are represented in the following pages as a network of linkages (some unidirectional and some bidirectional) among specific states or conditions in the climate-plant system.

A. Rationale

The general rationale behind these process–network models is to express the essential nature of a complex system in the most intelligible form possible, a form that is also amenable to hypothesis testing and conceptual development. At the outset the hypotheses tested may principally involve the model itself, such as the identification of any variables included in the model that are irrelevant to it, the search for variables omitted from the model that should be a part of it, identification of any inaccuracies in the model, evaluation of alternatives to the model structures, and recognition of improperly formulated constraints. As a model increasingly resembles the natural system, it becomes more and more useful in the testing of inferences or hypotheses about the system, anticipating unusual conditions and situations, identifying new problems and possible solutions, as well as developing new models for further analysis.

This last use is perhaps the most important for these particular models because they have led to the identification and development of multivariate statistical models which in turn are used to quantify and test the process–network models themselves. They have also led to the development of other multivariate statistical models which allow precise calibration of climate and ring-width data and objective statistical estimations of past climatic variations from the corresponding variations in ring widths.

B. Approach

Because of the many complexities among the specific biochemical reactions and the physical linkages in the system, it is extremely difficult to model the details of individual physiological processes. In cases where such process-by-process modeling has been accomplished, the results.

although very interesting and revealing, usually pertain to particular circumstances and deal with simplified estimates for subsystems rather than the entire system complex.

For the time being it is more practical, as well as sufficient for dendrochronological purposes, to generalize the processes in a nonquantitative fashion emphasizing the major pathways in the system, including the range but not all the possible physiological components. Such generalizations must be consistent with relevant biochemical and physiological experimental evidence, while allowing for the fact that almost all such experiments must deal with only one aspect of the whole system, and therefore may be incomplete. It is most important that the generalizations be consistent with the basic concepts, observations of the system as a whole, and field evidence from habitats and species to which the models are relevant.

Such modeling is not without its own type of experimentation and hypothesis testing. Field measurements on the actual trees to be modeled may be obtained, stratified sampling of various sites can be used to study natural changes in specified variables, and actual manipulation of particular environmental factors in the field is possible to test certain kinds of hypotheses.

The models used are in a sense always tentative in that they are based on the best inferences and the best data available at the time. Each one may be considered to be suitable, however, until the emergence of new evidence. When this happens, the models should be reexamined, tested, and revised to incorporate the new information. As more and more evidence and experience accumulates, the models will improve, and in time they may become considered adequate representations of basic principles and concepts of the growth–climate relationships.

Such an approach to modeling is probably more justifiable for dendroclimatic study than for biological research, because the primary object of dendroclimatology is to use the structure of the ring to statistically reconstruct past climate. It makes little difference to the statistical result whether the relationships arise because a winter drought affects photosynthesis and food reserves which alternately limit growth, or whether a winter drought affects soil moisture, hormone precursors, and differentiation of buds which control the concentrations of growth regulators affecting subsequent growth. Either model can explain the lag between the climatic cause and the effect on tree growth. New evidence will undoubtedly alter the details of the models described in this volume, but it cannot alter the statistical relationships. On the other hand, new information can improve understanding of the relationship in such a way as to suggest a new model which could improve statistical analysis and

change the results. For this reason, physiological and ecological study, as well as statistical analysis of correlated relationships, are important to continued development of dendroclimatic and dendroecological research.

C. Model Constraints

It has been shown that a climatic variable can limit a wide variety of plant processes, which in turn can become limiting to growth and ring width. While the growth process at a particular instant in time is essentially controlled by that process which is most limiting, there are variable interactions within the plant and nonlinear situations that can make a model structure intricate. Arrows are used to join and to specify the direction of such interacting situations, and the sign of the effect is indicated, but scales or numeric quantities are not assigned to any of these relationships.

Different segments of the model are used to distinguish between cases where a set of climatic variables may have a positive as opposed to an inverse effect, and the importance of each segment is considered to vary and be additive from one month to the next.

VI. A Model for Factors Affecting Cambial Activity and hence Ring Width

A convenient place to start is the model of cambial activity described by Wilson (1964) and Wilson and Howard (1968) (see Chapter 2 and Fig. 2.7). They look on the cambium as a kind of factory to which building materials, energy sources, hormones, and water are fed from the nearby phloem and xylem. Any factor limiting the supply of these materials can limit growth. The complex cell structures of the ring are manufactured and added in the processes of assimilation which are dependent on favorable temperature. Whenever temperatures in the cambium are low, assimilation can be limiting and growth can be reduced. Cell differentiation also occurs but does not need to be included in our model because once the cell is fully enlarged, changes due to cell differentiation will not affect ring width.

There are four primary limiting conditions that must be considered in such a model. They are temperature of the growing tissues, water stress in the tissue, concentrations of growth regulators, and the amounts of building materials including foods and mineral salts. Fig. 5.7 visually outlines the relationships among these factors with appropriate words and arrows. Any limiting situations in any one of these factors can affect
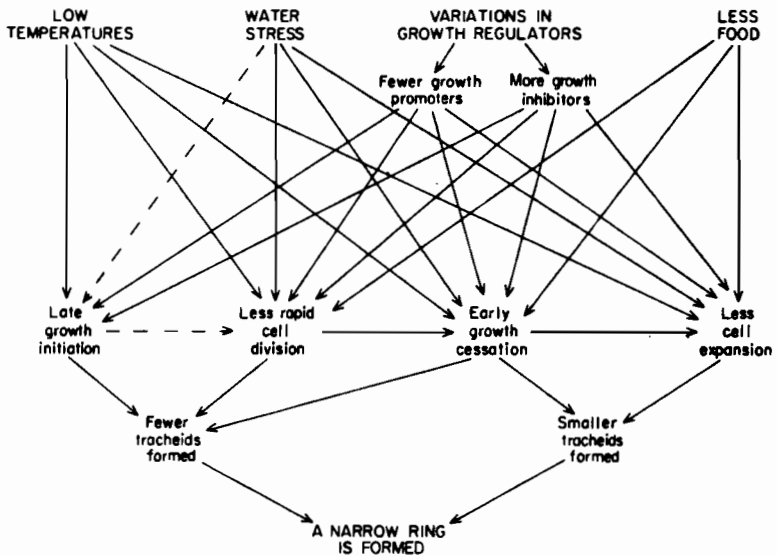
FIG. 5.7. A model describing the four major factors causing a reduction in growth of the cambium and production of a narrow growth ring. The arrows indicate cause and effect and include various types of interrelations among the processes and variables. It is implied from the diagram that the effect of the opposite extreme will increase both cambial activity and ring width.

the beginning and ending of the actively growing period, the rate of cell division, and the expansion of cells. These in turn affect number and size of the tracheids that are produced and thereby the ring width.

A. Temperature

Temperature of the cambium can be a directly limiting factor through its control of respiration and assimilation processes. The direct effects of temperature on radial growth are most frequently observed at the beginning of the season when unusually cold weather causes a delay in the breaking of dormancy. This favors a narrow ring by decreasing the length of the growing period. Once growth is started, any period of extremely cool weather near $0°$ C may limit growth, but as temperatures rise to those of summer other factors usually become more limiting. At high elevations or high latitudes, where the potential growing season is short and plant temperatures can be low while the cambium is still active, radial growth may be greatly reduced by cold weather during any time in

the growing season (Hustich, 1945; Mikola, 1952, 1962; Giddings, 1953; Eklund, 1957). Except at such extremely cold sites, cambial activity in late summer may cease due to internal conditions long before temperatures are low enough to be limiting to the assimilation and cell division processes (Fritts, 1969) (also see Fig. 4.16). Of course, if temperatures during the growing season become low enough to freeze the cambial tissues, much damage can result which will markedly affect the appearance and subsequent ring growth.

The energy budget of trees may be modified by the low temperatures and influence cambial activity in the stem. For example, trees at high elevations or high latitudes on south-facing slopes may receive direct solar radiation during the daytime causing temperatures to be higher than those in trees on north-facing slopes. On such exposures, temperature is most likely to become limiting to cambial activity during cloudy weather, at night, or when high wind dissipates the energy and reduces the cambial temperatures to levels too low for assimilation processes. Also on southern exposures, certain portions of trees near the ground may be warmed by longwave radiation from nearby objects and from the ground surface, stimulating early initiation of growth, before activity in the upper parts of the tree is underway.

Soils in the shade or on north-facing slopes may remain frozen and snow may persist for long periods of time, causing initiation of growth in the spring to be delayed by the persistence of low temperatures. Because of the limiting effect of low temperature on the initiation and continuation of cambial activity in trees on north-facing slopes, ring-width variations are more likely to be directly correlated with air temperatures of the early spring than for trees on south-facing exposures.

The microhabitats in polar regions may vary in a different fashion from those at lower latitudes because of the low sun angle and the long summer days near the poles. Radiation and heat loads on the plant are low, temperatures are moderate, and the diurnal range of temperatures is often less than at lower latitudes. Temperatures can become low enough during daylight hours to limit both respiration and photosynthesis, but in alpine habitats at lower latitudes, high rather than low temperatures may be limiting during the day and low temperatures are more apt to be limiting at night.

Much work on the growth-environmental relationships of trees at high latitudes and upper tree line is in progress. Evidence so far supports the generalization that unusually low air temperatures coupled with cloudy weather during the growing season can directly limit growth and cause rings to be narrow. Temperatures may also be limiting to photosynthesis, but in the model under discussion this would affect the amounts of

building materials and hence not be a factor directly limiting the growth processes.

In general there is little evidence that high temperatures are directly limiting to cambial activity in most trees used for dendroclimatological purposes, except for extreme heating resulting from such conditions as forest fires which can damage the cambial tissues. As in the case of frost damage, only when cambial tissues are killed outright or injured sufficiently to alter subsequent cambial activity is there a direct effect of such extreme temperatures on ring width.

B. Water

Water stress has been found to account for a large amount of ring-width variation. During a dry summer, water is obviously likely to be deficient enough to be limiting to the cell division and cell enlargement processes. Although much experimental evidence can be cited for a direct effect of water stress on cambial activity, the evidence is in large part circumstantial. This has led to considerable controversy over the question of whether water actually affects the growth process directly or affects some other factor such as photosynthesis or auxin synthesis which in turn influences the growth process. Zahner (1968) and Glerum (1970) present and describe some of the growing evidence supporting the hypothesis that moisture content of the cambium can become a direct limiting factor. This evidence includes numerous measurements and counts of cells that have repeatedly demonstrated that reduced rates of cell division and cell enlargement occur when the cambium is subject to internal water stress. The gross expansions and contractions of the stem diameter throughout the day and throughout the growing season, as documented in Chapters 2 and 3, represent some of the more obvious evidence.

However, unusually low solute and matrix potentials within the cambial tissue may enable the growing cells to compete favorably for water within the tree. As a result, cambial initials may remain relatively turgid and continue to divide, while other tissues such as the phloem and xylem are shrinking and undergoing water deficits. As the growing cells differentiate and mature, they become more vacuolated than the cambial initials, their solute potentials may rise and they may begin to show increasing amounts of shrinkage due to plant water deficits. These water deficits first affect the fully enlarged cells, and then the enlarging cells before they become limiting to the cells that are dividing. Thus, the first noticeable effects of water stress may be a reduction in cell size or a change in cell-wall thickening. These effects often vary from time to time, depending upon the degree of water stress and the life span and condition of the cell derivatives (Zahner, 1968).

If the drought persists long enough to induce dormancy, the last latewood tissue formed in the ring under severe drought may be markedly less dense and the latewood thinner than the latewood formed in a year with a more moist climate. A number of variations in tracheid structure and size, apparently due to water stress in a drought-subjected *Pinus ponderosa*, are shown in Figs. 2.19, 2.20, 2.22, and 2.23. The reader is also directed to a paper by Zahner (1968) for a detailed and informative discussion of the many indirect effects that water deficits can have on certain processes which in turn affect ring width.

C. Growth-controlling Substances

The concentrations of growth regulators may also be factors directly affecting radial growth. The influence of growth promotors and growth inhibitors on initiation, cessation, and rate of cambial growth has been described in Chapters 2 and 4.

In general the initiation of cambial activity is a result of a decline in growth inhibitors and an increase in growth promotors. If other factors are not more limiting the amount of cambial activity will increase to an optimum rate because of changes in the growth-regulating substances. The large earlywood cells formed during spring and early summer are associated with high auxin concentrations, while the shift to lower cambial activity and the formation of latewood is associated with a decline in auxins and possible changes in other growth regulators. The cessation of cell division and cell enlargement at the end of the growing season can be attributed to decreases in growth promotors and increases in growth inhibitors.

The rate of shoot growth may be controlling the production of these growth regulators which must then move to the region of the cambium before they affect growth rates (Larson, 1960). Also, water stress or low temperatures can reduce shoot growth or affect translocation which in turn governs the supply of growth regulators at the base of the stem. These factors of course are indirect controls, so they cannot be included in the particular model under discussion.

D. Amounts of Building Materials

Much circumstantial evidence has been accumulated which indicates that rates of growth in arid-site conifers are affected by changes in the amount of foods and related growth-controlling substances. If conditions are severely limiting to food manufacture and accumulation for long periods prior to the growing season, the rate of cambial activity in the

spring and summer can be most limited by food availibility. In such cases, the ring is narrow even though the temperature, moisture. and growth regulators are not limiting.

It is also possible that available minerals could be the most limiting factor to cambial activity. The cambial growth in *Pinus longaeva* on dolomitic soils may be limited by the low availability of certain minerals in the soil as some ions enter into the manufacture of protoplasm and certain proteins within the growth tissues. Minerals may also be indirectly limiting through their effects on the manufacture of foods and growth substances elsewhere in the plant.

Thus, the model of factors affecting cambial activity, as outlined by words and arrows in Fig. 5.7, includes four major limiting conditions in the operational environment surrounding the cambial tissues of the plant. It should be noted that temperature of the cambial tissues is the only climatic variable mentioned in the model and the model can account for only the direct temperature ring-width relationship. Although water stress is closely associated with variations in the water balance, it depends upon a variety of plant processes affecting water absorption in the roots and the transpiration from the leaves. These processes in turn can be affected by a variety of climatic factors including precipitation, humidity, temperature. wind, and light.

The growth-regulating substances are manufactured elsewhere in the plant so that the amounts in the cambium are governed indirectly by the conditions affecting growth and the activity of the stems, leaves, and roots as well as the translocation of the growth substances from their site of manufacture to the cambium. Mineral nutrition cannot be tied to any particular climatic factor and can be eliminated from a model of climate-growth relationships. However, the limiting effects of stored foods which become the building materials and energy source are highly dependent upon a variety of climate-affected processes, including photosynthesis, respiration, food manufacture, and assimilation.

VII. Modeling the Effects of Temperature and Precipitation on Ring Width

It was shown in the previous section that the climatic factors affecting ring width could not be adequately described in a model dealing only with the cambial tissue. It is necessary to consider the entire operational environment of the tree and the various effects of factors on processes occurring at different times in the year, and in different parts of the tree. Figs 5.8 through 5.10 diagram three segments of a model which describes these relationships. The variables of temperature and precipitation

were chosen as input variables because actual measurements of these variables could be used to test statistical models describing the same effects. In addition, these two climatic variables are easy to interpret in terms of other variables such as solar radiation, water vapor, wind, and atmospheric pressure; and they are variables most often used to describe changes in past climate. For the sake of simplicity, the linkages between macroclimate and microclimate have been omitted from the diagram. The following discussion treats the model in segments representing (A) the manner in which low precipitation and high temperature during the growing season lead to the formation of a narrow ring, (B) the manner in which the same two factors occurring prior to the growing season lead to the formation of a narrow ring, and (C) the ways and circumstances in which high precipitation and low temperatures can lead to the formation of a narrow ring.

A. Model Part A

The diagram referred to as Part A Fig. 5.8 represents relationships
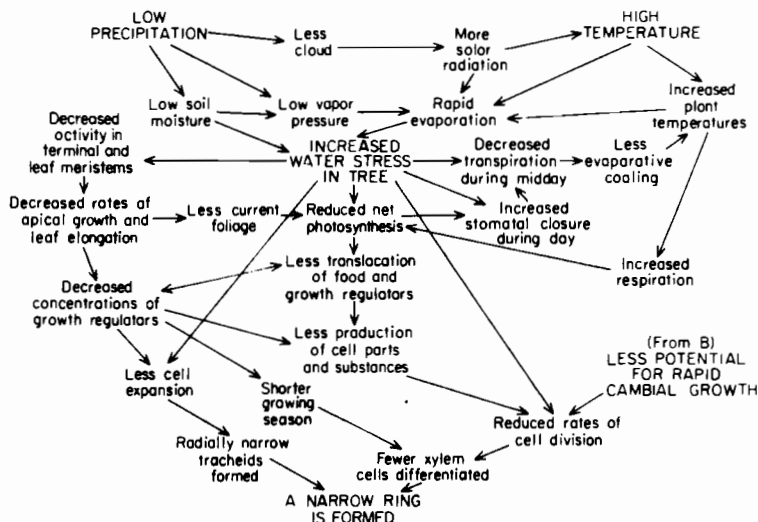
FIG. 5.8. Model Part A. A diagram representing some of the relationships that cause climatic factors of low precipitation and high temperature *during the growing season* to lead to the formation of a narrow ring in arid-site trees. The arrows indicate the net effects and include various processes and their interactions. It is implied that the effects of high precipitation and low temperature are the opposite, that is, ring width will increase.

that occur during the interval of time when the cambium is active. Low precipitation is generally associated with high temperatures, and high precipitation with low temperatures, because precipitation is usually accompanied by increased cloud cover which reduces the solar radiation flux (Q, Equation 5.1). Low precipitation and higher radiation, of course, increase environmental temperatures, and both climatic conditions accentuate water stress. Low precipitation results in low soil moisture recharge, which leads to reduced rates of water absorption. High temperatures increase the water potential gradients surrounding the tree and favor rapid water loss. As shown in Fig. 4.10, net photosynthesis in *Pinus ponderosa* is reduced during periods of high water stress and high temperatures. Depending on the situation, net photosynthesis may be reduced because water stress lowers photosynthetic rates directly, because increased temperatures raise respiration rates, or because of a combination of these two. With less net photosynthesis there is less food available for growth.

The left-hand portion of Part A describes the effects of water stress on activity in the apical meristems and growing leaves, which are the source of important growth regulators affecting cambial activity in the stem, as was discussed in the prior model and in Chapter 4. Increased water stress can limit the activity in the meristems so that there are lower concentrations of growth promoters (or higher concentrations of growth inhibitors) and reduced cambial activity in the main stem.

Increasing water stress can reduce cell expansion directly (see Fig. 5.7 and Zahner, 1968), and the production of new cells and the length of the growing season may be shortened as a result of water stress. Interactions are shown where decreased apical growth may cause less foliage to be formed, which in turn reduces net photosynthesis late in the season or in the following year. Interactions between growth regulators, translocation, and utilization of food are also shown.

B. Model Part B

Studies on ring widths and climatic relationships for conifers on arid sites repeatedly demonstrate that the climate during the growing season (Part A) is often less important to ring-width growth than the climate of the autumn, winter, and spring prior to the growing season (Fritts, 1965, 1969; Fritts *et al.*, 1965c; Julian and Fritts, 1968).

Part B, shown in Fig. 5.9, diagrams relationships which appear to be responsible for the preconditioning of growth or which, in statistical terms, account for the lag in the growth response behind the occurrence of climate. As in Part A, much of the biological evidence for the

B
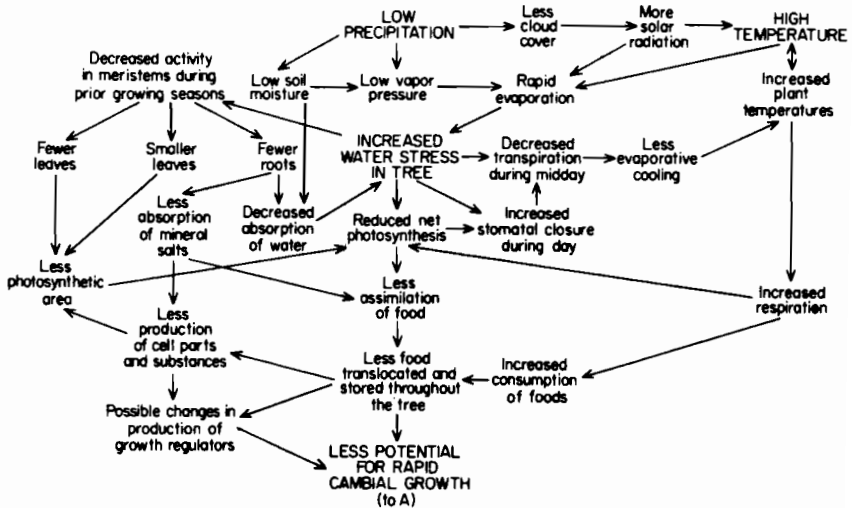
FIG. 5.9. Model Part B. A diagram representing some of the relationships that cause climatic factors of low precipitation and high temperature occurring *prior to the growing season* to lead to the formation of a narrow ring in arid-site trees. Compare with Fig. 5.8.

relationships expressed in this model is described in Chapters 2, 3, and 4. Of the three model segments Part B is most applicable to arid-site conifers on low-elevation sites near the lower forest border of the species. Temperatures there in autumn, winter, and spring are often above freezing (Fig. 4.16) and precipitation is low enough that the combined effect of low precipitation and high temperatures can create conditions of water stress during any time of the year. Because the trees can be photosynthetically active all year long as well, such water stress can limit net photosynthesis. High temperatures often reduce net photosynthesis by increasing the rate of respiration over the rate of photosynthesis and thereby reducing the accumulation of photosynthetic products as stored food. In such cases, when cambial activity commences in spring, the growth of trees can be most limited by a deficiency in the products assimilated from stored food.

Interacting relationships can also occur with the growth of prior seasons. Water stress during prior years may result in fewer and smaller leaves, buds, and roots, This reduces the total photosynthetic and absorptive areas of the tree, so that it is less able to photosynthesize or absorb moisture when favorable climatic conditions occur. In this manner, climatic conditions during prior years interact with those

occurring immediately before and during the growing period to affect the ring width.

Chapter 2 describes some of the variations in apical and radial growth on arid sites. Growth commences in late spring after much of the soil moisture from winter snow has been lost by evapotranspiration. This is a time when the remaining soil moisture in arid, forest-border sites in southwestern North America is diminishing and net photosynthesis has reached its peak rate and is beginning to decline. A large part of growth that takes place early in the season (especially in the regions of the roots and at the stem base) is dependent upon foods accumulated and stored in the tree during the autumn, winter, and spring, because photosynthates that are currently produced by the leaves are utilized primarily by the growing crown. This situation remains even after the summer rains commence. Net photosynthesis usually increases, but shoot growth, needle enlargement, and growth of the reproductive organs within the crown also increase. The tissues in the crown continue to receive most of the currently produced photosynthates. The cambia at the stem base and in the roots are the last to receive translocated food and are most likely to remain dependent upon the foods accumulated throughout the winter and stored in tissues of the stem and root.

Therefore, the coincidence of the first half of the cambial growing season with dry conditions and water stress and the coincidence of the latter half with rapid shoot and fruit growth, which compete with the cambium for large amounts of the currently produced photosynthate, could cause the ring width at the base of the stem of mature trees to remain dependent upon stored food reserves accumulated over the autumn, winter, and spring. This situation would explain why ring-width variation from the stem base of mature trees is correlated so well with moisture and temperature conditions during the autumn, winter, and spring preceding the beginning of growth. It will be shown later in the chapter and in Chapter 7 that, where the spring season is on the average more moist than on these arid sites, ring width is less well correlated with the winter climate and more highly correlated with the spring and summer climates.

C. Model Part C

Some trees used for dendrochronological studies grow on sites where temperatures in the spring, summer, and autumn are low, and temperatures in the winter are well below freezing for long intervals of time. Such conditions are often found on north-facing slopes, low areas where cold air may accumulate during calm nights, and high latitudes or

elevations where the annual net energy received by a tree may be low
(Equation 5.3). At certain times throughout the year, conditions of
extremely low temperatures and high precipitation may influence
environmental conditions which directly or indirectly limit growth. A
few of the important relationships leading to these conditions are shown
in Part C (Fig. 5.10).
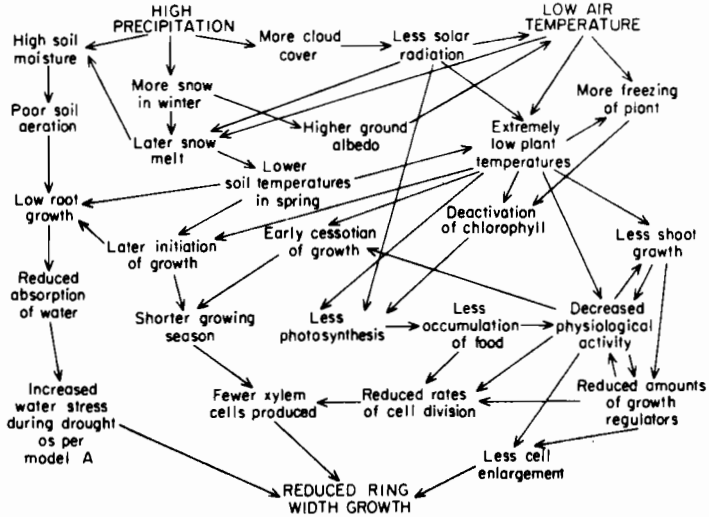
FIG. 5.10. Model Part C. A diagram representing some of the relationships that cause
the climatic factors of high precipitation and low temperature to lead to the formation of a
narrow ring. Compare with Figs 5.8 and 5.9.

As in Parts A and B, low temperatures are coupled with periods of high
precipitation because increased cloud cover reduces solar radiation and
the heat load. High precipitation in winter may result in increased snow
cover, which raises ground albedo (a, Equation 5.1) and helps to
maintain low air temperatures. Soil temperatures are determined by
the temperature prior to the onset of insulating winter snows. Severe
conditions in autumn, winter, and spring may ultimately curtail growth
through freezing of the plant tissues and deactivation of the chlorophyll
(see Chapter 4).

Cool temperatures during the growing season may also reduce
physiological activity of the plant. When cambial activity is initiated it
may be limited by low respiration rates, low concentrations of growth
regulators, or low amounts of food (Fig. 5.7). Cool temperatures and deep

snow cover may delay the onset of spring and cause initiation of growth to be late and slow. Unusually cold weather in late summer or in autumn may induce early cessation of growth. Both a shortening of the growing season and a reduction in the rates of cell division by cool temperatures can reduce the width of a ring. High precipitation during one season may saturate the soil in poorly drained sites, contribute to low aeration and low root growth, which in turn can induce water stress later in the year.

The growth–climate relationships shown in diagrams A, B, and C can vary in their relevance to a particular site throughout the year. Part C represents the most common relationships that occur in trees on temperate sites during abnormally cold months, while Parts A and B portray the most important relationships governing growth during the warmer seasons of spring, summer, and early autumn. With increasing elevation or latitude, Part C becomes applicable for an increasing number of months of the year. This varying relevance of the models to a particular site may itself be modeled mathematically in terms of the following equation:

$$W_t = G_t \left[\sum_{j=1}^{m} (\alpha_j A + \beta_j B + k_j C) \right] \tag{5.4}$$

where W_t is ring width and G_t the growth function which varies inversely with tree age t. The values of α_j, β_j, and k_j are weights representing the importance of each part of the model, A, B, and C, and they assume varying positive values for m months throughout the year. The limiting effect on growth of low precipitation and high temperature, relative to the effect of high precipitation and low temperature, may be expressed for the jth month of the year by adding α_j and β_j and subtracting k_j. These values would represent the tree-growth response to combinations of dry–warm conditions versus cool–moist conditions throughout the year.

There are also some very important relationships involving a positive association of both temperature and precipitation which have been omitted from the diagrams. Low temperatures and low precipitation occurring late in the summer or early in autumn together can prolong cambial activity in one year with the added utilization of stored foods, which reduces the amounts of food available for the next year's growth. These conditions can also affect the formation of vegetative and re-productive buds which can exert an important control over cambial activity in the following year. There is also evidence (Chapter 4) for low temperatures and low precipitation in late autumn promoting winter hardening and hence favoring survival of living tissues through the cold winter season. There can also be limiting effects of both low temperature

and low moisture occurring together as they can delay breaking of dormancy and shorten the length of the growing period for that year. Some other relationships not shown in any part of the model are the effects of climate on flower initiation, fertilization, fruit set, and maturation, and the interrelationships between the amounts of growth for the current season with growth for several prior years.

VIII. The Concept of the Climatic "Window"

The net effects of environmental factors on ring width can vary from species to species and from site to site. In addition, the climate during certain months of the year may have a greater influence upon growth than the climate of other seasons. The tree may be thought of as a "window" or filter which, by means of its physiological processes, passes and converts a certain climatic input into a certain ring-width output. Different species pass different amounts of information through their "windows" at different times of the year. These differences could be expressed by different absolute values of α, β, and k for different months within the year (Equation 5.4).

Figure 5.11 shows diagrammatically the mean climatic "windows" calculated from correlation analyses made on five different species or species complexes (Fritts, 1974). The diagrams are smoothed to express the relative effect of variability in climate at different times of the year upon the variability in width of the annual ring. The physiological seasons for these species are shown in Fig. 4.16. The ring-width variations for *Pinus longaeva* (P.l.) and *Pinus aristata* (P.a.), which grow at high elevations, reflect a large amount of climatic information from the summer and autumn prior to growth (25% and 26%). In the winter the climate accounts for 23% of the ring-width variation, while in spring it accounts for only 15%.

The ring-width variations of *P. flexilis* (P.f.), a species which has a larger ecological amplitude than *P. longaeva*, are influenced greatly by the climates of autumn (32%). The ring-width variations of *Pseudotsuga menziesii* (Ps.m.) and *Pinus ponderosa* (P.p.), two species which occur at lower elevations (see Fig. 4.16) and on drier and warmer sites, show the largest response to autumn and spring climate. *Pinus ponderosa* emphasizes the climate of late spring and early summer (13%) more than does *Pseudotsuga menziesii* with only 8% growth variation determined by summer climate. The ring-width variability of *Pinus edulis* (P.e.) and *Pinus monophylla* (P.mn.), species growing at the lowest elevations of the five groups shown in the figure, is more influenced by winter environment than the ring-width variability of the other four groups. The window for

this particular group passes a large amount of variation in climate of autumn, winter, and spring (29%, 27%, and 20%). During the summer concurrent with growth, the window allows climate to affect only 6% of the variance in growth.

The area under each curve in Fig. 5.11 included in the period of cambial activity (g) is proportional to the relative effect on ring-width variability of the climate during the growing season. The area may be compared to the remaining area under the curve which is proportional to the effect of climate for the period preceding growth. Such comparison clearly illustrates that the climate during the growing season (partly described in Part A, Fig. 5.8) is less important to growth than is the
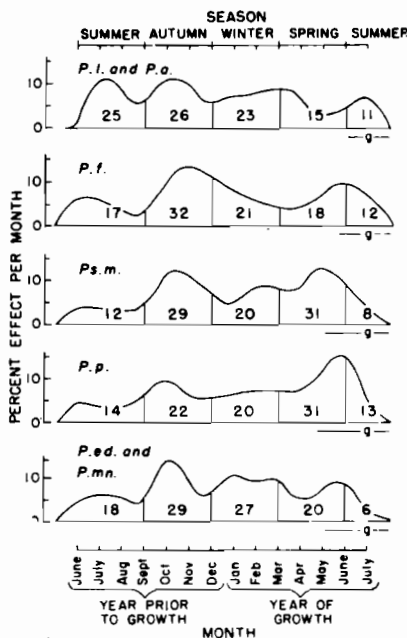
FIG. 5.11. The mean climatic "window" for five different coniferous species from a variety of arid sites in western North America. The plot shows the percent correlation of *mean* temperatures and *total* precipitation for each month with variation in the width of annual rings. Vertical lines designate the seasons and the numbers are the percentages of growth affected by climate during each season. The line marked g designates the portion of the climatic window included in the period of growth. The data are smoothed by averaging data for adjacent months. P.l. = *Pinus longaeva* and P.a. = *P. aristata* [25 sites analyzed]; P.f. = *P. flexilis* [4 sites analyzed]; Psm. = *Pseudotsuga menziesii* [40 sites analyzed]; P.p. = *Pinus ponderosa* [35 sites analyzed]; and P.e. = *P. edulis* and P.mn. = *P. monophylla* [15 sites analyzed].

climate prior to the growing season (partly described in Part B, Fig. 5.9).
In general, the climate prior to the growing season exerts the dominant
control over ring-width variation for the trees and sites used for den-
droclimatic analyses from semiarid North America.

IX. The Concept of the Response Function

The correlation between climatic factors and growth may show striking
changes from one month to the next. This relationship can be expressed as
response functions, a set of 28 statistics (to be further described in Chapter 7)
which represent the separate relative effects on ring width due to
variations in mean temperature and total precipitation during each
month of a 14-month period prior to and concurrent with the period of
growth. A positive value for the response function statistic for a given
month indicates a direct relationship (the greater the value of the climatic
variable, the greater the growth); a negative value indicates an inverse
relationship (the less the value of the variable, the greater the growth).
An inverse effect may be just as important as a direct effect, only the sign
of the coupling relationships is reversed. Figure 5.12 shows smoothed
plots of the response functions for the same sites and species included in
the analysis of the climatic "window" shown in Fig. 5.11. Three
additional statistics shown on the right in the plots represent the mean
effect of prior growth on ring width for lags of 1, 2, and 3 years.

It is evident from the mean response function shown in Fig. 5.12 that
the ring-width variations in the lower elevation species, those plotted at
the bottom of the figure, are more influenced by monthly precipitation
than by monthly temperature. Precipitation is directly related to growth,
especially in autumn, winter, and spring, while temperatures are often
inversely related to growth in autumn, late spring, and summer. The
growth of the two upper elevation species, those near the top of the figure,
are affected equally by precipitation and temperature, although the signs
of the relationship are different. There are also more months when high
precipitation and low temperatures, as shown in Fig. 5.10, may limit
growth (Fig. 5.12).

Ring width on the average for *Pinus edulis* (P.ed.) and *Pinus monophylla*
(P.mn.) is largely dependent on variations in precipitation for autumn
and winter. Ring widths for *Pinus ponderosa* (P.p.) and *Pseudotsuga menziesii*
(Ps.m.) are dependent more on varying precipitation in autumn and
spring. At the same time, variations in temperatures are less important to
ring-width growth of these two species than to growth of the other four
species. High growth in *Pinus flexilis* (P.f.), is dependent upon high
precipitation and low temperatures in the prior summer, autumn, early
winter, and late spring. High growth of *Pinus longaeva* (P.l.) and *Pinus*

aristata (P.a.) is dependent upon high precipitation and high temperatures in the prior summer, high precipitation in autumn and early winter, low temperatures in autumn, winter, and spring, and low precipitation in early summer at the time when the trees begin to grow (Fritts, 1969).
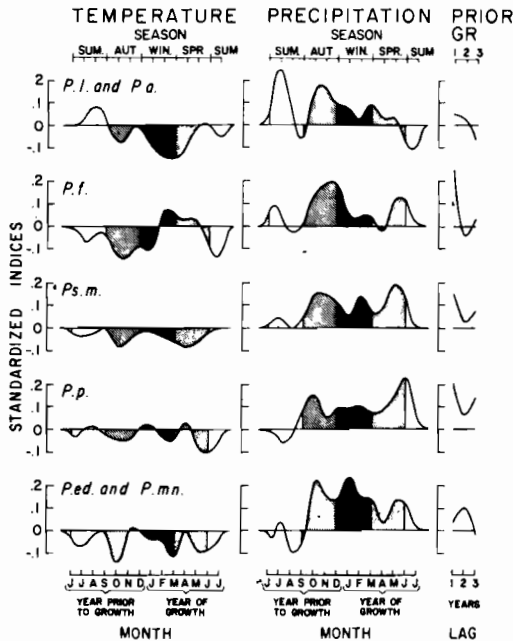
FIG. 5.12. The mean response functions for five different coniferous species from a variety of arid sites in western North America. The plotted values show the relative effect of variations in mean temperature and total precipitation for each month on the variations in ring width. A value above zero indicates a direct relationship (an increase in the variable is associated with an increase in growth), and a value below zero indicates an inverse relationship (an increase in the variable is associated with a decrease in growth). Differences in shading mark the various seasons. Sample size, species symbols, the growth period, and smoothing procedure are the same as for Fig. 5.11. Computational procedures for deriving response functions are described in Chapter 7.

The results shown in Figs 5.11 and 5.12 express the *average* climatic "window" and the *average* response function for a species growing on many sites. Large variations in climatic "window" and response functions also occur as a function of site factors and microclimate. The details of these variations are described more fully in Chapter 8.

X. Suitability and Limitations of
the Growth Model

It is obvious that no single model can resolve all the complexities of the growth–climate system. However, the above process-network models along with Equation 5.4. allow for both direct and inverse effects, for variations in the climatic "window" and response function from one month to the next, and to some extent for interactions among the physiological environmental processes. The most useful attribute of the model is that the arrows do not represent an individual plant process but rather the net effect of the climatic factors on all relevant processes.

For example, it has been mentioned (Chapter 4) that higher than normal air temperatures can affect ring width positively or negatively, depending upon the particular processes which are most active. It can elevate plant temperatures so that growth rates increase; it can hasten root growth ànd favor absorption of soil moisture; or it can increase leaf development, exposing to light more tissue which can carry on photosynthesis. However, the elevated plant temperatures also can increase respiration rates; they can decrease the rate of net photosynthesis; and they can increase transpiration which can accentuate conditions of water stress. The first three conditions are usually beneficial to growth, while all the latter conditions are usually detrimental to growth. Early in the spring when the beneficial effects dominate, the model could indicate that the net effect of elevated temperatures is to increase growth. Later in the season when the latter conditions may dominate, the model could indicate that the net effect of elevated temperatures is to decrease growth.

The process–network model is especially suited for cases where variables can also compensate for each other's effects. For example, low soil moisture can be offset by the favorable effects of low temperatures on reducing transpiration, or the reverse might also occur with high soil moisture offsetting the effects of high temperature. Such situations have been observed for low-elevation and arid-site trees, where subfreezing temperatures can limit net photosynthesis and hence the production of food (Fig. 4.3), but low temperatures cause freezing and hold moisture on or within the soil in the form of ice and snow. As long as it is moderately cold, little evapotranspiration and soil moisture depletion can occur. When temperatures are less severe and rise above freezing, the increase in net photosynthesis is accompanied by an increase in evapotranspiration so that soil moisture declines. A return to cold temperatures stops photosynthesis but also converts the moisture back to ice so evapotranspiration ceases as well. As a result of the association between

these two conditions, the unfavorable effects of low winter temperatures on photosynthesis are offset by the favorable effects which hold the moisture in the soil.

If a site on average is colder than the one described above, the detrimental effects of low temperatures may dominate because of deactivation of chlorophyll, so that low temperatures may be associated with low food reserves and the model would indicate low growth. However, if the site on average is warmer than the one described above, the effects of higher than normal temperatures may lead to increased evapotranspiration, so that higher temperatures rather than lower ones become associated with less available moisture, low reserves, and low growth.

The effects of many factors are often cumulative, so if they are limiting during many days throughout the year, they are modeled to have a marked net effect on growth. However, variable actions can sometimes involve short-period effects, such as the occurrence of freezing temperatures for one night during the growing season which can damage the cambium and produce a frost ring. The model used in this chapter does not handle the effect of single but severe events efficiently, but events which occur with some regularity are reflected in the mean and therefore *are* handled well.

When there is interaction among variables, their combined effects can be greater than the sum of their independent effects. For example, the combined effects can be many times more limiting if precipitation is low when air temperatures are high, than if either occurs separately. The model treats such interactions by combining the effects of high temperatures with those of low precipitation and the effects of low temperatures with those of high precipitation, which is a compromise short of using a logarithmic or other similar transformation.

Some factors may condition the plant or its environment so that the plant responds in a certain way at a later time. The rate of warming and the temperature regime in the spring is an example. Spring temperatures not only control evapotranspiration, but they also may control initiation and rate of root growth. In a normal spring when warming is gradual, root growth can maintain increasing absorptive surface to match the increasing water demand by the crown. If soil moisture is adequate, water stress is unlikely to be limiting to the tree. An unusually late and cold spring could delay the initiation of root growth and perpetuate low soil temperatures. If the weather suddenly turns hot and dry, transpiration may exceed the abilities of the roots to absorb water, both because of low growth rates of the roots and because the soil temperatures

are low. Water stress would result until enough time had elapsed for soils to warm up and for root growth to reestablish enough active surface so that water absorption equaled water loss.

Another example of delayed response is the growing crown which expands and intercepts both more sunlight and precipitation, and casts greater shade. Thus, the regimes of soil moisture and temperature may be gradually altered, causing possible changes in the timing of initiation and cessation of growth. Model Part B attempts to account for some of these interacting relationships, but changes from one month to the next and one year to the next are assumed to be additive; that is, the effect in one year or month is added to the effect in other years and months. Any relations of these characters are averaged to obtain the net effect; interactions involving multiplicative effects between months and years are not reflected in the model.

There may be other kinds of effects of variables on growth rates over long periods of time. For example, insects (Fig. 5.6), hail, and frost can defoliate the tree and produce an immediate and marked change in a variety of processes affecting growth. Fire, death, or windthrow of a neighbor, or a landslide might open the forest canopy, increase the available light and food, and affect other conditions which could cause a rapid increase in the growth rate. A change in the soil moisture regime arising from an alteration of a river channel or fluctuation in lake level may drastically change the amounts of water and air in the soil and produce an abrupt change in tree growth.

Depending upon the circumstances, the growth rate may accelerate or decelerate rather abruptly, and may then be associated with a gradual return to the original unaltered state, or the tree may remain at the altered growth rate for the remaining portion of its life. There are also some factors that become increasingly or decreasingly limiting very gradually over long periods of time. Variations caused by changing tree height, changes in soil, slope degradation, and certain kinds of competition may be indistinguishable from the biological changes associated with increasing age because they occur so slowly through time.

The same climatic factor can vary in its effect on growth depending upon the time scale of the reaction. A drought during a given year can reduce ring width for that year and for several years thereafter. However, the effects of the drought on growth may become less if the drought persists for a long period of time, for the forest may gradually change in structure making the tree more drought resistant. For example, weak neighbors die, the forest stand becomes less dense, and the roots and crowns of the remaining individuals can expand and occupy the vacated sites. Each tree remaining in the stand is less limited by comparable

moisture conditions at the end than at the beginning of the prolonged period of drought, because competition from neighbors is reduced. In this manner, the reduction in density of the forest community counteracts the deleterious effects of prolonged drought on the survivors. Thus, the ring widths in arid-site trees may become proportionately wider over a long period of time, even though drought conditions persist. In such cases, the ring-width variation will not record the long persistence of a drought. However, this may not apply to the most arid sites where trees are so widely scattered that they do not influence each other very much.

The generalities of the process–network model in Figs 5.8 through 5.10 appear flexible enough to handle a large number of the complicating and interacting relationships of growth and climate. While the models are representative of the most important relationships, they most certainly do not include all the individual processes that operate in the system, and they cannot be used in their present form to obtain quantitative estimates. However, they do adequately summarize the important physiological processes described in Chapters 2 through 4 which link precipitation and temperature to variations in ring width.

The following chapters will describe statistical and other methods for further study of this system and for testing the importance and significance of particular relationships. Techniques will also be introduced for calibrating specific ring-width variations with climatic variations in factors such as temperature and precipitation, and for reconstructing the same or similar climatic variations using ring-width variations for a number of species in a variety of locations and sites.

METHODS OF DENDROCHRONOLOGY - III

TREE RINGS AND CLIMATE
Volume Two

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Tree Rings and Climate

Chapter 6

The Statistics of Ring-Width and Climatic Data

I. Reliability of Measurements

The discussion in Chapters 2 through 5 has focused on the general problem of modeling the ring-width/climatic system. Attention will now be directed to the problem of objectively quantifying characteristics of both the tree-ring and climatic data which are to be used for statistical modeling, calibration, and climatic reconstruction.

The basic data under consideration in this chapter are ring-width measurements and climatic records. Each data set is made up of measurements which are averaged and transformed in certain ways to facilitate study and analysis. The numbers that are generated from these data are collectively referred to as *statistics* and may represent the means (averages), the variability, or some other feature of the data. However, statistics are no more reliable than the data from which they are derived.

The following paragraphs describe some . routine but important procedures that ensure that the original tree-ring and climatic data are collected and processed correctly, maintaining the maximum amount of useful information as well as data reliability.

A. Collecting Adequate Field Data

The first procedure of importance is an obvious one: to obtain complete field notes and information about the sampled trees and sites, not only as a matter of record but for use in subsequent analysis. The samples should be labeled carefully and clearly, and the date, species, location, elevation, exposure, slope, and any other noticeable characteristics should be recorded. Exact specification of location in terms of latitude and longitude is preferable to the use of local names since the latter often lead to ambiguity. Without proper site location on a map, there can be no assessment of distances to recording weather stations and to other stands, no evaluation of topographic factors, and little possibility of returning for subsequent collection. It may be helpful to cite the name

Table 6.I A checklist of collection and site information

1. Name and address of submittor. Name and address of collector(s).
2. Date collected.
3. Source of collected material (living trees; historical; archaeological; geological; or other source).
4. Name of site. Single or merged site?
5. Site elevation. Latitude. Longitude. Country. State. County.
6. Collected genus. Species. Variety (optional).
7. Number of trees collected. Total number of radii. Number of radii per tree.
8. Type of measurement (total ring width; earlywood; latewood; density).
9. Unit of measurement used (100ths mm; 100ths inch; other).
10. Beginning year of dated chronology. Ending year of chronology.
11. Name, type, and scale of map used. Is map available? Are site photos available?
12. Slope angle of site. Direction slope faces.
13. Predominant soil characteristics (organic, clay, silt, sand, loam, gravel, rock fragments, bedrock).
14. Soil drainage. Soil chemistry. Parent material of soil.
15. Was the collected species dominant (in crown area coverage)?
16. What percent of total forest was the collected species?
17. Associated species. Vegetation zone or life zone.
18. Canopy position and competition.
19. Is forest growth natural, successional; natural, stable; cultivated, native species; or cultivated, introduced species?
20. If there is site disturbance is it man-caused; natural; or of unknown cause?
21. Are climatic data available for locale of collection site?
22. Additional comments.

and edition of the map which was used to identify the precise location. If one is likely to return to the area at a later time for recollection, distances from neighboring towns and roads are helpful, as well as permanent labels which can be attached to the trees that are sampled. Records of slope, exposure, soil, plant community characteristics, and obvious site disturbance can be used to account for unusual results or to select data to test future hypotheses.

Table 6.1 is a checklist of site information requested from contributors to the International Tree-Ring Data Bank being established at Tucson, Arizona. Replicated well-dated ring widths are being placed on file along with a certain amount of site information. The first 10 items are required in order to identify the contributor, the character of the tree-ring materials, and the location of the site. The remaining items are listed as optional but are considered to be important for maximum scientific usefulness.

Other kinds of data may also be recorded, depending upon the nature of the problem and the goals of the project. The important point is that objective records must be kept in some way and that they should be summarized and made available in a usable form along with the ring-width measurements. Well-defined and complete records of site information assures that carefully dated and processed tree-ring materials will be of maximum value to future scientific analysis.

B. Ensuring Adequate Replication

A second important procedure is to ensure data reliability by sampling adequately. As mentioned in earlier chapters, two cores from each of 20 or more trees may be a typical sample, although smaller samples can be used where there is good crossdating and a large amount of ring-width variability. However, a sufficient quantity of materials should be obtained to allow for data loss when certain samples are found to be anomalous or to yield questionable dating. After a long, tiresome hike into a remote area, it is a temptation to stop collecting after the minimum number of trees have been sampled. Yet insurmountable difficulties are often encountered back at the laboratory which can invalidate a portion of the sample; and in such circumstances it is comforting to have collected enough extra specimens to compensate for the data loss due to the difficulties.

Some of these difficulties can be avoided by examining the sample in the field immediately after collection, before it is labeled and packed for transit. The rings for the last few decades can be surfaced using a sharp knife and examined with a hand lens to check whether there are any

obvious growth anomalies, whether the rings are sufficiently variable, and whether crossdating is evident. This information can be used to judge the potential quality of the record and to help decide whether the site and species are appropriate and how many trees should be sampled. A procedure using analysis of variance statistics, described later in this chapter, can be utilized to evaluate past decisions concerning choice of sites, sample size, and design of analysis as a basis for planning future improvements.

C. Preparing the Specimens

A third important precaution, also seemingly obvious, involves mounting and preparing specimens so that the rings are clearly visible and easy to examine. Some workers have floundered because their samples were incorrectly mounted and the rings could not be seen well enough to be dated. The Laboratory of Tree-Ring Research uses pregrooved sticks in which the individual cores are mounted to expose the transverse (not the radial) surface. If a razor rather than sandpaper is to be used in surfacing, the best visibility of the rings is obtained if the cores are rotated approximately 30° from their vertical position (Stokes and Smiley, 1968). Bulk samples should be cut along the transverse plane, trimmed to facilitate ease in handling, and surfaced with knife or sandpaper.

If the materials are sanded, coarse paper is used first; followed by finer grit sizes. For example, a sequence of sandpaper grit sizes might be 180 or 220, 320, 380, and 400 or 600, depending to some extent upon the quality of the cut surface and upon the hardness of the wood. Finishing with soft felt, lambs wool, steel wool, or very fine emery paper can produce an exceptionally fine surface, the choice again depending upon the character of the wood. The interested reader should refer to Stokes and Smiley (1968) for details on specimen preparation.

D. Crossdating

As described in Chapter 1, crossdating is perhaps the most crucial procedure in tree-ring analysis, although one commonly finds tree-ring and climatic studies where only ring counts are made. Chronologies resulting from such studies can contain errors due to counting, mistaken identification of ring features, and ring absence. A surprising number of absent sets or false rings occur, even for sites that are relatively temperate. As emphasized earlier, crossdating is of vital importance in assuring that each ring width and climatic value is placed in its proper time sequence.

In certain cases where few rings are missing and troublesome false rings rarely occur, the rings can be measured first, certain computations made, and the data plotted to facilitate the crossdating process. Since this practice may encourage excessive reliance on statistics and on ring-width measurements as opposed to other helpful ring characteristics, it is recommended that all rings be examined, under magnification if required, and that features other than ring width be used to confirm any decisions that were made using the ring-width data and graphical analysis.

The crossdating obtained in most North American studies by professional dendrochronologists at present involves visual examination of every specimen. The Laboratory of Tree-Ring Research requires that a routine dating check be performed by a second person, and if serious discrepancies are found, the dates for the entire set must be verified by yet another worker. No specimen is selected for climatic analysis if there is *any* question as to the dating, even if the problem involves only one ring. Not only are the specimens checked against one another, but the entire sample is checked against chronologies from neighboring regions.

It is highly likely that some of the tedium involved in the visual crossdating operation will be increasingly facilitated by computer analysis. However, at present there is no fool-proof shortcut to the procedure of careful visual comparison (see Chapter 1, and Table 1.II).

E. Careful Measurement

A fifth reliability check involves verification of the precision of measurement. After all rings are dated and measured, a number of samples are selected at random, and one to three intervals of 20 successive rings are remeasured by an independent worker. These remeasurements are subtracted from the first measurements to obtain a set of 20 differences. Each of the differences is squared, the 20 squares summed with the limit of acceptability set at a sum of $0\cdot10$ for arid-site conifers and at a sum of $0\cdot23$ for *Quercus alba* (Fig. 6.1). The acceptable limits were obtained by plotting the frequency of occurrences of the summed squared differences obtained by expert measurers (see Fig. 6.1). The figure shows that the sums equal to or less than the limit are easily obtainable by a careful worker, while those greater than the limit may indicate the possibility of unacceptable measurement. In the latter case, the cause of the errors is determined and all past work of the particular measurer may be checked more closely. The Tree-Ring Laboratory of the U.S. Geological Survey measures each specimen twice and calculates an error term from the differences. If the standard deviation (see Equation 6.2) of
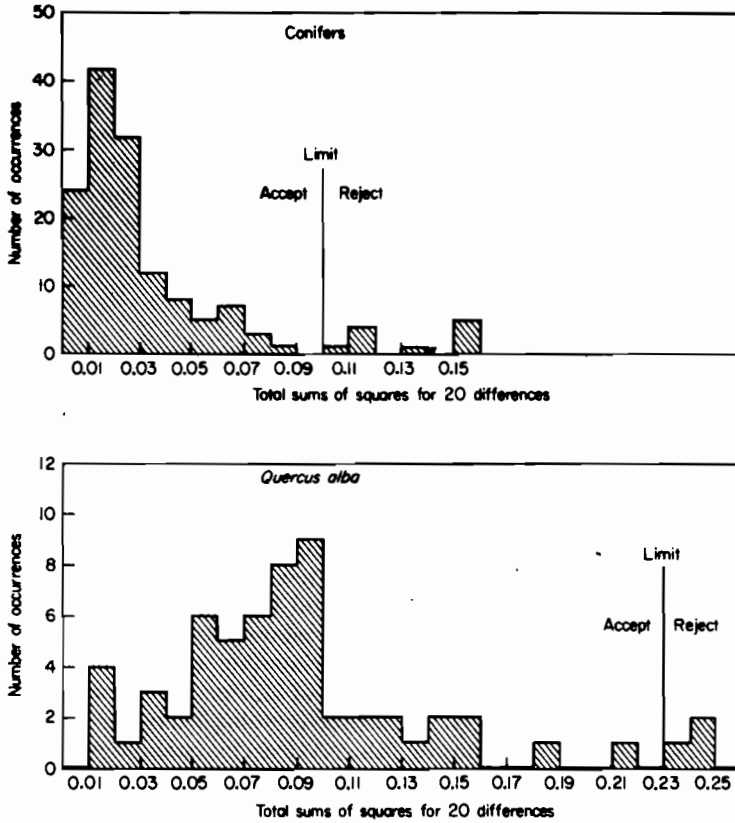
FIG. 6.1. A test of measurement accuracy can be made by comparing measurements of particular operators to those of experts. The above graphs are the frequency distribution for sums of squares of differences between replicate measurements of 20 successive ring widths obtained by experts on (1) arid-site conifers and (2) temperate forest *Quercus alba*. Each set of 20 measurements (expressed in millimeters) was made by different experts, and the differences between the first and second measurement for a given set of rings were computed, squared, the 20 squares summed, and the result tabulated in one of the frequency classes. Using the results from the figure, if the sum of 20 squared differences for a particular remeasurement from the first measurement is equal to or less than the limit, the measurements are judged to exhibit acceptable error, but if it is greater than the limit, the measurements are judged to be unacceptable and are sent back for reassessment and further checking.

the differences exceeds 0·10 mm the sample is remeasured (Phipps, personal communication).

The ring widths are also checked after they are key punched for analysis. This function is accomplished by running a computer program, *RWLST*, which checks for certain types of errors, calculates 20-year means, plots them, and lists all data. The errors in the computer listing are easily spotted and the plots scanned before choosing the curve-fitting option that is to be used in subsequent analysis (see Section III of this chapter and Table 1.II for time estimates).

F. Testing for Inhomogeneity of Climatic Data

Climatic data should also be carefully examined for missing information and for inhomogeneities. Records with large numbers of missing data, anomalous changes attributable to instrument relocations, or trends caused by nonclimatic changes such as urban growth, must not be used in dendroclimatic analysis unless they are corrected.

When less than 5% of the climatic record is missing, the missing values can often be estimated from those of a neighboring station, if they are available. Not only should the climatic record from the neighboring station be complete, but its location should be as similar in elevation, exposure, and topography as possible. A method for estimating precipitation data at one station from that at another utilizes the ratio of mean monthly precipitation for an interval of time that is common to both records (McDonald, 1957). The ratio is multiplied by the data that are present to estimate the missing value. At least two stations within 100 miles (161 km) of a station with missing data should be used, and these data should be averaged to obtain the best estimate.

Missing temperature data are usually estimated by a simple linear regression as described in standard textbooks on statistics. The monthly data common to neighboring stations are used for calibration, and the appropriate data are substituted into the equation to obtain a statistical estimate for the missing values. Separate equations are developed for each pair of stations and for each month to be estimated.

All climatic records should be examined and tested for inhomogeneities, because if anomalous trends or abrupt changes attributable to instrument relocations or other nonclimatic factors are present, they are likely to introduce significant error in the calibration relationships. Station histories which are published along with the climatic record may be checked for changes in either the instrumentation or geographical location of the station. Kohler (1949) describes one method for testing homogeneity of precipitation records (Fig. 6.2).
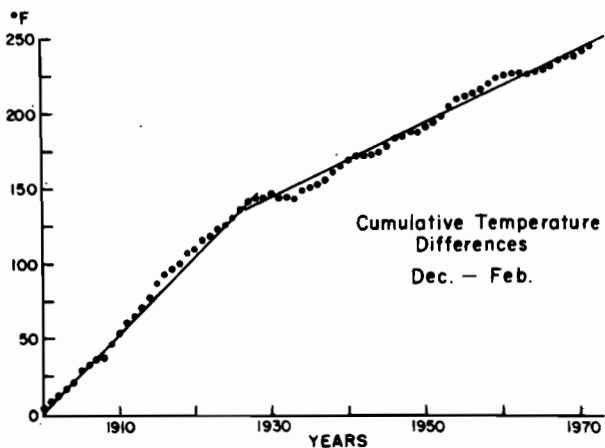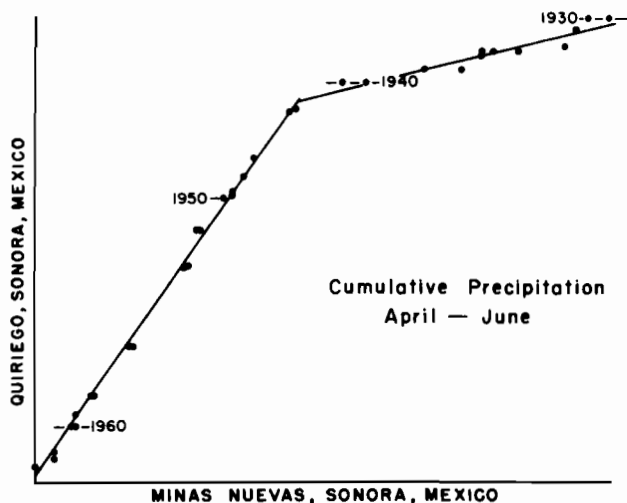
FIG. 6.2. Tests for homogeneity of precipitation and temperature at two stations in Mexico. Analysis of precipitation utilizes cumulative totals for April through June. The totals for one station are plotted as a function of the totals for the other station starting with the most recent record; the axes were scaled (not shown in figure) to facilitate comparisons. Analysis of temperature utilizes the cumulative differences between mean December through February temperatures for each year which are plotted as a function of the year. Inhomogeneity is indicated in both types of analyses by abrupt changes in slope. Straight lines are drawn by eye to accentuate the inhomogeneity, See text for explanation. (Data courtesy of Arthur Douglas)

Monthly precipitation data from each of several neighboring stations are summed to obtain totals for each season, and these data are compared. This procedure is facilitated by summing the seasonal data (monthly data are often too variable), starting with the most recent year, to obtain cumulative totals, which are plotted as a function of the equivalent totals for another station (Fig. 6.2). If the plotted totals fall along a straight diagonal line, the data for the two stations are judged to be relatively homogeneous. If there is a change in the slope, only one of the records is homogeneous. If both stations have been moved or affected by changes at different times, several variations in slope appear in the plot.

It may be necessary to compare several records to identify which one exhibits a particular inhomogeneity. One record already found to be homogeneous can be used to check a variety of neighboring stations. This technique, sometimes referred to as *double-mass analysis,* also provides a means of adjusting the data (Kohler, 1949). The precipitation associated with the shorter segment or the earlier record is multiplied by the ratio of the two slopes. Kohler (1949) provides a more complete explanation of this procedure.

The test for homogeneity of a temperature record requires somewhat more elaborate computations (Mitchell *et al.,* 1966). Sometimes, however, inhomogeneities can be identified from a simple plot of the temperature data averaged for a particular season or from the *first differences* of the averages (the value of each datum subtracted from its successor). The data are plotted as a function of year and the plots compared to those of other stations to identify errors as spikes or anomalous values in a particular record.

A shortcut method developed by LaMarche involves subtracting the seasonally averaged value for temperature in one record from the value for the same season in another record. These differences are then summed over time to obtain a cumulative difference (Fig. 6.2). As in the analysis of precipitation, a discontinuity in one of the records is accompanied by a change in slope of the cumulative temperature differences, and the ratio of the two slopes on each side of the change can be used to correct the faulty record. See Mitchell *et al.* (1966) and Panofsky and Brier (1968) for a detailed discussion concerning analysis and correction of climatic data.

II. General Statistics

Ring widths which are limited in large part by variations in the operational environment vary from one year to the next in a more or less irregular or quasi-random manner. It is customary to express these

variations as a series of values ordered chronologically according to year of formation, the resulting sequence being referred to as a *time series*. As has been discussed in earlier chapters, the size of growth rings in trees is the result of a number of causal factors acting within the tree and within the tree's environment. The manner in which these causal factors act to form a time series is referred to as the *generating process*. The primary objective in the remaining portions of this chapter is to describe a variety of techniques for characterizing, analysing, and handling such time series data. Many of the techniques could be applied to climatic time series as well as tree rings.

The general characteristic of a ring-width time series can be described by a number of standard statistical parameters. The simplest of these is the mean m_x, which is defined as

$$m_x = \frac{1}{n} \sum_{t=1}^{t=n} x_t \tag{6.1}$$

where Σ is the symbol for summations of the elements following it, x_t is the ordered ring-width sequence such that time (indicated by subscript t) varies sequentially from 1 (the calendar year of the earliest dated ring) to n (the last calendar year). The symbols above and below the summation sign indicate these two limits. The *mean* is the point that is closest to all values for the data set analogous to the center of gravity.

A second statistic typically generated from a ring-width time series is the *variance* (s_x^2), which is a measure of the scatter of values about the mean and is calculated as

$$s_x^2 = \frac{1}{n-1} \sum_{t=1}^{t=n} (x_t - m_x)^2 \tag{6.2}$$

where the symbols are the same as in Equation 6.1. This variance is often converted to a different statistic, the *standard deviation* (s_x), which is simply the square root of the variance. The variance is used for certain statistical tests, while the standard deviation is easier to visualize as a measure of scatter of the data values from their mean expressed in the units of the original measurements. If the data in the time series are *normally distributed*, that is if their distribution closely approaches that of a statistically normal curve, two-thirds of the data are expected to lie within a distance of one standard deviation on each side of the mean. For large samples, approximately 95% of the data lie within a distance of two standard deviations on each side of the mean.

While these two statistics represent specific measurements obtained from a given set of values, they will be somewhat different if another data set is taken from the same population. Therefore each statistic should be

regarded as an *estimate* of the true value which can only be computed from the entire population, or *statistical universe*. The following discussion will regard all statistical measurements as statistical *estimates*. It is possible to use the variance of the available data to obtain an estimate of how a particular statistic, such as the mean, varies from the mean of the entire population. This particular estimate is referred to as the *standard error* of the mean (SE_m) and can be calculated as

$$SE_m = \sqrt{\frac{s_x^2}{n}} \qquad (6.3)$$

where n and s_x^2 are the same as in Equation 6.2.

For large samples, the mean of the entire population, the *true value* in terms of the statistical universe, will lie within a distance of two standard errors from the sample mean in 21 out of 22 cases and within three standard errors of the mean in 369 out of 370 cases (Ezekiel and Fox, 1959). The possibility for error is greater for means of samples with less than 30 items because characteristics of different samples fluctuate by ·chance from those of the statistical universe, and the estimate of the standard error itself will vary from one sample to the next. The amount of this increased error or bias is a function of the sample size (Ezekiel and Fox, 1959) so that the bias or expected variation for a standard error based upon a sample of three trees is 50%; a sample of four trees is 41%; a sample of five is 35%; a sample of 10 trees is 24%; and a sample of 20 trees is 16%. Thus, in cases of a mean of four observations, the estimate of the standard error obtained from Equation 6.3 is itself in error, and its value should be adjusted upward by 41%. If the mean is based upon 10 observations, the value should be increased from the calculated estimate of the standard error by 24%. For explanation of this correction see Ezekiel and Fox (1959).

As a result of the above error, very small samples are subject to sizeable random variations; and increasing sample sizes from 5 to 10 trees, for example, can lead to considerable reduction in the expected random variation with improvement in the reliability of all its statistics. If samples are not available in sufficient numbers for a particular site, it may be necessary to avoid using the data or to combine them with those from a similar geographically related sample.

Because of the large error in small samples, data to be entered into the International Tree-Ring Data Bank mentioned earlier must be replicated with a minimum of 10 different trees, although additional replication including two samples per tree is recommended. Later in this chapter it will be shown that reliability of a ring-width chronology is not only dependent upon the number of items included in the collection but

also upon the amount of heterogeneity or homogeneity of the materials from which the data were sampled.

The *correlation coefficient* is another statistic which measures inter-dependence of association between two data sets, x_t and y_t, where t again represents the time dimension. As such, the correlation coefficient is used in dendroclimatology to measure associations between two time series, such as chronologies from different trees or sites, or a chronology and a climatic sequence. The correlation coefficient (r_{xy}) is defined as

$$r_{xy} = \frac{\sum_{t=1}^{t=n} (x_t - m_x)(y_t - m_y)}{(n-1)s_x s_y} \tag{6.4}$$

where m_x, m_y, s_x, s_y are the means and the standard deviations of the two sets of data; and n is the number of items compared, namely, the sample size. The correlation coefficient between the two data sets being compared can range from an upper value of $+1$, which indicates perfect and direct agreement, to a value of -1, which indicates perfect and inverse agreement. If the two data sets are completely independent or random with respect to one another, the correlation coefficient takes a zero value.

The correlation coefficient is used in dendroclimatology not only to measure association between two different time series, but also to measure associations between items lagged in time. For example, the ring width for a particular year (t) can be correlated with the ring widths in the previous or following year $(t-1$ or $t+1)$ or correlated with rings widths at lags greater than 1. Figs 1.10 and 1.11 diagram such relationships and Chapters 2 and 5 have described some of the biological causes of such time-related interdependence. To obtain the measurement the correlation coefficient $(r_{xy}$ Equation 6.4) is calculated for terms x_t and x_{t+L}, where, in the case of tree rings, L is the lag in years of the second ring behind the first and n is reduced in number by the length of the lag, L. The resulting statistic is referred to as the *autocorrelation* (or *serial correlation*) *coefficient*. When $L = 1$ year, it is the first-order autocorrelation coefficient; while a lag of 2 gives the second-order autocorrelation coefficient; and a lag of m is the mth-order autocorrelation coefficient. Of course if the items in a series are completely random with respect to their positions within the time series, the values of the computed autocorrelation coefficients at all lags will be small and will vary in a random fashion about a mean value of zero. However, many time series dealt with in dendroclimatology, especially those derived from ring widths, are autocorrelated to a significant extent.

Another statistic designed especially for tree-ring analysis measures the relative difference in width from one ring to the next and is referred to as

mean sensitivity (ms_x). Douglass (1936) describes this statistic as the "mean percentage change from each measured yearly ring value to the next." The average mean sensitivity for a series is calculated as

$$ms_x = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t} \right| \qquad (6.5)$$

where x_t is each datum and the vertical lines designate the absolute value (neglecting the sign) of the term enclosed by them. The denominator of the term scales the absolute values of the differences between adjacent ring widths, x_t and x_{t+1}, so that the differences are proportional to the average of the two widths. The values of mean sensitivity range from 0 where there is no difference to 2 where a zero value occurs next to a nonzero one in the time sequence.

In general, each series of ring-width measurements can be regarded as a time series made up, at least in part, of randomly varying components. Usually, the sizes of successive growth rings are statistically dependent on one another due to persistence, trends, cycles, or other nonrandom components produced by climate and the generating process of tree growth. The dendroclimatologist, therefore, is concerned with identifying as clearly and unambiguously as possible the precise nature and extent of both the randomness and nonrandomness in each ring-width time series, not only for accurate reconstruction of past climate, but also to provide information on the nature of the tree growth-generating process itself. Also, certain undesirable characteristics must be properly assessed and analyzed in an appropriate manner designed to meet important statistical assumptions.

For example, when successive values of a time series such as ring widths are found to be statistically interdependent, the *effective size* of the sample (the number of elements which are truly independent) is reduced. Therefore, special precautions are necessary when using familiar textbook methods for evaluating the characteristics and statistical significance of time series interrelationships (see Chapter 7 and Mitchell *et al.*, 1966).

One type of nonrandomness is *autoregression*. The term *regression* is used in cases where one value is affected by the condition of another value, and the prefix, *auto*, is used when the relationship involves values ordered in a single time series. *Correlation* refers to association of two variables without implying the direction of the dependence. However, autocorrelation coefficients calculated for a number of different lags can be used to estimate the nature of autoregressive linkage. The simplest type of dependence is first-order autoregression, representing a linkage of each value in a time series with only the condition of the item immediately preceding

it. In such cases the *first-order autocorrelation* (L = 1) is all that is needed to estimate the degree of the relationship, and the autocorrelations for higher lags (L > 1) will decrease in the following fashion:

$$r_L = r_1{}^L \tag{6.6}$$

where r_L is the correlation between the items at the specified lag L, r_1 is the first-order autocorrelation, and the superscript L is the power to which the value for r_1 must be raised in the calculation. Thus if r_1 has a value of 0.5, the correlation at a lag of 2 is $(0.5)^2$ or 0.25, and the correlation at a lag of 3 is $(0.5)^3$ or 0.125. The theoretical values for higher-order autocorrelations remain positive although they approach zero.

Growth cycles, long-term variations in ring width lasting for several years or decades, or trends in the data all affect autocorrelation which may be either positive or negative depending upon the lag and the nature of the relationship. In the case of cycles, the autocorrelation coefficients will be positive from a lag of 1 up to a lag that is approximately one-fourth of the cycle wavelength. The coefficients are negative for higher-order lags, with the largest negative value occurring at a lag equivalent to half the wavelength of the cycle. In the case of trends or very long-term persistence, the higher-order autocorrelation coefficients remain positive and higher at greater lags than in cases where only first-order autoregression is present (Equation 6.6). It is most common to encounter a mixture of several types of nonrandomness in time series of ring widths.

Autocorrelation coefficients calculated for a number of lags may be plotted to help identify the nature of the nonrandomness in a time series. However, as the lags become larger the reliability of the autocorrelation estimate decreases because the number of observations common to the lagged and unlagged set becomes smaller. This does not create serious difficulty in analyses if the number of lags does not exceed 20% of the number of observations (Jenkins and Watts, 1968). Thus, for a time series of 100 items, only the autocorrelations for lags 1 through 20 should be considered.

It is useful to deal with these types of nonrandomness as if they could be represented by cycles with varying wavelengths. For purposes of discussion this text will consider all nonrandom variations in ring width that last longer than eight years (represented by cycles with wavelengths greater than eight years) as *low-frequency variance*. Such long-term variations in ring widths can arise from changes in tree structure or the environment, including relatively long-term variations in climate. When wavelengths are greater than the length of the entire ring-width series, the variance is referred to as a *trend*. Trend results from such things as the changing growth potential of the tree resulting from increasing age,

successional alterations in the forest community, geological changes, or very gradual variations in climate. Changes which are of shorter durations, representing cycles with wavelengths of eight years or less, will be considered as *high-frequency variance*. Included in this category would be year-to-year ring-width variations, fruiting cycles in trees, and short-term variations·in climate.

In addition to the presence of autocorrelation, cycles, or trends, the variance of ring-width series is usually nonhomogeneous through time in that it decreases with increasing age of the tree (Fig. 6.3). Also, the mean ring width, ᵗhe standard deviation, and the autocorrelation structure can vary markedly depending upon site conditions as well as tree age. When
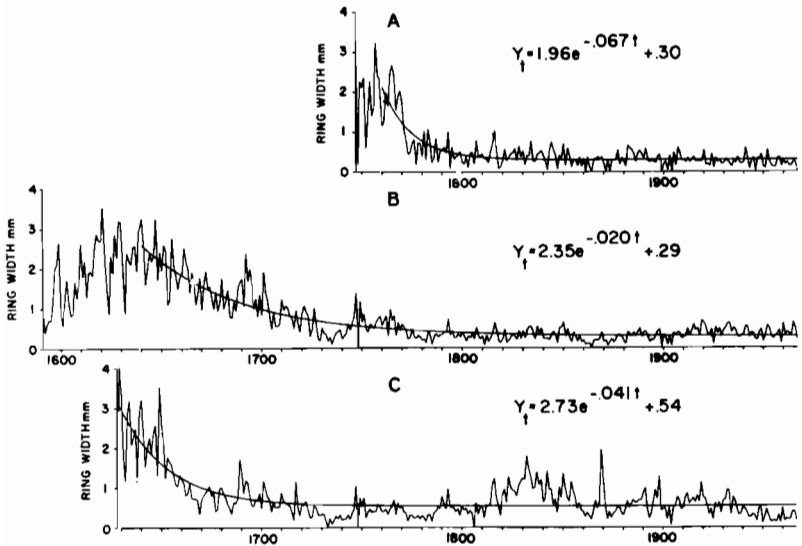
FIG. 6.3. Time series of ring widths from three Douglas-fir *(Pseudotsuga menziesii)* growing in New Mexico, plotted as a function of the dated year along with the exponential curve that was fitted to each data set and the equation that describes it. (See Equation 6.7 and text for explanation.)

such variations prevail, the data must be transformed by a particular procedure referred to as *standardization*, to form a new time series with trend removed and a mean and variance that are more homogeneous with respect to time (Matalas, 1962). Details of the standardizing procedure and its effects on statistics are described in the next section.

III. Standardization

Three unstandardized series of ring widths are plotted as a function of time in Fig. 6.3, and some of the statistics derived from them are shown in Table 6.II. Each series shows a general decline in ring width and in variance, both of which are associated with increasing tree age (for a biological explanation of this trend see Chapters 1 and 2). The A series in Fig. 6.3 has a mean of 0·53, a standard deviation of 0·42, a first-order autocorrelation of 0·75, and a mean sensitivity of 0·64 (Table 6.II). The large value of mean sensitivity indicates the presence of considerable high-frequency variance. A trend of declining growth with increasing age for the first 70 years in the life of the tree is apparent from the figure. The plot for series B shows a more gradual trend than that for A; the lower mean sensitivity indicates less high-frequency variance; and the presence of more low-frequency variance as evidenced by the high autocorrelation and the excursions in ring widths from the fitted curve that last for 10 or more years (see 1730's, and 1857–66 for negative excursions, and 1687–96, 1760's, and 1913–1922 for positive excursions). Series C exhibits less high-frequency variance as indicated by lower values of mean sensitivity,· trend is also apparent, and there is more low-frequency variance than in the other two, represented by several long excursions from the fitted curve persisting more than 20 years.

An examination of other statistics included in Table 6.II shows that the mean ring width is highest for series B and lowest for series A, and the standard deviation for ring widths is markedly lower in A than in B and C. As would be expected from the presence of trends, first-order autocorrelations are high in all three series of ring widths.

TABLE 6.II Statistics of three ring-width series and their indices[a]

Statistic	Series		
	A	B	C
Mean ring width - mm	0·53	0·80	0·73
Mean index	1·00	1·00	1·00
Standard deviation of ring widths – mm	0·42	0·60	0·60
Standard deviation of indices	0·54	0·45	0·55
1st order autocorrelation of ring widths	0·75	0·81	0·78
1st order autocorrelation of indices	0·10	0·31	0·60
Mean sensitivity of ring widths	0·64	0·43	0·39
Mean sensitivity of indices	0·64	0·44	0·39

[a]See Figures 6.3 and 6.7.
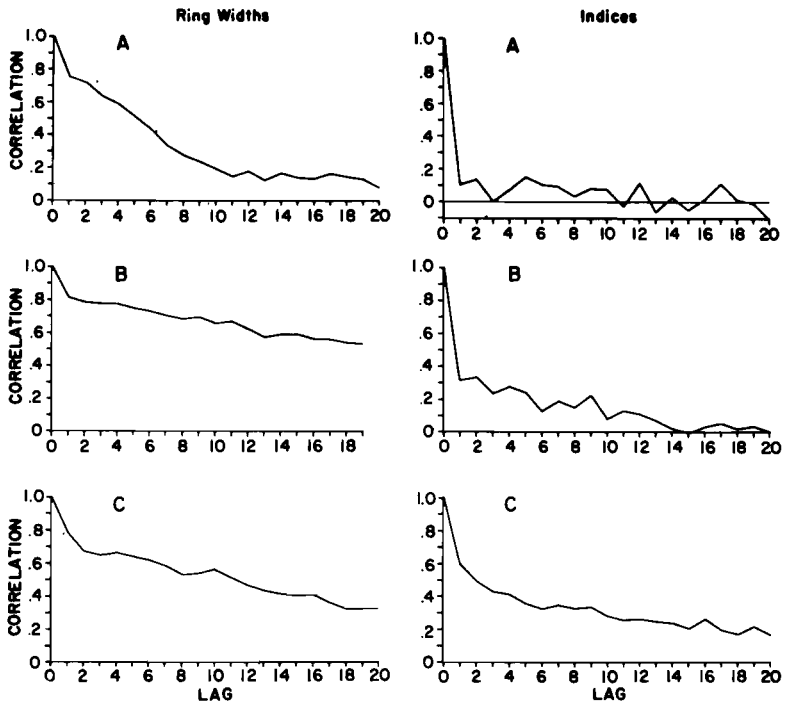
FIG. 6.4. Autocorrelations for lags from 0 to 20 years for each ring-width series shown in Fig. 6.3 and for each derived index series shown in Fig. 6.7.

Figure 6.4 (left) shows plots of autocorrelation coefficients for the three ring-width series in Fig. 6.3 for lags 0 to 20 years. At lag 0 each series is correlated with itself, so the value of the coefficient is a perfect 1·0. The values at lags greater than 0 decline from left to right with increasing length of the lag. For series A the plotted values most resemble the expected decline for a first-order autoregressive process (Equation 6.6), indicating the least amount of long-term or very low-frequency variance. The values of the autocorrelation coefficients in B decline in a more or less linear fashion after a lag of 1, although these values are somewhat larger than in A and C due to the greater length of the trend in the B series (Fig. 6.4).

Repeated experience has shown that the plots in Fig. 6.3 are typical of ring-width data derived from many coniferous species growing on drought-subjected sites. Such curves are generally satisfactorily

estimated by fitting a curve to the data with the following *exponential* form:

$$y_t = ae^{-bt} + k \qquad (6.7)$$

where the values of a, b, and k vary from series to series depending upon the slope of the curve required to fit the data, e is the base of natural logarithms and y_t is the expected growth at a given year t. The values of t as in previous equations vary from 1 to n. The curves shown in **Fig. 6.3** represent the best statistical estimate of this exponential form to the particular ring-width sequence. The values for the equation used to generate the curves are shown above each plot.

Often there is an increase in ring width for the first 10 to 30 years in the life of a tree and these portions cannot be adequately fitted by the exponential curve (see the early portions of A and B', Fig. 6.3 where no curve is drawn). These data may either be disregarded, fitted with an upward-trending straight line, or the entire curve fitted with a polynomial equation or other function capable of expressing an increase in width of the first-formed rings. Since these early rings often provide the least reliable climatic information anyway, they can be discarded without any substantial loss of information.

A variety of biological growth functions has been used for the curve-fitting process, such as parabolas, hyperbolas, logarithmic functions, polynomials, and moving averages. The use of some functions is defended on theoretical grounds, while the use of others, such as polynomials and moving averages, is justified because they can be applied to a wide variety of situations. However, the exponential function has been found to be adequate for many North American conifers because it approximates the various parabolic, hyperbolic, and logarithmic forms, and resembles the declining rate in the conifer biological growth function.

As a result of the many dendroclimatological studies now being attempted on deciduous species, in dense forests, and in other new regions, there are more complications which cannot be handled by fitting an exponential function. These complications result from a variety of changes that can occur throughout the life of a tree within a forest due to stand disturbance and the changing forest environment. The more versatile orthogonal polynomial curve, using coefficients at higher and higher powers (Figs 6.5 and 6.6), is now applied in such cases, although care must be taken not to use it where interesting climatic information might be approximated and removed by the polynomial function. There are many situations, as illustrated in Fig. 6.6, where the complex curves described by a polynomial equation with many coefficients are the only

means of obtaining an adequate growth function. In such cases there is a
risk that some climatic variation will be removed by the more flexible
curve-fitting option. Because of this possibility a test is made as
coefficients are added, and the procedure is terminated before the curve
becomes too flexible when 5% or less of the variance is reduced by the
addition of a coefficient.

An alternative to calculating a complicated statistical equation is the
construction of a growth curve by hand using a graphical approximation,
as was done by early dendroclimatologists. This method involves
computing 10- or 20-year means at 10-year intervals, drawing a curve or
straight line through the points, reading the curve value for every year,
and adjusting the curve upward or downward so that its mean matches
the mean of the ring widths to which the curve was fitted (Stokes and
Smiley, 1968). When the graphical procedure is used, no values for the
constants a, b, and k are available.

A computer program for ring-width series standardization developed
by Fritts *et al.*, (1969) attempts first to fit the exponential form of
Equation 6.7 to each ring-width series with the following restrictions: If
the value of b in the equation is found to be positive rather than negative
(that is if the slope of the exponential curve is upward and thus opposite
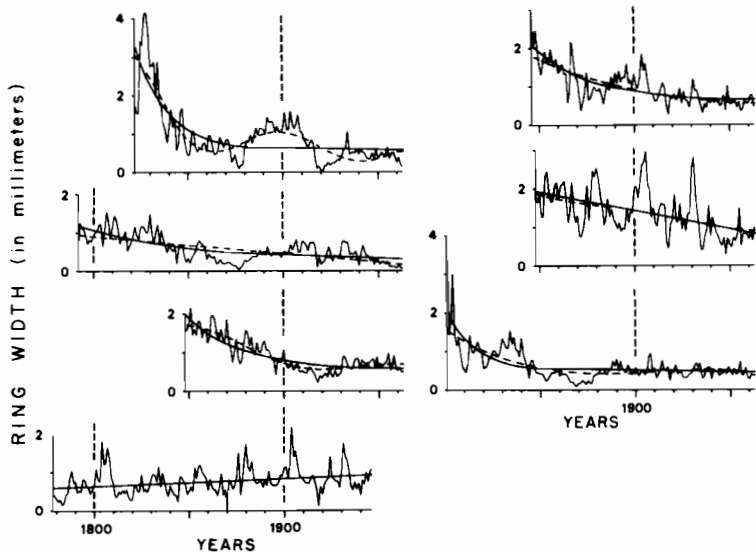
FIG. 6.5. Seven ring-width series which were fitted by an exponential or linear curve
(solid line) and by a polynomial curve (dashed line).

the slope expected for normal trees) or if a and k are negative, the computer rejects that particular exponential equation as it is inappropriate to the negative exponential growth model (see Fig. 6.3). In its place a straight line is fitted to the ring widths as a function of time depending upon specifications provided by the investigator. In certain situations there is justification for using only a straight line with a negative or zero slope. In such cases if the slope is positive, the least-squares fitted line or curve is rejected and a horizontal line is fitted through the mean ring width as the expected growth at all ages. Since the program is designed to be flexible, it requires that the investigator choose the specific kinds of curves to be fit to the data, and that he specify whenever the growth model changes between one ring-width series and the next.
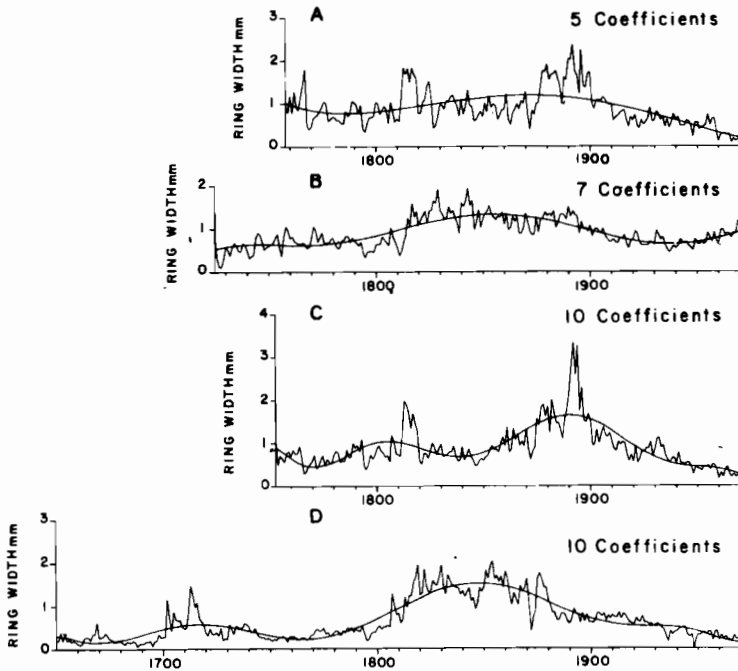
FIG. 6.6. Four ring-width series which required the fitting of high-order polynomials to remove the long-term nonclimatic variations in growth. Since the trees were from the same general area, it is likely that the differences among the polynomial curves reflect local conditions surrounding the trees and sites and not variations in the macroclimate. The greater the numbers of coefficients for each polynomial equation, the greater the degree of complexity in the shape of the curve.

Some trends and a large portion of the low-frequency variance in growth cannot be approximated by the exponential equation, by a straight line of negative slope, or by a polynomial equation. These changes are purposely left in the ring-width series if they are not excessive, because they can provide potential information on long-term climatic variations. In some European studies a 22-year *moving average* (Bitvinskas, 1974) is used for the curve function, but the procedure removes all growth variations including those due to climate that occur on time scales equal to or greater than a 22-year duration. Since information about this time scale is important to climatic analysis, the use of a 22-year moving average is not advisable for use in most dendroclimatic analyses.

After an appropriate curve has been ascertained for the growth changes that are associated with increasing tree age, the equation is solved for the expected yearly growth (Y_t). The measured ring widths (W_t) are then converted to ring-width indices (I_t) by dividing each width for year t by the expected growth (Y_t), as follows:

$$I_t = \frac{W_t}{Y_t} \tag{6.8}$$

Division by the expected growth both removes the trend in growth and scales the variance so that it is approximately the same throughout the entire length of the time series. The result of the division by (Y_t) for the data points graphed in Fig. 6.3 are plotted in Fig. 6.7. The latter represents a new time series referred to as *ring-width indices* or the *standardized ring-width chronology*. The indices from each of these ring-width time series (Table 6.II) exhibit increased similarity in their statistical properties. The means of the tree samples all approximate a value of 1, the differences in the standard deviations are less than those for ring widths, and most of the autocorrelation due to trend is eliminated. However, mean sensitivity estimates are the same as those for the ring-width data sets.

The standardized ring-width indices are then averaged to obtain a mean chronology as shown at the bottom of Fig. 6.7. Standardization, in Douglass' words (1936), equalizes or brings all ring-width curves to a uniform mean value (a value of 1, see Table 6.II) so that one tree record with a large average growth will not dominate other records of small average growth when the two series are combined into a mean chronology.

The scaling of all series to mean values of 1 is an important feature of standardization, for the slow-growing trees that are under climatic stress often provide more information on climatic variation than the fast-growing ones. Thus, if the ring widths rather than indices were averaged

before standardization, the variance of the series would be dominated by the fast-growing individuals whose ring widths fluctuate the most but are least limited by climate. Standardization before averaging converts all series to the same relative variance so that each is given the same weight when the series are averaged. In addition the variances, standard deviations, and autocorrelations of indices are calculated so that the basic characteristics of each growth response are automatically computed in the standardization process.

If climate changes slowly over a long period of time, it may be impossible to distinguish long-term effects of climatic change from the effects of increasing age. Depending upon the curve-fitting option, standardization will inadvertently remove some of these long-term growth changes due to low-frequency variations in climate. Because the
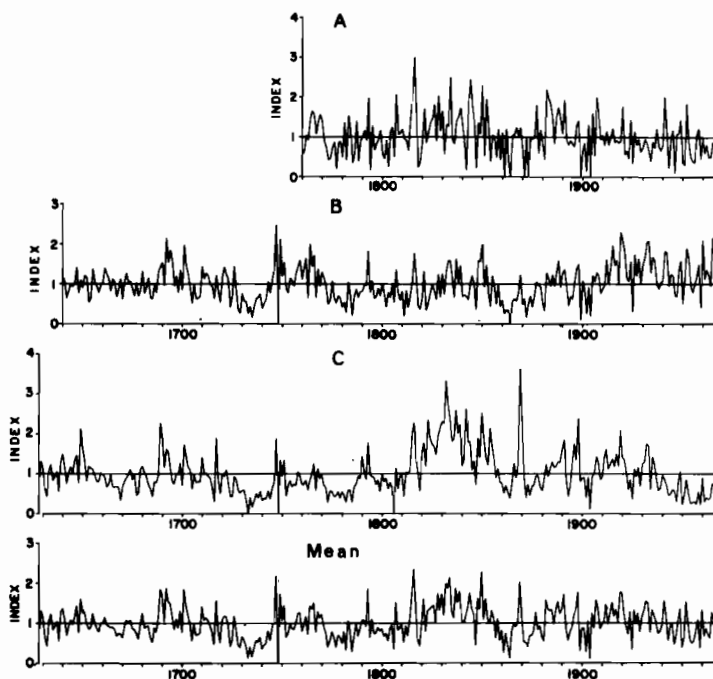
FIG. 6.7. Standardized indices calculated from ring widths by fitting a growth curve (Fig. 6.3) and dividing each ring width by the value of the growth curve. The indices from each year in series A, B, and C are averaged to obtain a mean chronology shown at the bottom of the figure.

polynomial curve-fitting option is more flexible, it is more likely than the exponential option to fit and remove some effects of long-term climatic changes. There are certain cases where an investigator may decide that there is important low frequency climatic information in the ring record (LaMarche, 1974a) and that it is better to live with· the undesirable characteristics of ring widths than to risk removing or altering the information on climate by indiscriminately fitting an exponential or polynomial function.

The plots of autocorrelation coefficients derived from the indices may be compared to those for the ring-width time series (Fig. 6.4). The greatest differences between the autocorrelations of ring widths versus those of indices are most evident for series A and B (Table 6.II), in which most of the low-frequency variance was trend and was removed in the standardizing process. Since the autocorrelation coefficient at a lag of 1 for the indices of series A is near 0 and no clear systematic variations at higher order lags occur, it can be inferred that the information remaining in the indices of series A has more high-frequency than low-frequency variance. The first- and second-order autocorrelation coefficients for indices of series B (Fig. 6.3) are larger than those of A and are significant. This confirms the presence of more low-frequency variance. The high autocorrelations for series C up to lags of 20 years indicate that a significant amount of low-frequency variance remains in series C, although there is less than in the ring-width sequence (see Fig. 6.7 and Table 6.II).

Generally, there is an inverse relationship between mean sensitivity and autocorrelation in tree-ring chronologies, because the former measures the proportion of high-frequency variance, while the latter measures the proportion of low-frequency variance. The standard deviation, however, is a measure of variations in both frequency domains. As will be shown later, these three statistical measurements are useful in the selection of chronologies for dendroclimatic analysis.

IV. Filtering Techniques

Another method for studying variance at particular frequencies involves filtering out the undesirable variance by means of digital filters or moving averages, sometimes called *running means*. Moving averages are simply ring-width averages for a given number of successive rings, the sequence being moved ahead by one year each time the average is computed. In a three-year moving average the first is a mean of x_1, x_2, and x_3, the second x_2, x_3, and x_4, and the third x_3, x_4, and x_5, and so on. Each average is assigned to the year of the central ring in the sequence. Three-year and

five-year moving averages were used in early dendrochronological studies (Douglass, 1936; de Martin, 1970) to smooth the year-to-year variability in proportion to changes occurring over periods greater than three years duration.

The common three-year moving average as described above places equal weight on all values being averaged, and this can produce peaks and troughs for the generated series in locations other than those which originally existed. However, the numbers to be averaged can be weighted, giving the central value twice the weight of the value on each end, in which case the peaks and troughs are the same as in the original series. In early studies a commonly used moving average weighted the central value by one-half and the end values by one-fourth. A variety of weighted moving averages have been applied, some including terms for 21 or more years.

The number and value of weights may vary, depending upon which frequencies of variation are to be retained and which are to be eliminated. The actual weights used to obtain particular types of moving averages are referred to as *filters*, which are analogous to color filters that change the optical spectrum of light passing through them. An unfiltered time series with equal variance at all frequencies is analogous to white light. The three-year weighted moving average described above blocks out the rapidly changing growth variations (high frequencies, analogous to blue light) and passes the slowly changing variations (low frequencies, analogous to red light). When the resulting averages retain only the long-term or low-frequency variations as in the case of the three-year weighted moving average, the weights are referred to as a *low-pass filter*.

Specially designed filters have been created for dendrochronological purposes which emphasize variance at certain prescribed frequencies. For example, 11-year and 22-year weighted means have been used to emphasize the 11-year and 22-year sunspot cycles. *First differences*, mentioned earlier in the chapter and calculated by subtracting the value of each item in a series from its immediate successor, is a type of *high-pass filter*. Mean sensitivity also acts as a high-pass filter, since it measures the absolute value of high-frequency variations observable in the differences between adjacent widths or indices. Mitchell *et al.*, (1966) present a brief discussion concerning the use and design of filters for climatological analysis.

Table 6.III includes the weightings for two specially designed filters of particular value to tree-ring analysis. They are *reciprocal filters*, which is to say that each of the two filters is designed to pass variance at opposite extremes of the frequency spectrum. The high-pass filter transmits or passes high frequencies (those with short wavelengths) and blocks most of

TABLE 6.III Weights of two reciprocal digital filters

Weight number[a]	Weight value	
	High-pass filter[b]	Low-pass filter[c]
+6	−0·0003	0·0003
+5	−0·0030	0·0030
+4	−0·0161	0·0161
+3	−0·0537	0·0537
+2	−0·1208	0·1208
+1	−0·1933	0·1933
0[d]	0·7744	0·2256
−1	−0·1933	0·1933
−2	−0·1208	0·1208
−3	−0·0537	0·0537
−4	−0·0161	0·0161
−5	−0·0030	0·0030
−6	−0·0003	0·0003

[a]Weight number expressed as position relative to central values of the data to be summed. [b]Passes variance with approximate wavelengths < 8 years. [c]Passes variance with approximate wavelengths > 8 years. [d]Central weight.

the variance with wavelengths greater than eight years, while the low-pass filter transmits or passes low frequencies (those with long wavelengths) and blocks the variance with wavelengths less than eight years. Since they are reciprocal, the filters can be applied to the same ring-width or ring-index series to separate the variance into its high- and low-frequency components. Neither filter is perfect and there is a certain amount of ambiguity in handling the variances at wavelengths near eight years. Consequently, a small portion of the variance is not passed by either one. A variety of filters can be developed to pass variations at a variety of different wavelengths (Craddock, 1957).

The weights of a filter, as in the case of a moving average, are multiplied by the appropriate ring-width values and the products summed as in the following equation (Mitchell, et al., (1966).

$$\overline{X}_t = \sum_{i=-n}^{i=+n} w_i x_{t+i} \qquad (6.9)$$

where $\overline{X}_t$ is the filtered value of the series corresponding to the tth term and w_i is the weight by which the value of the series i units removed from t is multiplied (Mitchell et al., 1966).

Using the three-year moving average mentioned above, $n = 1$ and i varies from -1 to $+1$. Both values on each side of the central value are multiplied by 0·25, the central value by 0·50, and the three products are

summed. Using the weights in Table 6.III, n is 6, and weight numbers -6 to -1 and $+1$ to $+6$ are multiplied by the corresponding six items on either side of the central value and summed with the product of the central weight and the central value. The next filtered value is obtained by shifting the matching of weights and data one year ahead and repeating the operation. Note that the sum of all 13 filter weights for the low-pass filter has a value of 1. This feature preserves the mean and variance of a time series which has been operated upon so that the low-pass filtered data always have the same mean and same low-frequency variance as the original data. The sum of the weights in the high-pass filter equals 0 so that the high-pass filtered data have a zero mean. As in the low-pass filter, the values of the weights are chosen so that there is the same high-frequency variance in the filtered set as in the high-frequency component of the original data.
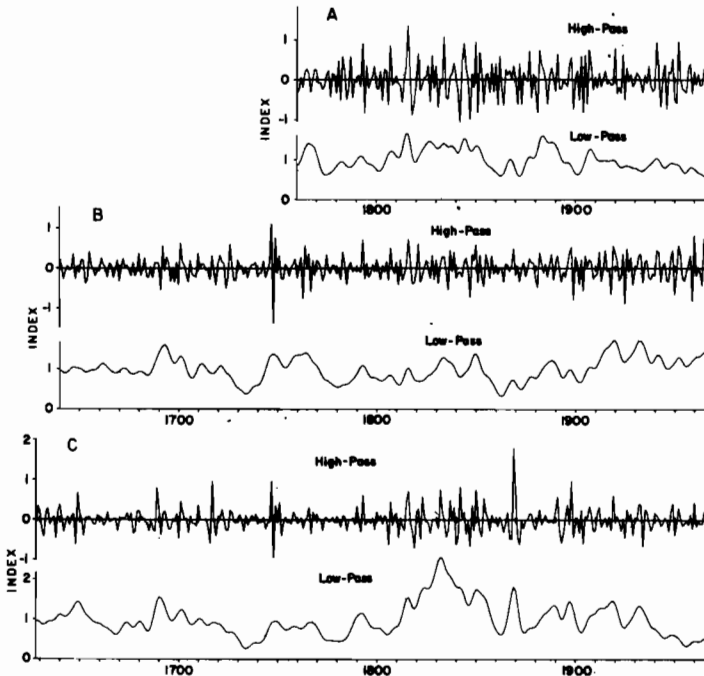
FIG. 6.8. Data from the three index series shown in Fig. 6.7 after they have been treated with the high-pass and low-pass filter weights included in Table 6.III.

Figure 6.8 includes plots of the filtered data from indices for A, B, and C (Fig. 6.7) which were passed by the two filters (Table 6.III). Table 6.IV includes the variances of the original indices and the two filtered sets, along with the percentages of variance passed in each case. Also shown are the correlation coefficients for comparisons (1) among the three index chronologies, (2) among the three high-pass data sets, and (3) among the three low-pass data sets. The data in Table 6.IV confirm the inferences derived from the measurements of mean sensitivity and autocorrelation, in that series A has more high-pass variance (66%) than low-pass variance (23%). The filtered series from C exhibit the greatest low-pass information or variance (59%) and the least high-pass information (31%). The filtered series from B have nearly equal amounts of information at high and low frequencies, respectively representing 48% and 41%. As mentioned earlier, a small amount of variance is not passed by either filter, due to rounding and smoothing by the filter weights, so that the percentages passed by the two filters do not add up to 100%.

Correlation analysis of the filtered sets (Table 6.IV) indicates varying associations among the three chronologies, depending upon the frequencies of the variances. The high-pass portions of choronology B are relatively well-correlated with A and C (0·695 and 0·619), but the low-pass components of B are not as highly correlated with the other two sets (0·198 and 0·252). The low-pass variances for A and C are more highly correlated (0·605), though the amount of low-pass information differs markedly between the two sets (0·176 versus 0·067). These results suggest

TABLE 6.IV Variances and correlation among the three chronologies before and after filtering[a]

	Ring-width index series		
	A	B	C
Unfiltered data			
Variance	0·289	0·202	0·299
Correlation with A	—	0·486	0·458
Correlation with B	—	—	0·379
High-pass filter			
Variance	0·190	0·097	0·092
% of unfiltered variance	66%	48%	31%
Correlation with A	—	0·695	0·403
Correlation with B	—	—	0·619
Low-pass filter			
Variance	0·067	0·083	0·176
% of unfiltered variance	23%	41%	59%
Correlation with A	—	0·198	0·605
Correlation with B	—	—	0·252

[a]See Figs 6.7 and 6.8.

that the processes generating the two frequency domains may be different among the three data sets.

Although these examples may be inconsequential in themselves, the data illustrate how the two reciprocal filters can be used to separate and study the variances at different frequencies with respect to time. When the variances are more poorly correlated at low frequencies than at high frequencies, it may be inferred that either the generating processes or the histories of the particular forests have differed among the trees and sites. Dissimilarities at high frequencies may be inferred to result from varying microclimates, or varying nonclimatic factors that create short-term (high-frequency) variations that persist for only a few years.

Julian and Fritts (1968) employed these filters to study chronology characteristics from 11 stands including trees of three different species in an area of similar topography near Denver, Colorado. The stands were separated from one another by varying distances ranging from less than 1 to 150 kilometers. The 11 chronologies for the interval 1860–1964 were correlated with one another and then were treated with the high- and low-pass filters shown in Table 6.III. Correlations were again calculated between sets of filtered data. Plot A (Fig. 6.9) includes the correlations for the unfiltered sets and shows a linear decrease in correlation with increased separation distance. However, when the variances in the chronologies were treated with the high-and low-pass filters (plots B and C, Fig. 6.9), it became apparent that the decline in correlation with increasing separation distance was mostly a feature of the high-frequency variance.

A search as to the cause for the lack of correlation among some of the low-frequency components led to the discovery that disturbance of the *Pinus ponderosa* sites could have been a factor. Actual plots of the *Pinus ponderosa* data revealed diverging trends in ring widths that could have been associated with disturbance from mining and grazing activity in the area, both of which had in fact occurred. Thus it was concluded that disturbance of the *Pinus ponderosa* sites produced the slowly changing variations in ring widths that were uncorrelated with the slowly changing variations in the chronologies from other sites. However, the correlations for the low-pass variance from stands of *Pseudotsuga menziesii* (as indicated by triangles in Fig. 6.9) were like those of the high-pass variance, so it was concluded that there was apparently less disturbance on these steeper and more moist sites.

Julian and Fritts (1968) also filtered data from three nearby climatic stations and calculated the correlation between precipitation and ring-width indices for what they judged to be the better tree-ring sites (Fig. 6.10). These results show a consistent and gradual decline in correlation
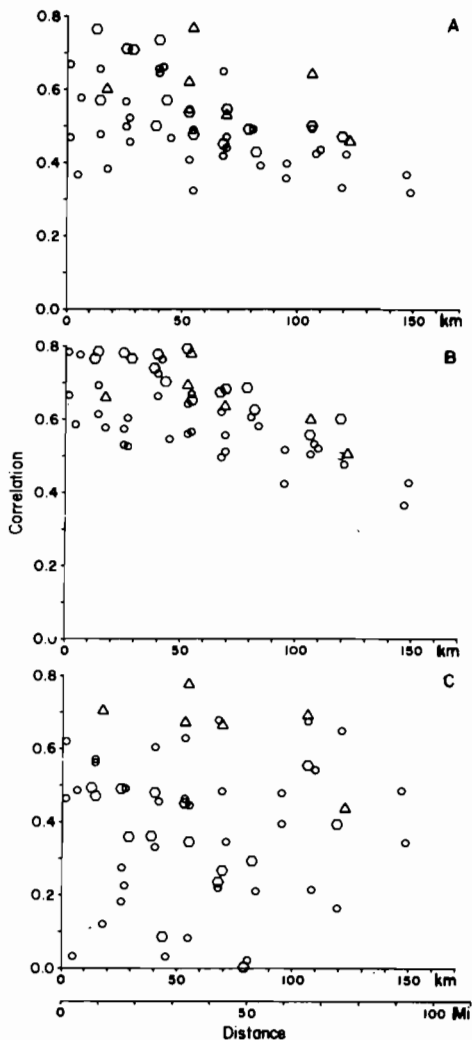
FIG. 6.9. The correlation among index chronologies from 11 stands of trees representing three different species plotted as a function of separation distance. Correlations are for (A) the mean indices, (B) the high-pass variance of the mean indices, and (C) the low-pass variance of the mean indices. Triangles designate those comparisons for chronologies of *Pseudotsuga menziesii*, hexagons designate those comparisons for chronologies of *Pinus ponderosa*, and circles designate comparisons for chronologies differing in species, one being *Pinus edulis*. For further discussion of these data, see text and Julian and Fritts (1968).

between the high-pass components of tree growth and climate with increasing separation distance, although considerable differences in correlations were noted for the low-pass components.

Stockton and Fritts (1971b) applied the same filtering and correlation techniques in a study of four chronologies from Arizona which are related to the average statewide climate (see section VII, Chapter 7). The tree-ring data were subjected to filtering and subsequent correlation analysis for varying intervals of 20 years from 1650 to 1957 (Fig. 6.11). There appeared to be certain 20-year periods of time when the low-frequency variations differed among the four chronologies within the state. It was first thought that the trees may have been affected by varying disturbance of the sites during these time periods. However, an examination of chronologies from neighboring sites and nearby states revealed similar low-frequency changes in growth, so it was concluded that in this case the differences among those particular chronologies were the result of climatic changes which produced a gradient across Arizona during the above-mentioned time spans. LaMarche (1974b) uses the same filtering techniques to test for differences in the generating processes between high-elevation and low-elevation *Pinus longaeva*.
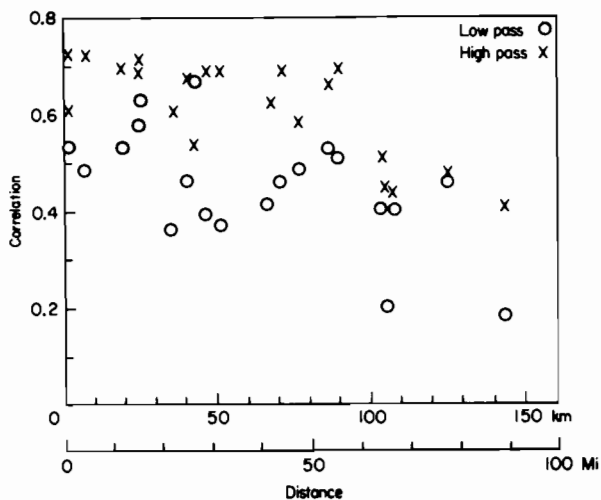
FIG. 6.10. The correlation between four ring-width chronologies and precipitation from three weather stations plotted as a function of separation distance. Monthly precipitation was transformed into a yearly precipitation index by use of a multiple regression relationship derived from analysis of the rings, and the data were subjected to the low-pass and high-pass filters before correlation coefficients were obtained. The first circle on the left represents two data points (see Julian and Fritts, 1968).
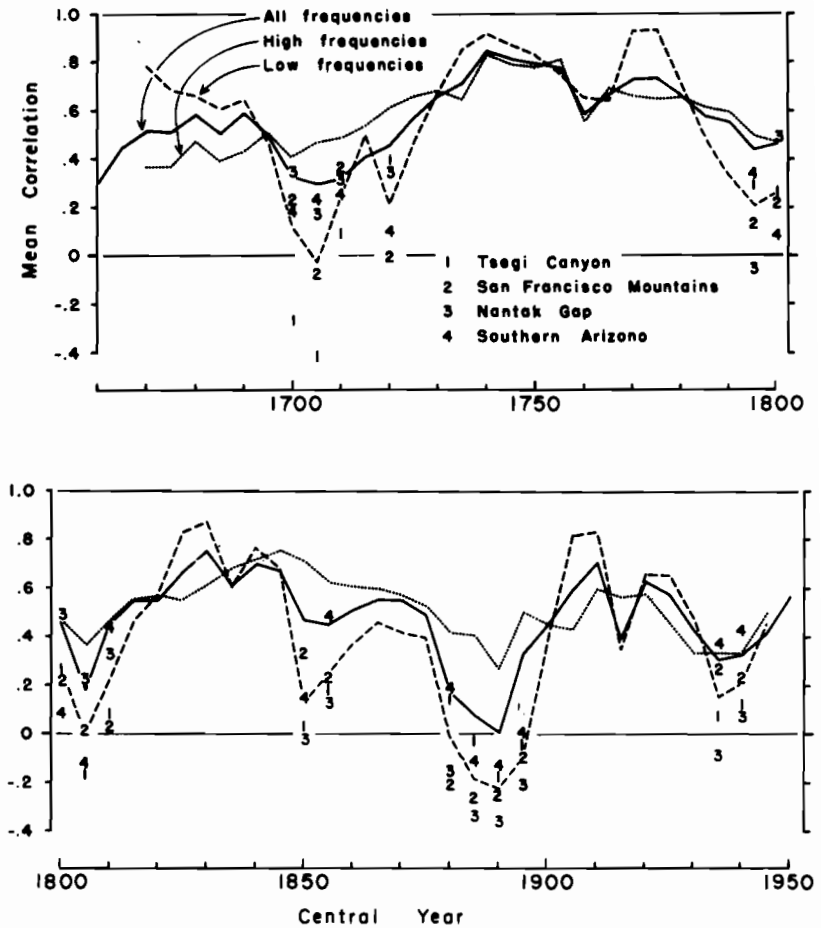
FIG. 6.11. The means of correlation coefficients plotted every five years for all possible correlations among indices of four Arizona ring-width chronologies calculated for overlapping 20-year intervals of time. Correlations were obtained for the unfiltered index data which include all frequencies, and for filtered data including either high frequencies or low frequencies as described in the text. The mean correlation for each of the four chronologies with the other three is plotted as the central position of numbers 1-4 only when the average correlation for the low-frequency data was low (less than 0·3). A negative value in the mean correlation indicates trends in the data that diverge from those for the other three chronologies. (Stockton and Fritts, 1971b)

The crossdating procedure involves a visual inspection and check for agreement which in essence utilizes the high-frequency variance in ring width. It is physically more dificult to scan a ring-width series by eye for the slowly varying changes in growth which may be nonclimatic in origin and which do not correlate from tree to tree and from site to site. Therefore, low-pass filters and correlation analysis can be of great assistance in identifying dissimilar low-frequency variations in growth. Chronologies to be used for climatic purposes may be screened by applying both the high- and low-pass filters and correlating the resulting series with similar data from neighboring sites. If the low-pass information in a particular chronology is poorly correlated with that of its neighbors, nonclimatic factors may be inferred to be excessively limiting and the particular chronology is deleted from the candidates for the climatic set. The ratio of high-pass to low-pass variance is also calculated and used to identify chronologies with disproportionate amounts of high- versus low-pass variance (Fritts and Shatz, 1975).

V. Other Methods for Assessing the Growth Curves

Systematic variations in ring widths may be assessed in a variety of ways other than those described above. Some workers regard systematic changes in ring width as purely geometric constraints, hypothesizing that the volume of wood added each year, in addition to being a function of ring width, is a function of the circumference of the cambium and height of the stem (Phipps, 1967). According to this model, ring width could be converted to a volume increment of growth for the entire stem, and a simple function of this increment would provide a good estimate of changes associated with tree age (Baker, 1950).

Other workers (Duff and Nolan, 1953; Smith and Wilsie, 1961) analyze ring growth on cross sections at every internode along the main stem and classify and plot ring features along three different gradients (Fig. 6.12). One gradient represents the usual horizontally arranged sequence of rings which is affected by climatic variation and the increase in tree age. The second represents the diagonal series of ring widths at various stem heights for the same year and expresses changes associated with increasing stem height and decreasing *cambial* age. The third series represents a vertically arranged sequence with each ring sampled at a given cambial age (that is, a constant ring number from the pith for all cases). This vertically arranged sequence often exhibits less systematic variation in ring width associated with increasing tree age than the other two sequences because cambial age was the same for all rings in the sequence. A number of internode-by-internode analyses using the Duff

and Nolan approach have contributed considerable useful information about anatomical features and about certain growth factors and wood density changes (Richardson, 1961).

Theoretically, ring-width variability along the vertically ordered sequence should be the best dendroclimatic sequence, but the technique is generally impracticable for most dendrochronological studies, because it requires a cross section for every increment in the stem corresponding to a year's growth. However, a modification of this classification approach was used to study ring characteristics throughout the stem of a mature *Pinus ponderosa*. The data were classified into 20-year units rather than
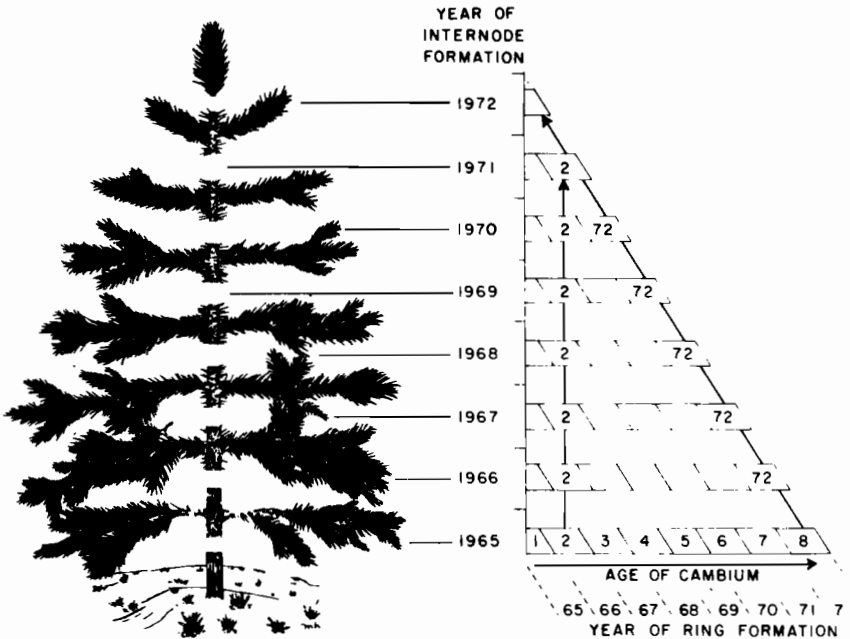
FIG. 6.12. The three classification schemes described by Duff and Nolan (1953) and Smith and Wilsie (1961). Each measurement corresponds to a parallelogram in the figure and these data for each year and season can be plotted as shown by the arrows in (1) the horizontal direction to show effects of changes in both year of formation and cambial age; (2) the diagonal direction to show increasing height in the tree, keeping year of formation constant; and (3) the vertical direction to show effects of changes in year of formation (holding cambial age constant). The horizontally averaged series is the one commonly used in dendroclimatology, but the vertical series is proposed by some to be a better representation of variations in climate. See text for further discussion.

one-year units and these data were compared to variations in ring characteristics associated with stem height, cambial age, and increasing tree age (Fritts *et al.*, 1965a). See Figs. 6.20 and 6.21 and accompanying discussion on pages 304–310.

Some workers have proposed that the ring width from all trees of a given species and site can be expressed as a simple mathematical function of increasing age. For example, Mitchell (1967), following the lead of Scandinavian scientists, obtained a large sample of varying ages, classified each ring according to tree age, averaged the ring widths in each class, and plotted these averages as a function of tree age (Fig. 6.13).
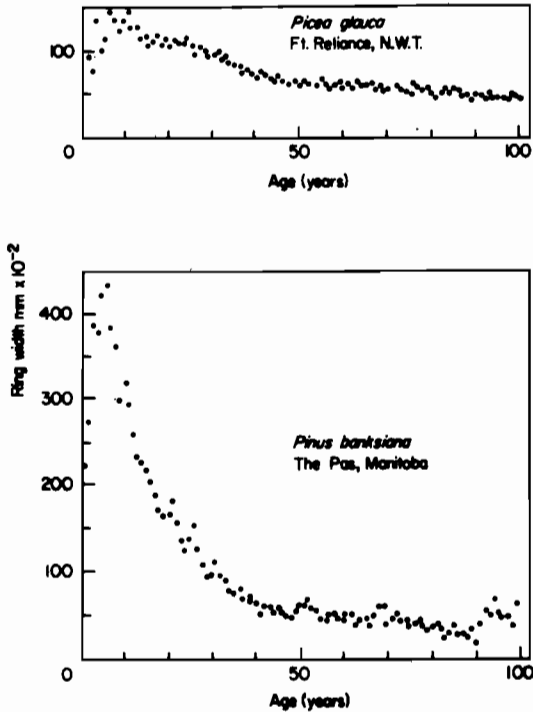
FIG. 6.13. The mean change in ring width associated with biological factors related to increasing age can be estimated by using trees of many age classes and averaging widths for rings of the same age. This procedure assumes that the environmental factors limiting growth in trees are randomly distributed through time and that the variations in these environmental factors become insignificant when large numbers are averaged from trees of all ages. A single smoothed curve fitted to the mean of all data shown in the figure is then used to standardize the ring-width series for all trees in the site. (Mitchell, 1967)

Variations in ring width due to climatic fluctuations are minimized in the averaging process, and the resultant curve presumably expresses the growth function that should be used for the sampled trees.

However, all individuals of a species rarely attain optimum growth at the same age, and individual trees differ in their growth rates because of differences in soil factors, competition, microclimate, and other factors governing the productivity of the site. Therefore, individual trees will deviate markedly and systematically from such a mean growth curve, and standardization by this method leads to more error in the chronology than is obtained by the empirical method of curve fitting described in Section III.

The use of a single growth curve could aid studies at the upper tree line or polar limits, where both increasing tree age and long-term changes in climate produce long-term variations in ring widths. It is possible that a single growth curve could be developed and applied to each measured set to distinguish between long-term changes due to increasing age from those associated with long-term variations in climate.

Ring widths are sometimes transformed to logarithms or they are plotted on a semilogarithmic scale. The general effect of this transformation is to lessen the variations in large rings and to increase the variations in small rings, but the effects of increasing tree age are not removed. An additional transformation (Jonsson, 1969) is one in which the logarithms of ring widths (lni_t) are averaged year-by-year and then a polynomial with two or more coefficients is fitted to the mean of the logarithmic series $(\overline{lni_t})$. Sometimes it is possible to simultaneously solve for the climatic relationships at the same time that the polynomial equation is obtained (Jonsson, 1969). Ring-width index values are then derived as follows:

$$x_t = \exp(lni_t - \overline{lni_t} - \sigma^2/2) \tag{6.10}$$

where σ^2 is the variance of lni_t. This term is used to adjust for the difference in means between the arithmetic and logarithmic scales so that the mean of the indices has a value of $1\cdot0$. Jonsson and Fritts compared their two standardization techniques on identical data and found 77% variance agreement. Differences were attributed to variations within and between trees which were not removed by the polynomial curve that was fitted to the mean of logarithms. While the computational procedures are easier, there is much less flexibility in the Jonsson method since the length of record for all sampled trees must be the same; also there is no possibility for statistical analysis of variance and correlation, both of which are described in the following sections.

Hollstein (1975) has suggested a very promising and interesting

alternative to standardizing procedures. He converts ring-width data to ratios by dividing each width by the width of the preceding ring and then takes the logarithm. These values for each year, which he calls "wuchswert," are averaged by year for all available samples. A simple linear regression is fit by least squares methods to the mean logarithmic series and yearly values of the regression subtracted to correct for the growth trend and to obtain a mean series which is zero.

One apparent difficulty with this method is that the resulting indices are logarithms of ratios which are dependent upon the climate of two successive years, so that the results are difficult to interpret and meaningful calibration of the values with climate is not easily obtained. However, this particular difficulty can be circumvented by taking the exponent of the mean ratios and converting the mean sequence of ratios back to mean yearly values which are comparable to the indices derived in the usual way. Also, it may be appropriate to allow for non logarithmic growth curves by fitting a straight line or polynomial to the logarithm of ratios for each ring-width sample and subtracting the value of the curve before the averaged *wuchswert* is obtained. A computer program to perform these calculations is now available.

No single method has been developed that is applicable to removing the growth functions for all species and sites. The computer-derived exponential function has proven satisfactory for a variety of coniferous species on arid sites and it appears to apply to many sites in Europe and the Arctic. The polynomial curve-fitting routine has been added to allow for cases with more complicated growth variations. Both types of curves are chosen for pragmatic reasons, that is to say they work for dendroclimatic analysis. While the using of a polynomial has no theoretical basis, it is the most convenient method for fitting a curve to accomplish standardization. Since the polynomial curve can approximate the exponential function, it is at present the best over all model for standardization, as long as care is taken to restrict the number of coefficients so that variations due to long-term climatic changes are not lost. If the simpler method of Hollstein, or some modification of it, proves feasible, it could be a suitable alternative to the more complicated standardization by division of a polynomial, computer-derived curve.

These standardizing techniques should never be applied blindly. It is routine practice at the Laboratory of Tree-Ring Research to plot all ring-width data as a function of tree age before computer analysis. Occasionally none of the available growth functions will adequately fit particular ring-width data. In such cases it may be inappropriate to apply the data to dendroclimatic study unless an alternative method can be derived for the growth-trend analysis.

VI. Analysis of Variance

The first five chapters have described a variety of factors that affect the tree ring-climate system and contribute to the ring-width chronology variance. Certain statistical measurements have been defined in this chapter which allow quantification of this variance. It is now appropriate to turn attention to analysis of variance, a very powerful technique which sorts out and measures the various sources in the tree ring-climate system that govern the chronology variance.

For example, the mean year-to-year pattern in ring-width indices from many trees in a region may be identified as variance resulting from limiting macroclimatic factors. Differences in these patterns from one stand to the next may be considered to result from a different source such as varying soil properties, different slopes, and the unique conditions of each plant community interaction with the macroclimate. The term *interaction* refers to the influence of one variable such as a site factor upon the effect of another variable such as macroclimate on growth. Differences also occur among individual trees within a stand which may be attributed to variations in tree vigor, competition, and the available operational environment. Variations in the growth within the tree stem may also occur as a result of growth in major branches and roots, local microclimatic variations, and other factors which control the operational environments for different tissues and organs. The relative importance of these sources of variation is assessed by a particular *analysis of variance* developed specifically for indices, derived from ring-width data which have been collected in a particular manner to represent several sources of variance. The following paragraphs describe the technique by means of a simple example. General descriptions of the technique may be found in Neter and Wassermann (1974), Simpson *et al.* (1960), and Steel and Torrie (1960).

A stand of *Pinus longaeva* in California was divided into two classes or groups of equal size, one of young trees and one of old trees. Since the age classes were intermixed within the same stand, differences in the mean chronologies of the two groups could be attributed to tree age as the source of variance. Differences in the chronologies between trees within each age class could be attributed to differences among trees as a source of variance. In addition, two cores were sampled from each of the trees in each group so that the chronology differences between them could be used to assess the sides of the tree stem as a source of variance. Four trees were sampled at random from each age class within the site, including two radii per tree which were subsequently placed in separate growth-rate classes, depending upon which core for each tree had the greatest average ring width.

The samples were mounted, dated, widths of rings measured, and the indices derived for the entire length of each sampled stem radius. An interval of time common to all samples was specified to be 1950–1954. Usually this interval includes a common period of 100 or more years, but in this example only rings for the five years were analyzed. Table 6.V includes all indices for each age class, tree, core, and year.

The first required computations are the sums and the sums of squares for the five indices on each core, as shown in columns 9 and 10 of Table 6.V. (The individual data were analyzed by the computer but have been rounded in the table; therefore, small differences will occur in the least significant digits if recalculations are made from the data in the table.) The variances are calculated from sums and sums of squares statistics using the equations in Table 6.VI.

The indices from the different sides of each tree stem (Table 6.V, columns 4–8) are summed year by year to obtain five yearly values for each tree, and these values are summed, squared, and the squares summed (columns 11 and 12). The data for each growth-rate class within the young and old group are summed, these values squared, and the squares summed (columns 13, 14). In this example, all cores numbered as 1 are from the slower-growing sides of the trees and those numbered 2 are from the faster-growing sides. The sums and sums of squares for the slow-growing class are listed first. The two core classes between age groups are summed to obtain combined core-class chronologies for both groups (columns 15 and 16). All indices within groups are then summed year by year to obtain the sums and sums of squares for chronologies of young and old groups (columns 17 and 18), and finally all indices for all 16 cores are summed year by year to obtain the sums for the chronology for both groups as shown at the bottom of Table 6.V.

The next step in the analysis is a complicated procedure shown in (Table 6.VII). Rows 1–5 are the variance of group, core, and tree means. sums of squares as shown in Tables 6.V are adjusted (corrected) by subtracting the squares of several sums as shown in Table 6.VI working from row 1 to row 11. Each of these adjusted values is divided by the number of degrees of freedom to obtain the mean squares or variances (Table 6.VII). Rows 1–5 are the variance of group, core, and tree means. There is usually no significant variance accounted for by these values, because the standardizing procedure has forced all samples to have the same mean. Occasionally when the period of analysis is a small subset of a larger one, some of the variances for means are significant.

The *component variances* computed in Table 6.VI are obtained for the mean chronology (Y in row 6) and the other sources of variance that interact with it (rows 7–11, Tables 6.VI and 6.VII). They are the estimates

TABLE 6.V Sample data for analysis of variance[a]

			Years					Cores[b]		Trees		Core class within group		Core class		Groups	
								C×T/G Sums	Y×C ×T/G Sums of squares[c]	T/G Sums	Y× T/G Sums of squares	C×G Sums	Y× C×G Sums of squares	C Sums	Y×C Sums of squares	G Sums	Y×G Sums of squares
Group	Tree	Core	1950	1951	1952	1953	1954										
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Young	1	1	0·341	1·031	1·026	0·713	0·817	3·928	3·408	9·042	18·104	19·264	76·064	37·885	298·936	39·544	321·296
	1	2	0·415	1·251	1·395	0·928	1·125	5·114	5·810			20·281	84·768	38·071	300·488		
	2	1	0·479	1·291	0·814	1·105	1·088	4·777	4·963	8·953	17·210						
	2	2	0·581	1·226	0·785	0·960	0·625	4·177	3·769								
	3	1	1·116	1·385	1·164	1·205	0·931	5·801	6·837	11·667	27·602						
	3	2	1·069	1·308	1·159	1·349	0·980	5·865	6·977								
	4	1	0·844	0·921	0·980	1·095	0·918	4·758	4·563	9·882	19·668						
	4	2	0·882	1·295	1·000	0·971	0·977	5·125	5·352								
Old	1	1	0·706	0·974	1·355	1·336	0·935	5·306	5·942	10·825	24·346	18·621	74·132			36·411	281·329
	1	2	0·711	1·083	1·145	1·305	1·276	5·518	6·315			17·790	66·788				
	2	1	0·261	1·050	1·255	1·130	1·070	4·766	5·167	9·166	18·754						
	2	2	0·366	1·000	1·059	1·172	0·804	4·401	4·275								
	3	1	0·788	0·939	0·971	0·955	0·692	4·345	3·836	8·808	15·604						
	3	2	0·713	0·928	0·870	0·846	1·106	4·463	4·065								
	4	1	0·100	1·203	0·524	1·379	0·938	4·204	4·529	7·613	14·600						
	4	2	0·184	1·047	0·495	1·058	0·625	3·409	2·885								
Sum of all groups, trees, and cores			9·616	17·932	15·997	17·505	14·907	75·957	1198·572								

[a] Indices from *Pinus longaeva* for 5 years, 4 old trees, 4 young trees, 2 cores collected from each tree. [b] See Table 6.VI, left column, for definition of symbols, and equations for computations. [c] Each value is squared and the squares are summed. Key: groups (G) = 2; trees per group (T) = 4; cores per tree (C) = 2; rings per core (N) = 5.

of variances for each source which are calculated by separating the mean squares into their respective components and dividing by the number of elements in each part (Table 6.VI).

The analysis pools the variance in the appropriate ways and uses the differences to assess the importance of each source. The operation is described in conceptual terms in the following paragraphs. (For specific details consult Tables 6.V, 6.VI, and 6.VII.)

The pooled variances for the tree chronologies are subtracted from those of the individual 16 cores. There is always less variance in the former because divergent variations among the individual core chronologies are canceled out in the summing process. The greater the differences among the paired core chronologies within the same trees, the greater the reduction in variance resulting from the summing process and the greater the component attributed to the core chronology source (Table 6.VI, line 11).

The variances for the sums representing each of the two age groups are subtracted from the pooled data for the individual tree chronologies and the difference in variance is attributed to the tree chronology source (Table 6.VI, line 8). The variances in the summed chronology for both groups are subtracted from those for the sums of young and old groups and the difference is attributed to the age source (Table 6.VI, line 7). Likewise, the sums of the group variances are subtracted from the corresponding values of the core classes to derive the fast-growing versus slow-growing components (Table 6.VI, lines 9 and 10). Finally, the amount of variance remaining in the five totals for each year summed for all cores, trees, and groups represents the mean variance in the year-by-year chronology or that attributed to the macroclimatic source (Table 6.VI, line 6).

If a large amount of ring-width variability coincides in all cores, trees, and groups, only a small amount of variance is lost in the averaging process and a large amount remains in the year-by-year chronology of the site (the macroclimatic source). It may be inferred from this result that some large-scale factor, such as climate, has varied from year to year and has affected growth in the same way on all sides of all trees and in all groups. If, on the other hand, there are large differences in core and tree chronologies (with the result that the chronology summed for all trees and groups has little variance), it may be inferred that during each year a variety of factors have limited growth in a variety of ways in the different radii, trees, and groups diminishing the effects of macroclimatic variations on growth.

Sometimes there will be a greater reduction in variance when core chronologies are averaged into tree chronologies than when the tree

TABLE 6-VI

Calculations for Analysis of Variance of Tree-Ring Chronologies

Row	Source of Variation	Sum of Squares and Correction	Corrected sum of Squares
1*	Group means (G)	$\dfrac{1}{tcn}\left[\sum_{h=1}^{g}\left(\sum_{i=1}^{t}\sum_{j=1}^{c}\sum_{k=1}^{n} y_{hijk}\right)^2\right] - K$	$= G_c$
2	Core class means (C)	$\dfrac{1}{gtn}\left[\sum_{j=1}^{c}\left(\sum_{h=1}^{g}\sum_{i=1}^{t}\sum_{k=1}^{n} y_{hijk}\right)^2\right] - K$	$= C_c$
3	Tree means in groups (T/G)	$\dfrac{1}{cn}\left[\sum_{h=1}^{g}\sum_{i=1}^{t}\left(\sum_{j=1}^{c}\sum_{k=1}^{n} y_{hijk}\right)^2\right] - G_c - K$	$= T_c$
4*	Core means in groups (C × G)	$\dfrac{1}{tn}\left[\sum_{h=1}^{g}\sum_{j=1}^{c}\left(\sum_{i=1}^{t}\sum_{k=1}^{n} y_{hijk}\right)^2\right] - G_c - C_c - K$	$= CG_c$
5	Core means with trees in groups (C × T/G)	$\dfrac{1}{n}\left[\sum_{h=1}^{g}\sum_{i=1}^{t}\sum_{j=1}^{c}\left(\sum_{k=1}^{n} y_{hijk}\right)^2\right] - G_c - C_c - T_c - CG_c - K$	$= CT_c$
6	Mean indices in total chronology (Y)	$\dfrac{1}{gtc}\left[\sum_{k=1}^{n}\left(\sum_{h=1}^{g}\sum_{i=1}^{t}\sum_{j=1}^{c} y_{hijk}\right)^2\right] - K$	$= Y_c$
7*	Chronologies of groups (Y × G)	$\dfrac{1}{tc}\left[\sum_{k=1}^{n}\sum_{h=1}^{g}\left(\sum_{i=1}^{t}\sum_{j=1}^{c} y_{hijk}\right)^2\right] - Y_c - G_c - K$	$= YG_c$
8	Chronologies of trees in groups (Y × T/G)	$\dfrac{1}{c}\left[\sum_{k=1}^{n}\sum_{h=1}^{g}\sum_{i=1}^{t}\left(\sum_{j=1}^{c} y_{hijk}\right)^2\right] - Y_c - G_c - T_c - YG_c - K$	$= YT_c$
9	Chronologies of core classes (Y × C)	$\dfrac{1}{gt}\left[\sum_{k=1}^{n}\sum_{j=1}^{c}\left(\sum_{h=1}^{g}\sum_{i=1}^{t} y_{hijk}\right)^2\right] - Y_c - C_c - K$	$= YC_c$
10*	Chronologies of core classes with groups (Y × C × G)	$\dfrac{1}{t}\left[\sum_{k=1}^{n}\sum_{h=1}^{g}\sum_{j=1}^{c}\left(\sum_{i=1}^{t} y_{hijk}\right)^2\right] - Y_c - G_c - C_c - YG_c - YC_c - CG_c - K$	$= YCG_c$
11	Chronologies of cores with trees in groups (Y × C × T/G)	$\left[\sum_{k=1}^{n}\sum_{h=1}^{g}\sum_{i=1}^{t}\sum_{j=1}^{c}\left(y_{hijk}\right)^2\right] - Y_c - G_c - C_c - T_c - CG_c - CT_c - YG_c - YC_c - YT_c - YCG_c - K$	$= YCT_c$

*When g=1, these sources of variation do not exist, and the mean squares are zero.

$$K = \frac{1}{gtcn}\left(\sum_{h=1}^{g}\sum_{i=1}^{t}\sum_{j=1}^{c}\sum_{k=1}^{n} y_{hijk}\right)^2$$

Degrees of freedom	Mean Square		Variance Component		Percentage
$g-1$	$G_c/g-1$	$=MS(G)$			
$c-1$	$C_c/c-1$	$=MS(C)$			
$(t-1)g$	$T_c/(t-1)g$	$=MS(T)$			
$(c-1)(g-1)$	$CG_c/(c-1)(g-1)$	$=MS(CG)$			
$(t-1)(c-1)g$	$CT_c/(t-1)(c-1)g$	$=MS(CT)$			
$n-1$	$Y_c/n-1$	$=MS(Y)$	$\dfrac{MS(Y) - MS(YT)}{gct}$	$=VC(Y)$	$\dfrac{VC(Y) \times 100}{TOTAL\ VC}$
$(n-1)(g-1)$	$YG_c/(n-1)(g-1)$	$=MS(YG)$	$\dfrac{MS(YG) - MS(YT)}{ct}$	$=VC(YG)$	$\dfrac{VC(YG) \times 100}{TOTAL\ VC}$
$(n-1)(t-1)g$	$YT_c/(n-1)(t-1)g$	$=MS(YT)$	$\dfrac{MS(YT) - MS(YCT)}{c}$	$=VC(YT)$	$\dfrac{VC(YT) \times 100}{TOTAL\ VC}$
$(n-1)(c-1)$	$YC_c/(n-1)(c-1)$	$=MS(YC)$	$\dfrac{MS(YC) - MS(YCT)}{gt}$	$=VC(YC)$	$\dfrac{VC(YC) \times 100}{TOTAL\ VC}$
$(n-1)(c-1)(g-1)$	$YCG_c/(n-1)(c-1)(g-1)$	$=MS(YCG)$	$\dfrac{MS(YCG) - MS(YCT)}{t}$	$=VC(YCG)$	$\dfrac{VC(YCG) \times 100}{TOTAL\ VC}$
$(n-1)(c-1)(t-1)g$	$YCT_c/(n-1)(c-1)(t-1)g$	$=MS(YCT)$	$MS(YCT)$	$=VC(YCT)$	$\dfrac{VC(YCT) \times 100}{TOTAL\ VC}$

where
 $h = 1, 2, \ldots, g$
 $i = 1, 2, \ldots, t$
 $j = 1, 2, \ldots, c$
 $k = 1, 2, \ldots, n$

 g = number of groups
 t = number of trees per group
 c = number of cores per tree
 n = number of years

TOTAL VC = VC(Y) + VC(YG) + VC(YT) + VC(YC)
                    + VC(YCG) + VC(YCT)

TABLE 6.VII Analysis of variance results for *Pinus longaeva* sample[a]

Row	Source of variation		Raw sum	Corrected sum	Degrees of freedom	Mean square	Variance component	% variance component
1	Group means	G	72·243	0·127	1	0·127		
2	Core class means	C	72·117	0·001	1	0·001		
3	Tree means in groups	T/G	73·242	0·999	6	0·167		
4	Core means with groups	C×G	72·282	0·038	1	0·038		
5	Core means with trees in groups	C×T/G	73·518	0·237	6	0·040		
6	Mean indices in total chronology	Y	74·907	2·791	4	0·698	0·039	48
7	Chronologies of groups	Y×G	75·328	0·294	4	0·074	0·001	1
8	Chronologies of trees in groups	Y×T/G	77·944	1·617	24	0·064	0·025	30
9	Chronologies of core classes	Y×C	74·928	0·020	4	0·005	−0·002	0
10	Chronologies of core classes with groups	Y×C×G	75·438	0·051	4	0·013	−0·001	0
11	Chronologies of cores with trees in groups	Y×C×T/G	78·691	0·400	24	0·017	0·017	21
		K = 72·116			N = 80			

Total Variance Components
(disregarding minus values)
= 0·082

[a]From data in Table 6.V using equations in Table 6.VI.

chronologies are averaged into larger groups. Thus, a large variance is attributed to the core source and it may be inferred that the core chronologies within trees differ from one another because of factors such as irregularities in the tree crowns, injuries, or even carelessness in ring measurement. If there is a large reduction in variance when tree chronologies are summed, a high variance is attributed to the tree source, and it may be inferred that tree microclimates, local site variations, or other local factors have modified the tree responses to macroclimate.

In each analysis, the investigator collects his cores, trees, and groups in such a way as to analyze a particular component of the environment. Slope effects are studied by comparing groups of trees on contrasting slopes, soil effects by selecting groups on different soil types, and elevational effects by varying elevations of sites. Effects on ring-width variations around the tree due to the lean of the stem, exposure of slope, or crowding by neighbors is assessed by selecting the appropriate stem side that is used in the core class, while effects of drought years versus wet years are assessed by choosing appropriate years for analysis.

The sampling design for analysis of variance described here must be balanced and replicated like the example in Table 6.V. All samples must include the same years of growth, all trees must have the same number of replicated cores, and all groups must include the same number of trees. However, the trees are assumed to be randomly chosen so they are nested but not classed within groups. In other words, tree 1 of group 1 has no relation to tree 1 of group 2, but the same number of trees must be included in each group. The years, the core classes, and the groups are assumed to be fixed, that is, not selected in a random manner, but according to a conscious decision as to specific years, specific core classes, and specific groups.

The actual values of the variance components differ from site to site in proportion to the nature of the sampled materials, including the amount of autocorrelation in them. To make comparisons possible between chronologies with markedly different variance, the components are reduced to percentages as shown on the right of Table 6.VII.

The component variance for core classes (Table 6.VII, lines 9 and 10) frequently is near zero as there is rarely any contribution by that particular source. That is to say, the chronologies in the core classes are not significantly different. In the example, the variance components for core classes at both levels are negative (lines 9 and 10, Table 6.VII). Sometimes negative values do occur by chance or by round-off error, if the particular core classification is not important. As long as the negative values are small, they can be replaced by zeros in the calculation of the percentages. Since all variances are theoretically positive, no variance

components should be large and negative. When such cases are encountered, they usually indicate that the wrong sums and sums of squares were used or some other computational error has been made.

The core classes were originally included in the analysis of variance to test hypotheses regarding chronology variability throughout the tree stem. Only a few cases with significant variance in a core class have been observed, and these cases usually represent samples from the upper and lower sides of leaning trees or from the up-slope and down-slope sides of trees on very steep slopes.

The results from the example in Table 6.VII show that the variance component in all cores, trees, and groups (the total group chronology variance Y was 48%. The variance due to differences in the chronologies of trees ($Y \times T/G$) accounted for 30% of the variance. The differences in the individual core chronologies ($Y \times C \times T/G$) accounted for 21% of the variance. The differences between the chronologies for the two groups ($Y \times G$) accounted for only 1% of the total variance.

Trees on dry sites can retain as much as 80% common variance in the total or group chronology for the site. The value of 48% in this particular example suggests that the sampled trees for the particular five years were only moderately limited by factors of the macroclimate. The high variance for tree components (30%), indicates a relatively heterogeneous site with varying factors affecting the ring-width chronology somewhat differently in each tree. If the component variance for core chronologies ($Y \times C \times T/G$) had been higher than that of the trees, it might be concluded that irregularities of crown size, competition, and distribution of food-and growth-controlling substances produced a larger amount of ring-width variability within the trees of the site. The 1% difference between age groups indicates that, at least for the five years and four trees that were tested, there are very few differences between the chronologies of the old vs young group. Additional examples of analyses of variance are presented later in this chapter.

VII. Analysis of Chronology Error

It was pointed out in Section II that statistics, such as the mean or variance, which are derived from small samples are likely to deviate from the true value of the particular statistical universe and that the error of these statistics can be estimated from the *standard error* statistic (Equation 6.3). In the case of a chronology developed from a number of cores and trees within several groups, the individual yearly values are in error depending upon the amount of error variance contributed by each source (cores, trees, and groups).

The standard error for any yearly value of a chronology (SE_y) is calculated from the component variances (such as those shown in Table 6.VII) as follows:

$$SE_y = \left(\frac{VC(YT)}{t} + \frac{VC(YCT)}{ct} \right)^{\frac{1}{2}} \qquad (6.11)$$

where $VC(YT)$ and $VC(YCT)$ are the calculated variance components (Tables 6.VI and 6.VII) and t and c are the number of trees used and number of cores per tree in the chronology under consideration. Since core classes and groups are assumed to be statistically fixed (not randomly chosen), the calculations involve only the variances for tree chronologies and their interactions with the cores.

The components are unbiased estimates of these variances (that is, the results apply to the statistical universe and are independent of the sample size) so that different values for trees (t) and cores (c) can be substituted into Equation 6.11 to calculate the errors in samples of varying sizes. Table 6.VIII includes such calculations using the components in Table 6.VII and cases including from five to 20 trees per sample and from one to four cores per tree. Similar computations may use the component

TABLE 6.VIII Calculated mean standard error of estimates for various numbers for trees and cores[a]

Number of trees	Number of cores per tree			
	1	2	3	4
5	0·092	0·082	0·078	0·077
6	0·084	0·075	0·072	0·070
7	0·078	0·069	0·066	0·065
8	0·073	0·065	0·062	0·061
9	0·068	0·061	0·058	0·057
10	0·065	0·058	0·055	0·054
11	0·062	0·055	0·053	0·052
12	0·059	0·053	0·051	*0·049*
13	0·057	0·051	*0·049*	0·047
14	0·055	*0·049*	0·046	0·046
15	0·053	0·047	0·045	0·044
16	0·051	0·046	0·044	0·043
17	*0·050*	0·044	0·043	0·042
18	0·048	0·043	0·041	0·040
19	0·047	0·042	0·040	0·039
20	0·046	0·041	0·039	0·038

[a]Based upon variance components for tree chronologies of 0·025 and core chronologies of 0·017 in Table 6.VII and Equation 6.11.

variances of other samples to test for differences among sites (Fritts, 1969). Such analysis of variance statistics are especially useful for evaluating sampling strategies in terms of the information gained and the statistical reliability of the results.

For example, the data in Table 6.VIII confirm the generalization that the standard error decreases with any increase in the number of cores or trees. However, because of differences in the variance structure of the sample as indicated by the component variances, the error reduction is dependent more upon the number of trees in a sample than upon the number of cores sampled from each tree in the group. The data in Table 6.VIII indicate that if only one core is sampled per tree a sample size of 17 trees must be obtained to reduce the standard error to 0·050 or less (see values in italic type in the table). However, if two cores are sampled per tree, 14 trees are required; if three cores are sampled per tree, 13 trees are required; and if four cores are sampled per tree, 12 trees are required.

It could be inferred from the above results that a sample of one core per tree for 17 trees is the most efficient sampling scheme, but on a steep, rocky slope it may be easier to extract a second core from 14 trees than to find three extra trees. Since variance and other analyses require at least two cores per tree, the extra time required for sampling the second core is justified. In special circumstances where only a limited number of trees is available on a given site or where more information is needed from individual trees, the collector might decide to increase the sample to three or four cores per tree. On the other hand, where time is extremely limiting, the most efficient and desirable sampling scheme might be one which would utilize the time saved in collecting only one core per tree to obtain samples from additional trees.

Another feature of standard error computations was first noted in *Pinus edulis* from Mesa Verde National Park, Colorado. The standard error for a mean index of a chronology was found to be directly proportional to the average value of the index. That is, those years with high average indices generally exhibited higher standard errors than years with low average indices (Fig. 6.14). This manifestation is undoubtedly a consequence of the law of limiting factors described in Chapter 1. The cambia producing the narrow rings formed during years of severe climate are highly limited by similar characteristics of the macroclimatic factors, so that ring widths vary little from one tree to the next. The wide rings formed in less severe years are more limited by local site conditions than by factors of the macroclimate, and thus a larger variability in widths within trees, among trees, and among groups prevails. A test for this relationship is made routinely by checking the correlation between value of standard error and average index. The relationship varies in its importance among ring-

width chronologies from arid sites, but at present no one has studied the
problem sufficiently to explain its variance.
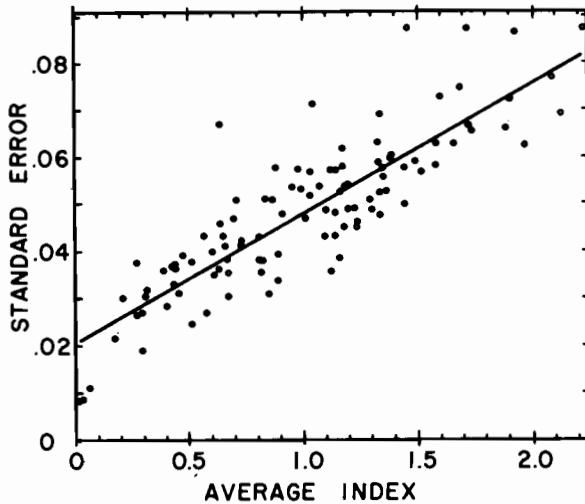
FIG. 6.14. The standard errors for average yearly values of some chronologies vary as a
direct function of the average value in the index. The higher the value, the greater the
standard error and the less precision of the index. The above sample is calculated for the
average yearly index chronology from three groups of *Pinus edulis* from Mesa Verde,
Colorado.

VIII. Correlation Analysis

It is not always possible to obtain adequate replication to perform an
analysis of variance. In such cases correlation coefficients can provide
information similar to analysis of variance. This information, however, is
generally less useful than variance analysis, for correlation provides only
a relative measure of variability in common between two data sets and it
cannot be partitioned as easily into separate components. Nevertheless,
because correlation is a simpler concept and easy to compute, it is
sometimes favored over analysis of variance.

Correlation statistics are derived after standardizing the ring widths
for individual cores. Correlation coefficients are obtained for all
combinations possible within a group of chronologies. The correlations
for cores paired within trees are tabulated separately from those paired
between trees. The former measures the similarity within tree variance,
while the latter measures the similarity between tree variance. In fact, the

mean correlation for all pairs between trees is closely related to percent
variance component for the group chronology in the analysis of variance
[VC(Y), Table 6.VI]. That is, as the mean correlation increases between
core chronologies in different trees, there is a parallel increase in the
percent variance that is common among all cores, trees, and groups.

The relationship between the two measurements is so well correlated
for arid-site conifers that the correlation results can be substituted into a
simple regression equation to statistically estimate the corresponding
variance component (Fig. 6.15). The equation shown in the figure is for
the straight line fitted to the data points where Y is the group-chronology
percent variance component and X is the mean correlation among core
chronologies from different trees within groups. When analysis of
variance is not possible, the correlation data can be substituted into the
equation in Fig. 6.15 to estimate the percent common variance
component.

Correlation analyses can be run for a number of time intervals such as
for 20-year periods lagged every five years. A comparison of the results for

$$Y = -1.28 + 98.09 \; X \; \pm 2.56$$
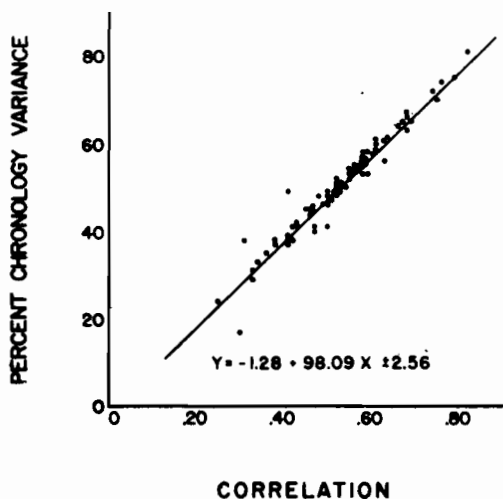
CORRELATION

FIG. 6.15. The mean of correlation coefficients for all combinations of core
chronologies paired between trees (excluding comparisons of cores from the same trees) is
highly correlated with and may be used to estimate the percentage of variance in the
group chronology [VC(Y) × 100/total VC] (Table 6.VI) as shown by the plotted points.
The regression equation shown is for the line and is the least square fit to the data shown in
the figure, where Y is the percent chronology variance and X is the mean of the correlation
coefficients. The data are for semiarid North American conifers from a variety of species
and sites.

different periods can be used to assess when ring widths were best correlated and hence most limited by climatic conditions as opposed to site factors. Correlation analysis can also be run on the mean chronologies for trees and the mean chronologies for groups to study the similarities and dissimilarities in these components. Analysis using correlation helped Charton and Harman (1973) to identify a decline in agreement among ring-width indices from *Quercus rubra* that could have been due to limiting effects of air pollution or possibly to anomalies in precipitation resulting from industrial pollution near the tree sites.

A dendrochronologist who selects cores from trees with the best crossdating and the highest sensitivity is simultaneously selecting for high percent variance in the group chronology, for high correlation among trees, and for a high proportion of climatic information in the chronology of the site. Analyses of variance and correlation allow the dendroclimatologist to evaluate his samples and to make decisions as to which ones are most likely to provide the best results for a particular experiment. The conclusions from these data can also guide future selections of tree-ring materials and sites and help in developing the most productive lines of research.

IX. Power Spectrum and Cross-power Spectrum Analyses

It is sometimes helpful to study nonrandomness in a ring-width time series using *power spectrum analysis*, which describes the data in a manner that presupposes nothing as to its nature in the frequency domain. For example, the ring-width index series may be regarded as an infinite number of oscillations or cycles described by an infinite number of wavelengths. The power spectrum analysis estimates the variance (the power) of each wavelength and expresses the results as a continuous distribution of wavelengths throughout the entire spectrum, ranging from the shortest wavelength that can be resolved by the annual values (a half cycle per year or one cycle every two years) to infinite wavelength (linear trend) (Mitchell, *et al.*, 1966).

The procedures for computing a power spectrum use the methods of Tukey (1950) and Blackman and Tukey (1958). First the autocorrelation coefficients are computed from one to a prescribed number of lags (Figs. 6.4, 6.16). These coefficients plotted against lag constitute the *autocorrelation function*. The power spectrum is then obtained by means of a Fourier transform of the autocorrelation function. The resolution of a power spectrum estimate is proportional to the number of lags that can be used to generate the autocorrelation function, which in turn is

constrained by the record length. Very detailed estimates may be obtained if the time series is long, but they must be generalized to a few frequencies if the time series is short or few lags are analyzed (Jenkins and Watts, 1968).

The plotted autocorrelations and the power spectra of three ring-width chronologies are shown in Fig. 6.16 (Stockton, 1971, and Stockton, 1975). If the variations in the time series are purely random, the spectrum will approximate a horizontal line (all spectral estimates are the same for all frequencies) (Mitchell *et al.*, 1966). Since such a spectrum is analogous to white light, which includes equal amounts of light at all wavelengths, it is called a "white noise" spectrum. If a time series is a pure sine wave, the spectrum will contain a relatively sharp peak at the appropriate frequency for the sine wave. If there is a regular periodicity having a nonsinusoidal shape, the spectrum will contain not only a peak at the basic wavelength, but other peaks at wavelengths corresponding to one or more higher harmonics of its basic wavelength. If there is a quasi periodicity, or irregular rhythm, the spectrum will express it as a relatively broad hump spanning an appropriately wide range of wavelengths. Finally, if there is persistence whereby each value of the series is related to those values preceding it, the spectrum will be distorted across all wavelengths so that the greatest variance is at low frequencies and there is a decrease in power from long to shorter wavelengths. This spectrum is said to resemble that of "red noise" (Mitchell *et al.*, 1966). Most power spectra of ring-width series, like those shown in Fig. 6.16, exhibit "red noise" spectra indicating more persistence than would be expected if they were made up of completely random events. For more discussion of these and other techniques of time series analyses see Box and Jenkins (1970), Jenkins and Watts (1968), and Kisiel (1969).

The three power spectra in Fig. 6.16, in addition to showing "red noise," indicate that the chronology from site A has the least power (variance) of the three at high frequencies from 0·1 to 0·5 cycles per year while the chronology from site C has the most. The first is a cool and moist site and the chronology has moderately low mean sensitivity, while the latter is the driest and warmest site and the chronology has the highest mean sensitivity (Stockton, 1971, and Stockton, 1975).

The above techniques, in addition to being applied to single series variations, may also be used to study covariance between series expressed in the frequency domain (Jenkins and Watts, 1968). Studies of this type are referred to as a *cross-power spectrum analysis*. The computations utilize the autocorrelations of two series and the cross correlations between two series at various lags. Fourier transforms of the autocorrelation and cross correlation functions along with the phase relationships are obtained.
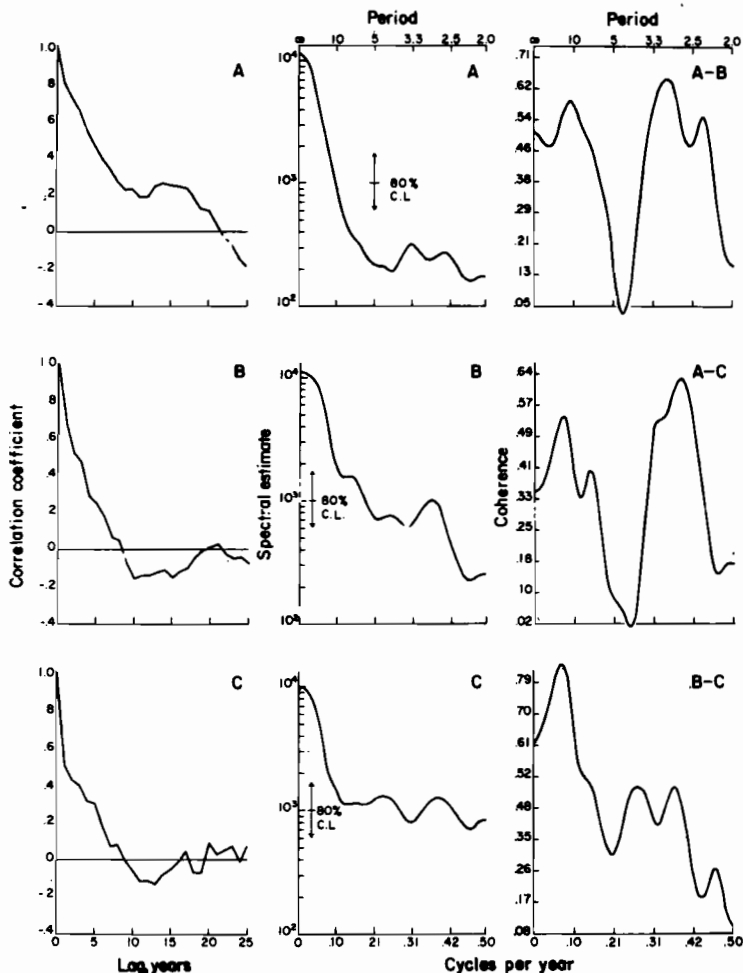
FIG. 6.16. An example of results from power and cross-power spectrum analyses of three site chronologies of *Pseudotsuga menziesii* in northern Arizona. The left-hand plots are the autocorrelations for lags from 0 to 25 years. The plots in the middle of the figure are the power spectra, while the right-hand plots show the coherence among the three chronologies obtained in the cross-power spectra analyses. Chronology A is from trees on a moist, cool site. Chronology C is from an arid site. Chronology B is from a relatively intermediate site. (Redrawn and reprinted by permission from "Long-term Streamflow Records Reconstructed from Tree Rings", Paper of the Laboratory of Tree-Ring Research at the University of Arizona, No. 5, by C. W. Stockton, Tucson: University of Arizona Press, © 1975.)

These data are used to measure *coherency* which represents the similarity between the two series at each frequency as in power spectrum analysis. Coherency is analogous to the square of the correlation between the two paired series at each frequency band.

The plots on the right of Fig. 6.16 are the coherencies among the same three chronologies. All pairs exhibit high coherency at 0·08 cycles per year or at periods of approximately 12 years. Pairs A–B and A–C exhibit higher coherency at 0·30 to 0·45 cycles per year than the pair B–C. The same two pairs exhibit little or no coherency at 0·24 cycles per year. This implies that the variance generated by series A near frequencies of 0·24 cycles per year is uncorrelated with the variance at the same frequency in the other two series.

Often power and cross-power spectrum analysis can lead to considerable insight into the biological and statistical relationships in regard to possible periodicities in factors controlling growth. For example, LaMarche (1974b) studied four chronologies of *Pinus longaeva* in the Snake Range of Nevada ranging from the low-elevation semiarid forest border to the high-elevation upper tree line. He noted that the chronologies at the lower and upper tree lines appeared relatively uncorrelated; but when the data were treated with the high- and low-pass filters shown in Table 6.III, there was high and direct correlation between the high-frequency variations and high but inverse correlation between the low-frequency variations.

The data were then subjected to power and cross-power spectrum analysis because LaMarche was concerned that the arbitrary spectrum selection of filters may not have divided the series into the "natural" frequency bands. He noted that the biggest difference between the two spectra occurred in the frequency range from about 0·1 to 0·5 cycles per year. As was the case for Stockton's results (1975) shown in Fig. 6.16, the arid forest border trees exhibited more variance at high frequencies than did the trees at high elevations on more moist and cool sites.

Cross-power spectrum analysis of LaMarche's data revealed that a portion of the variance in the chronologies was out of phase; that is, when a maximum in growth occurred at the lower tree line there was a tendency for it to be followed in three years by a minimum in growth at the high-elevation tree line. Also, the inverse correlation was found to be most pronounced at frequencies from 0·10 to 0·01 cycles per year.

LaMarche (1974b) attributed the high positive correlations at high frequencies to the direct effects of precipitation on ring widths for both the low and high elevation sites. The coherency at low-frequency and the out-of-phase relationships were attributed to the differing effects of climate on the growth of needles, which in turn affect photosynthesis and

ring width (see Chapter 4). At the lower forest border short needles were formed during years when precipitation was low and temperatures were high, but at the high elevation short needles were formed when temperatures were low. Since the needles are retained and are photosynthetically active for 15 or more years, the growth response to temperature was not only different for the two sites but it was averaged over 15 years and it lagged behind the occurrence of climate.

The coherency between the two chronologies enabled LaMarche to identify four frequencies which were best correlated. These are shown in Fig. 6.17 as peaks from right to left at 0·45, 0·30, 0·14, and 0·037 cycles per year with periods corresponding to 2·2, 3·3, 7, and 27 years. LaMarche suggested that the tree-ring coherency at 0·45 cycles per year (with a period of 2·2 years) was probably linked to the well-known rhythmic variation in wind and pressure from equatorial regions known as the "quasi-biennial oscillation" which exhibits a period of 26 to 27 months (Landsberg, *et al.*, 1963). He also suggested that coherency at periods of 27 years could be a result of solar-lunar tidal influences in the atmosphere as described by Brier (1968), which could control both warm-season temperatures in the central Great Basin and the tree needle lengths.
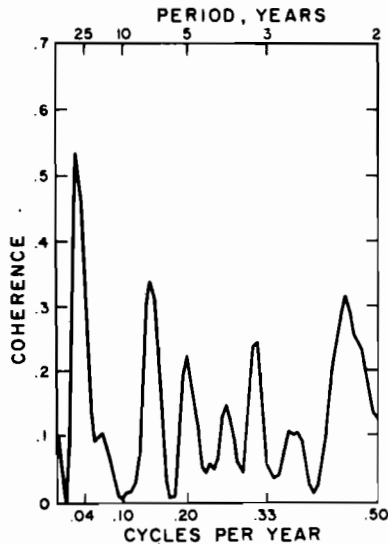
FIG. 6.17. An example of cross-power spectrum analysis showing the coherence between two *Pinus longaeva* chronologies in the Snake Range of Nevada. One chronology was from trees at the semiarid lower forest border and the other from the upper tree line. The peaks indicate coherency at about 0·45, 0·30, 0·14, and 0·037 cycles per year. (Redrawn from LaMarche, 1974b)

Power spectrum analyses also were employed by **Bryson** and **Dutton** (1961), LaMarche and Fritts (1972), and Sirén and Hari (1971) to study periodicities in ring-width data that might be associated with the 11-year and 22-year periodicity in sunspots. Although several apparent relationships were proposed, no ring-width series was proven to be significantly linked to sunspot numbers and none was confirmed to exhibit a significant spectral peak at the appropriate frequencies (LaMarche and Fritts, 1972).

X. Variability in Statistical Characteristics of Ring Widths among Sites

It has been shown that a number of statistical parameters may characterize the time series of ring widths and ring-width indices. These statistical parameters may vary because the generating functions of the time series differ among trees and sites.

Figure 6.18 portrays six tree-ring characteristics which vary with increasing aridity of a site and decreasing arboreal dominance of the stand. The area to the left of K in the diagram represents forest interior trees which exhibit little ring-width variability, while the area to the right of K represents trees of greater sensitivity and ring-width variability, generally those in semiarid forest border sites. To the left of J there is insufficient variability in common among trees to allow rings to be crossdated. To the right of M, there are so many partial or absent rings that cros-dating is excessively difficult.

The changes occurring from left to right across the diagram are (1) decreasing average ring width, (2) decreasing arboreal dominance (density of the forest stand), (3) increasing correlation of ring widths within and among trees, (4) increasing correlation of ring widths with climatic variations, (5) increasing mean sensitivity and standard deviation, and (6) increasing percentage of rings that are locally absent. Sometimes there is a reduction in autocorrelation with increased aridity, except to the right of L where autocorrelation may begin to increase. The above characteristics change from left to right in proportion to decreasing amounts of effective precipitation and increasing variability in that precipitation. As these factors become more extreme, they result in more days when moisture becomes limiting to tree processes.

As mentioned in Chapters 1 and 4, such changes in ring-width characteristics are not only a direct result of macroclimatic variations but also of individual site factors which affect the degree to which climatic factors become growth-limiting. For example, the amounts of precipitation can vary due to topographic factors, or site-to-site
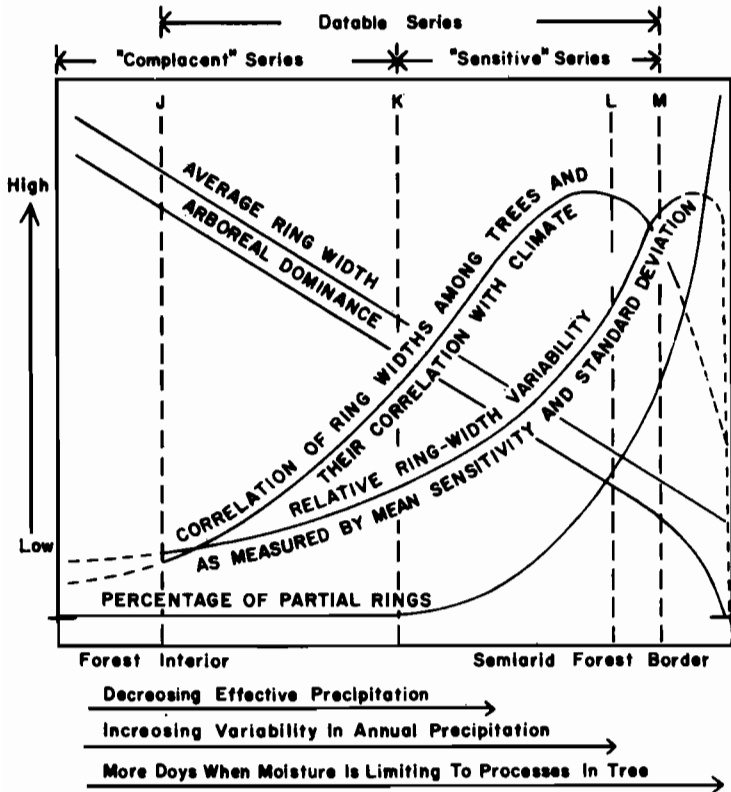
FIG. 6.18. Statistical and dendrochronological characteristics of ring-width chronologies from semiarid regions vary as a function of the proximity of the sampled site to the forest border. J is in the forest interior, where arboreal dominance (density of the stand) is high, rings are wide and "complacent," and there is little correlation in the ring-width variation among trees or between ring widths and climate. K marks the difference between "complacent" and sensitive series and L is near the forest border where arboreal dominance is low (the trees are more scattered), rings are narrow, mean sensitivity and standard deviation of the chronologies are high, and there is a high correlation of the chronologies among trees and with climate. Climatic and physiological conditions that change along the gradient are indicated. (Modified from Fritts *et al.*, 1965b)

variations in soil characteristics can cause different amounts of moisture to infiltrate the soil. Differences in site exposure can affect temperature, wind, and radiation, all of which affect the rate at which moisture is lost by evapotranspiration processes; and exposure of the site can affect the removal and drifting of snow, which modifies the soil moisture reserves.

Since the statistical characteristics of ring-width indices are generally related to the moisture availability on arid sites, their values can be used to estimate the amount of environmental stress on tree growth.

The utilization of tree-ring statistics to assess environmental differences at several tree sites is demonstrated in Fig. 6.19. A number of statistics were calculated from replicated ring-width indices for the last 100 years from *Pinus longaeva* in southeastern California. The statistics for each site included (1) the percentage of partial or absent rings, (2) mean sensitivity, (3) standard deviation, (4) mean correlation between cores within trees, (5) mean correlation among cores between trees, (6) the first-order autocorrelation (serial correlation), and (7) the percent variance components for cores [VC(YCT)], trees [VC(YT)], and for the entire group [VC(Y)]. The samples were obtained from sites representing differences in topography, elevation, and soil substrate. Differences among species and among trees of varying mean sensitivity were also considered. The data were arranged to represent particular environmental gradients, shown by the labels and diagram at the top of Fig. 6.19; the percentages of slope are plotted immediately below them.

The statistics for sites 6, 7, 8, 9, and 10, shown in Fig. 6.19, represented a topographic gradient from a steep and exposed SSW-facing slope across a small valley to a steep and exposed NNE-facing slope. Site 8 included the four young and four old trees used in this text to illustrate analysis of variance; but the results shown here include data for 10 trees of each age class and for 100 years.

Most of the statistics indicate that trees on the lower NNE-facing slope (site 9) were generally the least limited by climate. Few rings were absent, mean sensitivity and standard deviation were low, correlation within and among trees was low, the percent variances for cores was high, and the variances common to all trees were low. However, on the upper north-facing slope where the trees are exposed to wind (site 10) and on the south-facing slope (sites 6 and 7), the tree-ring statistics indicate that the environment was more limiting to growth.

Sites 11 and 12 in Fig. 6.19 face WNW and ESE near the sites discussed above. It was thought that the prevailing winds from an open meadow to the west might carry snow into the WNW-facing site although not into the opposite slope. However, only slight differences in statistical characteristics were apparent, and it was concluded that in this instance exposure had little effect upon ring-width characteristics.

An interesting topographic phenomenon is apparent from the data for sites 15, 13, 14, and 16 which were on a SSE-facing slope. The statistical characteristics of ring widths from trees on sites 13 and 14 indicate that relatively mesic conditions prevailed on the middle of the slope.
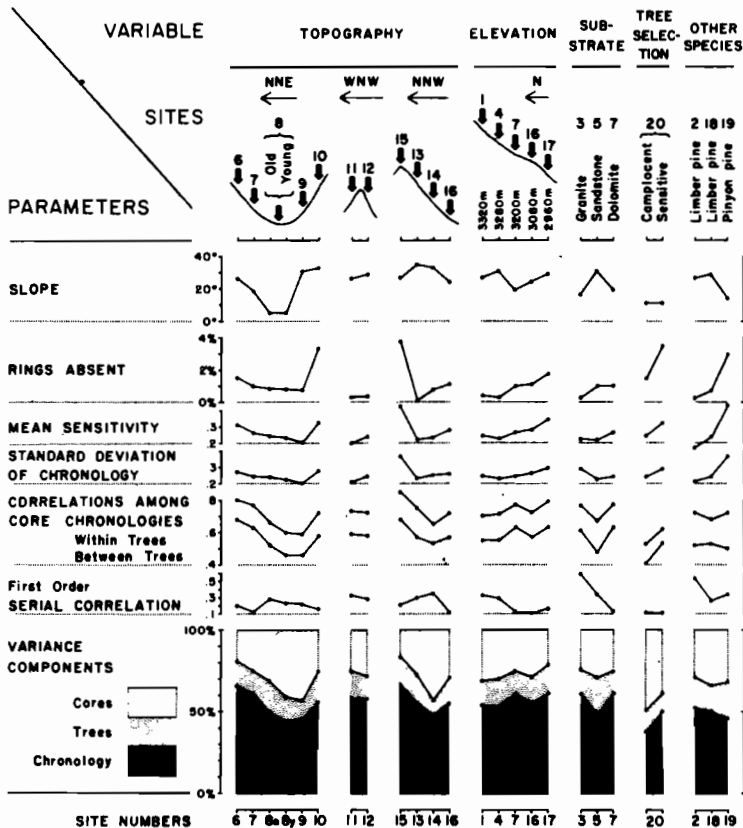
FIG. 6.19. The statistics of ring-width chronologies can be used to assess the stress of particular sites. The data are derived from analyses of replicated samples from *Pinus longaeva* in the White Mountains of California. Site variables of topography, elevation, and substrate are diagrammed at the top, as well as selection criteria of complacency as opposed to sensitivity, and differences among species. The variations in slope and values of statistical parameters are plotted below as a function of the variables shown at the top. (Reprinted by permission from "Bristlecone Pine in the White Mountains of California, Growth and Ring-width Characteristics", Paper of the Laboratory of Tree-Ring Research at the University of Arizona, No. 4, by H. Fritts, Tucson: University of Arizona Press, © 1969.)

However, the characteristics of rings for sites 15 and 16, which were above and below the two midslope sites, indicate more aridity. A greater number of rings were absent, and both mean sensitivities and standard deviations were higher. The correlations within and between trees and the percent variance of the group chronologies were highest for site 15. Aerial photographs made in the spring showed snow banks on slopes of

this particular exposure. Therefore the decrease in ring-width variability and the decline in other arid-site characteristics of the midslope tree rings was attributed to increasing amounts of moisture from drifting snow.

The statistical characteristics along the gradient of elevation (sites 1, 4, 7, 16, 17) show changes associated with increasing aridity as a result of decreasing elevations. However, the magnitude of differences is less than those in the topographic comparisons (sites 6, 7, 8, 9, 10) depicted on the left of the figure. It was concluded that topographic variations in the White Mountains of California have a greater effect on arid conditions than elevation and hence a greater effect on ring-width characteristics.

Classifying trees into varying substrate, species, and sensitivity revealed differences in first-order autocorrelations, which were highest for *Pinus longaeva* on granite and for site 2 with limber pine, *Pinus flexilis*.

XI. Statistical Characteristics of Ring Widths within a Tree

The previous section described a number of statistical characteristics that can vary from site to site. The dendrochronologist may not only be interested in site variations, but he may also wonder about statistical variations in ring width and cell structure that can occur throughout the main stem and branches of trees. The following is a study of this within-tree variation.

The main stem of a 295-year-old *Pinus ponderosa* which was growing near Flagstaff, Arizona, had been sectioned at specified levels in 1935 by Glock (1937), and the samples were stored in the archives of the Laboratory of Tree-Ring Research. It was noted by Fritts *et al.* (1965a) that the dates of the innermost rings on eight of the sections differed by intervals of approximately 20 years. Thus, the rings within each section could be divided into 20-year intervals (Fig 6.20 and 6.21).

The first 20 rings on the lowermost section (section 1) represented approximately the first 20 years of growth in the life of the tree. The second set or segment of 20 rings on section 1 was formed during the second 20 years in the life of the tree and corresponded to the first 20 rings on the next section above it. The third segment of 20 rings on section 1 corresponded to the second one on section 2 and the first one on section 3. In a like manner, the eighth segment of 20 rings on section 1 corresponded to the first segment of 20 rings on section 8. Another way to view and classify the data set is to consider the outermost 20 rings in all eight sections which were formed during the last 20 years in the life of the tree (1915–1934) while tracing the rings inward; the seventh set of 20 year segments represented the first 20 years on section 8 and the seventh section from the center for section 1. The rings along four radii on each

cross section were crossdated, examined by 20-year segments, and analyzed in terms of eight different statistics. The 80 rings for each group (20 on each of four radii) were used to calculate average ring width, average percentage of intra-annual growth bands (false rings), and average percentage of rings that were absent.

The ring widths for each of the four radii were converted to indices by standard techniques (Equations 6.7 and 6.8). Correlations were obtained by pairing the four radii on each section and segment. There were six possible paired combinations of the four radii, so six correlation coefficients were computed from the indices within each segment. The mean of these six coefficients is referred to as the intracorrelation for that particular time period and section.

The indices from the four radii were also averaged, and the mean index series was used to calculate the first-order autocorrelation (serial correlation), the standard deviation, and mean sensitivity for each 20-year segment. Correlation coefficients were also computed for the average indices on each 20-year segment paired with the average indices on other sections in the tree that were dated in the same 20-year time period. For example, the indices for the second 20-year segment of section 1 were correlated with those on the first 20-year segment of section 2. The indices for the third segment on section 1 were correlated with those for the second segment on section 2, as well as those in the first segment on section 3. In this latter case a third correlation coefficient was also obtained between the indices for the second segment on section 2 and the first segment on section 3. Extending the process to more segments and sections involves the computation of 84 correlation coefficients which express the intercorrelated variability in ring-width indices from section to section throughout the tree. All coefficients involving a particular 20-year segment were averaged. These averages are referred to as the *inter*correlation of indices among sections for each 20-year period, as opposed to the *intra*correlation of indices within a particular section described in the preceding paragraph.

Figure 6.20A portrays the 84 mean width values for the groups of 20 rings in their respective positions diagrammed as a half-radial section within the stem. The data for each of these blocks or segments were then pooled in four different classifications labeled as A, B, C, and D.

As shown by the emphasized lines in Fig. 6.20, the A classification included data which were pooled and averaged along columns of the 20-year segments aligned with the pith. The resulting averages which are plotted in column A of Fig. 6.21) are analogous to the horizontal sequence of Duff and Nolan (1953) (see Fig. 6.12). The first average, plotted on the left of column A, includes date from all rings formed by one- to 20-year-

old cambia; the second includes data from all rings formed by 21- to 40-
year-old cambia, and the last (plotted on the right of each graph)
includes data from all rings formed by 121- to 140-year-old cambia.
Thus, the averages express the variations associated with increasing
cambial age and to some extent, tree age. Every average includes one
segment from each section so that height is held constant.

The same data were utilized in classification B, but they were pooled
and averaged in the direction of rows, each corresponding to one cross
section. The resulting averages for ring width, which are also shown in
Fig. 6.20 and plotted in column B (Fig. 6.21), are analogous to Duff and
Nolan's vertical series (see Fig. 6.12). These data portray the variations
within the tree stem (from left to right) associated with increasing height.
However, cambial ages from one to 140 years are included in each
average so that cambial age is held constant. As in the previous
classification, the successive averages at increasing stem height also
include some changes associated with the aging tree.

In classification C the data were pooled along the rows, but the
segments represented by blocks in Fig. 6.20 were aligned with the outer
wood surface, not the pith. The resulting averages and plots are
analogous to the diagonal series in Duff and Nolan. From left to right they
express the effects of increasing stem height, with tree age (the dates of the
rings) held constant.

The averages for classification D were pooled in a diagonal direction

FIG. 6.20. Statistical data from eight sections of *Pinus ponderosa* are separated into 20-
year segments and pooled in four classifications to study various patterns that occur
throughout the stem. Data for mean ring widths for each 20-year segment are shown in 84
blocks in the upper left. The left margin of each diagram is aligned with the pith in the
stem, the right with the bark, and the bottom and top rows represent the lowermost and
uppermost sections. The mean values for each 20-year segment, shown in the boxes, are
then pooled and averaged vertically in classification A in the direction of the emphasized
columns. The resulting means express the effects of increasing cambial age starting with
the first 20 years next to the pith. The same data are used in classification B (upper right),
but the data are pooled in a horizontal direction shown by the emphasized rows. The
resulting averages express the association of mean ring width with increasing height
within the stem, but cambial age is held constant. For classification C the data are also
pooled in a horizontal direction as shown by the emphasized rows in C, but the segments
are chosen according to their alignment with the outer wood surface. The averages of this
classification express changes in ring width associated with increasing height within the
stem, but tree age, not cambial age, is held constant. Classification D uses the same block
of data as classification C, but the data are pooled in a diagonal direction to obtain the
mean ring width throughout the stem associated with each 20-year period of time. Plots of
the average values obtained in each classification are shown in Fig. 6.21 (Fritts *et al.*,
1965a).

A

MEAN CAMBIAL AGE

SECTION	10			50			90			130				
8	45	39												
7	55	46	51	59	45									
6	123	64	70	57	64	44								
5	99	100	82	69	56	59	50	37	95					
4	158	107	73	66	85	71	62	41	102					
3	223	150	88	62	62	78	64	56	46	106				
2	182	166	99	108	84	57	58	63	79	53	61	98		
1	164	133	120	124	101	79	87	65	55	78	52	64	101 45	95
AVERAGE	131	101	91	80	72	64	65							

B

MEAN CAMBIAL AGE

10   50   90   130

AVERAGE

SECTION	
8	57
7	59
6	74
5	78
4	88
3	107
2	111
1	115

C

MEAN YEAR

1805   1845   1885   1925

AVERAGE

SECTION	
8	57
7	66
6	66
5	68
4	64
3	68
2	68
1	64

D

MEAN YEAR

1805   1845   1885   1925

AVERAGE

58   75   66   52   61   43   101

SECTION
8
7
6
5
4
3
2
1

parallel to the outer surface of the wood. These data are analogous to the traditional dendrochronological series and the second horizontal series in Duff and Nolan, except that 20-year averages rather than individual indices are utilized. These averages express (from left to right) the effects of both increasing tree age and variations in climate. As in classification A, height within the stem is constant, but unlike A, cambial age decreases to some extent with increasing height; so cambial age does affect the plots to a limited extent.

The following discussion examines the variations in each statistic revealed by the four classifications plotted in Fig. 6.21 and relates them to material discussed in earlier chapters. Ring widths show the expected decline with increasing cambial age (A) and with increased height within the stem when cambial age is held constant (B). However, when tree age, not cambial age, is held constant (C), ring width does not change as a function of height except for a slight decline in width in the uppermost section. The sequences compared in this classification (as well as D) include rings formed after the tree had attained two-thirds its full height, so that the vigorous growth of youth is not considered. Thus, looking back at classification B the inverse correlation between ring width and tree height is probably more an effect of increasing tree age than of a height factor The variations shown in classification D show a general decline in ring width with increasing tree age and a marked increase in width centered in 1925. This particular 20-year interval of high growth is associated with and undoubtedly caused by a period of exceptionally favorable climate.

The percentages of double rings are directly correlated with ring width, as shown in sequences A, B, and D. However, classification C indicates a tendency for more double rings in the uppermost sections. As mentioned in Chapters 2 and 4, double rings are often found in close proximity to the stem apex which is the source of growth regulators. Thus, the high frequency of double rings in the upper stem can be attributed to (1) the closeness of the rings to the stem apex which is the growth regulator source, (2) the vigor of the younger tissues, and (3) the greater propensity for water stress with increasing stem height.

FIG. 6.21. Changes in ring-width statistics in a *Pinus ponderosa* associated with the four different classifications using eight sections of the main stem and 20-year segments within the sections which are pooled and averaged as illustrated by the diagram at the top (also see Fig. 6.20). Every second section in the diagram and every other 20-year segment is shown in the diagram, and the solid lines connect the blocks of data that are pooled in each case. The plots express the averages of each statistic as a function of the 20-year segments from the inside toward the outside or the cross-section number, ordered from the bottom to the top. See text for further explanation. (Fritts *et al.*, 1965a)
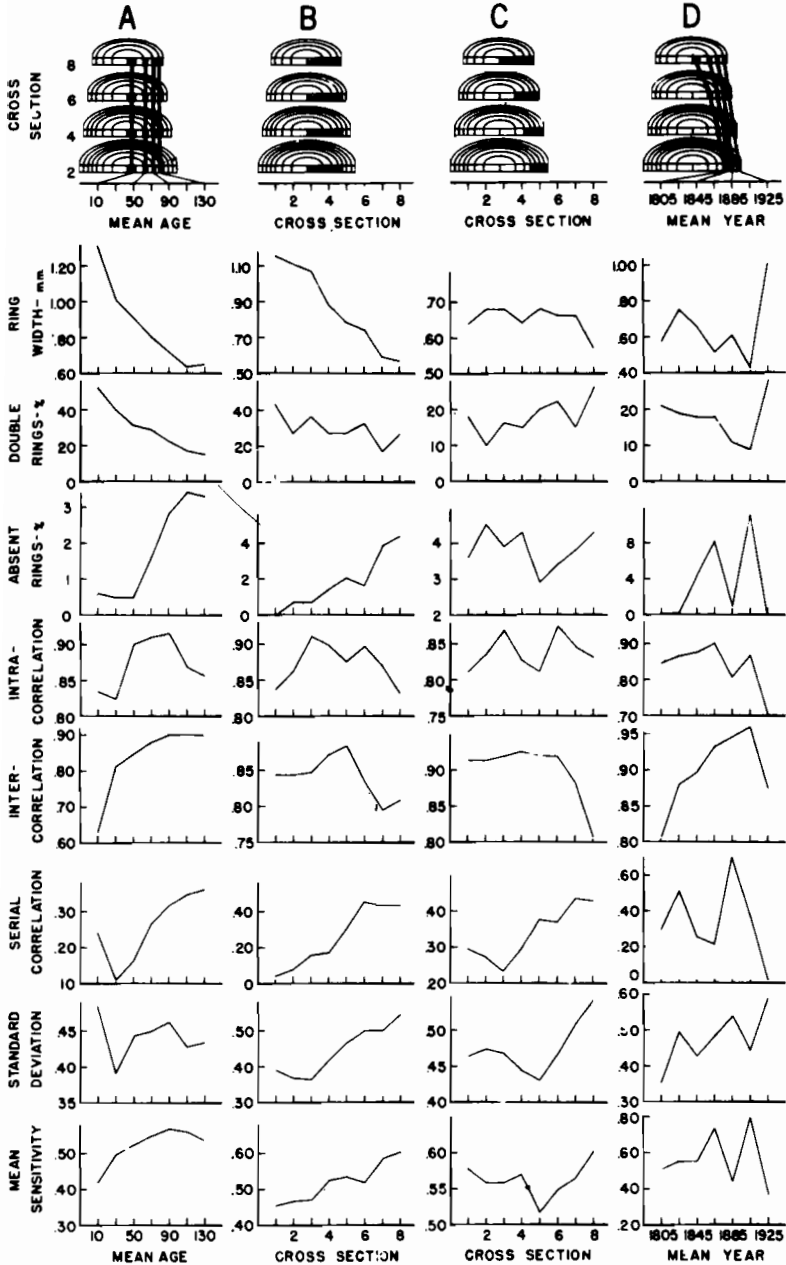
The percentages of absent rings show an expected inverse correlation with ring width in all four classifications. If the rings on the average are wide, there is a low probability that rings are absent. Cambial age (classification A) is also important in that absences are rare for tissues derived from one to 60-year-old cambia, but absences increase as a function of cambial age from 60 to 120 years; for greater cambial ages the percentages appear relatively constant. Classification C shows declining absence for those sections affected most by the lower crown (sections 5 and 6), a relationship attributable to a strong cambial initiation stimulus in the stem immediately below the major branches.

Both the intracorrelation (the correlation within a section and segment) and intercorrelation (the correlation among sections) show the poorest agreement among rings derived from one- to 40-year-old cambia (classification A). This result supports the contention that the first-formed rings on a stem yield the least information on climate. Intracorrelations are also low, indicating somewhat less agreement (1) in the uppermost portions of the stem, sections 7 and 8, (2) in sections near or just below the main branches, (3) at the ground line, and (4) in segments produced when rings were widest and climatic factors most favorable. Intercorrelation indicates that there is excellent agreement in ring-width patterns throughout the first six sections and for time periods when rings were narrow and climatic factors were highly limiting.

Autocorrelation, standard deviation, and mean sensitivity are all high in the uppermost and outermost stem segments. This is evidence of increasing variance at all frequencies with increasing tree height and age. These statistics also show marked variations associated with changing climatic conditions and with variability in other statistics for the same periods of time (column D). The anomalously high autocorrelations and standard deviations at cambial ages from one to 20 years are due to a brief period of increasing ring width in the first 10 rings in some sections. This increase in width was not adequately modeled by the negative exponential curve that was used in the standardization process, so that the divergent trend of growth inflated the autocorrelation and standard deviation statistics.

The above analysis illustrates how statistical characteristics can be objectively assessed throughout a tree stem. Classification by segments and section can be used to identify changes associated with various gradients representing height, age, or spatial variations within the stem. One highly significant conclusion from the study is that the ring-width variations at breast height (approx. 4·25 ft. or 1·3 m from the ground) in the stem provide good estimates of the ring-width variations throughout

the entire stem and thus are probably the best estimates of variations in the macroclimate.

Many of the statistics dealt with in this chapter are readily available for analytical work, since they are routinely calculated in the tree-ring standardization programs. If used properly, the statistics can provide an objective and powerful tool for assessing variations from site to site, from tree to tree, and from one segment in the tree stem to the next. The statistics of new and old collections can be compared to obtain objective measures of their respective qualities. Inferences from such statistics can guide future collections, assist in model development, and suggest new approaches.

Statistical measurements will become increasingly important for assessment of site characteristics as tree-ring analysis is applied to new areas where the relationships between growth and climate are less apparent. Careful use of statistics should also make it possible to distinguish previously unrecognized phenomena in many and varied fields that lend themselves to dendrochronological analysis.

Chapter 7

Calibration

I. Introduction

Ring widths in trees on stress sites have been shown to vary from one year to the next in a more or less irregular manner, with a large portion of this variation being a function of fluctuating climatic conditions prior to and during the growing period when the rings were formed. This occurs because variations in the macroclimate for each year affect the operational environments of the trees which, in turn, influence the processes governing growth. The degree of relationship between climatic factors and ring-width variation is dependent upon (1) the ecological amplitude of the species, (2) the proximity of the sampled trees to their environmental limits, and (3) the range of variability in the limiting factors affecting growth.

As mentioned in earlier chapters, the growth-controlling processes in trees on moist sites with mild climates will be less limited by conditions associated with variations in climate than those on stress sites, but they will instead be limited by nonclimatic conditions such as shading by

neighbors, lack of soil minerals, size of crown, and tree age. In such cases ring widths will vary widely from one tree to the next and only a small amount of variation will be common to all trees of a given site. This common variation, although it is less precisely defined, represents potential information on variations in the macroclimate.

From the point of view of a dendroclimatologist, the ring-width variation due to climatic factors would be considered analogous to the *signal* in an electronic system, while those due to nonclimatic factors would be analogous to *noise*. In such an analogy, the ring-width variations in trees experiencing moist and mild climates would have a small signal-to-noise ratio. The ring-width patterns in trees highly limited by climatically related environmental factors would have a large signal-to-noise ratio.

Not only does the ratio of signal to noise vary, but the specific values of ring width that are associated with specific values of climate can vary as a function of growth rates of the trees and the severity of the site. Furthermore, a lag may exist ranging from several months to 15 or more years between the climatic input of the system and the corresponding growth output. This chapter will describe procedures that can be used to identify the standardized ring-width variations that result from variations in climate and to transform them as well as other growth indicators into estimates of climate. Consideration will also be given to methodologies for determining the structure of a relationship including any lags in the growth response behind associated conditions of climate.

II. The Procedure of Calibration

The variations in ring widths might be considered analogous to the length of a column of mercury in a thermometer measured at regular intervals of time or to the dial reading on a scientific instrument which is sensing an environmental variable. The readings are compared to the actual conditions which the instrument is sensing to obtain a *calibration* between the two. New gradations can be made on the thermometer which take into account the association between the direct measurements of temperature and the observations on the instrument. In the case of dial readings, a calibration equation can be obtained with appropriate constants which converts the measurements on the instrument to units appropriate to the variable that is sensed. If the instrument produces a voltage, an equation may be found that converts voltage to a temperature measurement.

A *variable* is defined here as a characteristic, feature, or factor which can assume different values in successive individual cases. In each of the

above examples there are two variables, those values observed on the instrument to be calibrated and those observed on a previously calibrated instrument which is now considered a standard. In the case of ring-width chronologies the indices are the values for one variable, and monthly precipitation or average monthly temperature represent the values of climatic variables with which the indices are calibrated. The success of such calibration is measured as the percent variance accounted for or reduced on one set of variables when another is used to estimate it. If the values of the chosen variables express important associations, the reduced variance is greater than that which could be obtained by chance.

The object of calibration as presented in this text is to establish the appropriate statistical or mathematical transformation which converts measurements of climate to those of growth or converts measurements of growth to those of climate, depending on the goals of the research. Such calibrations can be obtained in a number of ways, some of which involve relatively simple classifications and counts and others which involve rather complicated statistics. The simpler procedures often involve one factor at a time and require *a priori* judgments as to the nature of the relationships. Some of the more complex methods use statistics which help to identify the relationships, to eliminate unnecessary variables, and to assign appropriate weights. These complex methods often involve fewer *a priori* judgments.

All calibration procedures include a certain amount of modeling which describes or quantifies the biological–climatological linkage. A number of qualitative biological models already have been presented (Chapter 5). The task described in this chapter is to simplify these or similar models and to make them quantitative.

A. The Biological Model

Part A of Fig. 7.1 is a flow diagram which summarizes the task of developing biological models. First, some sort of meaningful biological–climatological linkage is hypothesized (step 1). A simple example might be that the width of a ring is controlled by available soil moisture and is therefore proportional to the precipitation over a several-month period ending when ring growth is complete. Another example might be that ring width is proportional to the hours of physiological activity allowed by favorable plant temperatures; thus, the length of time when temperatures are above a critical value during the biologically active period would correlate with ring width. A more complex model is described in Figs. 5.8, 5.9, and 5.10.

The researcher hypothesizes a particular model and then examines

(a)
Development of biological model
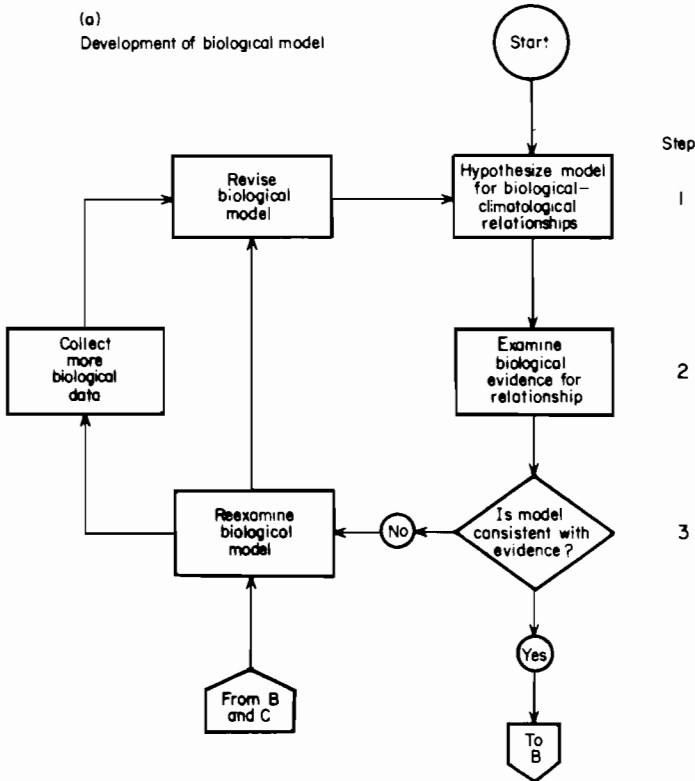
FIG. 7.1a

FIG. 7.1a, b, and c. Flowchart illustrating the steps necessary to obtain reliable calibrations between variations in ring widths with variations in climate. Steps are the same for both response functions and transfer functions except for the final use of the result.

the data, testing them against his experience or against evidence described in the literature of the field (Fig. 7.1a, steps 1, 2, 3). If there is insufficient biological information for the proposed relationship, he may collect more data before attempting to revise or test the model further; or if there are inconsistencies between the biological information and the model, he may reexamine the hypothesis, revise·the model, and proceed to test the new relationship (steps 2 and 3). When sufficient information is consistent with the˙ hypothesized biological model, he proceeds to calibration, part B of Fig. 7.1.
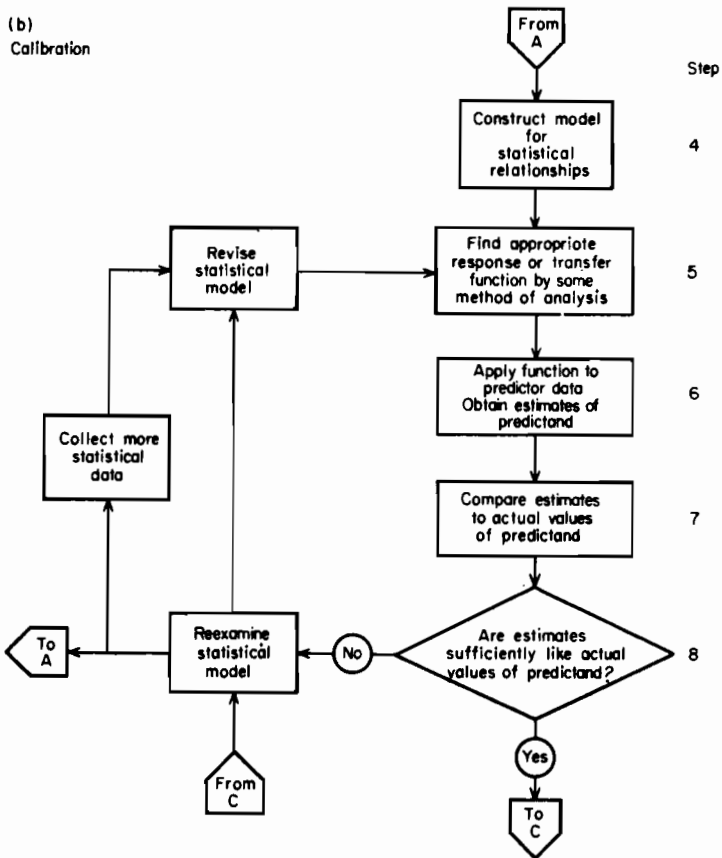
FIG. 7.1b

B. The Statistical Model

A statistical model is constructed which suitably portrays the general features of the biological one. Often this is accomplished by making simplifications and then by transforming the growth and climatic data in a manner that simulates the relationship. The transformations are compared to the actual data they are supposed to estimate (Fig. 7.1b, steps 4, 5, 6, 7). If the statistical model resembles the true biological relationship closely enough, the variation in computed values will closely resemble the variations in the observed values of the system output.

In the example using precipitation and growth, a linear relationship can be assumed between growth and total precipitation falling during the

(c)
Verification
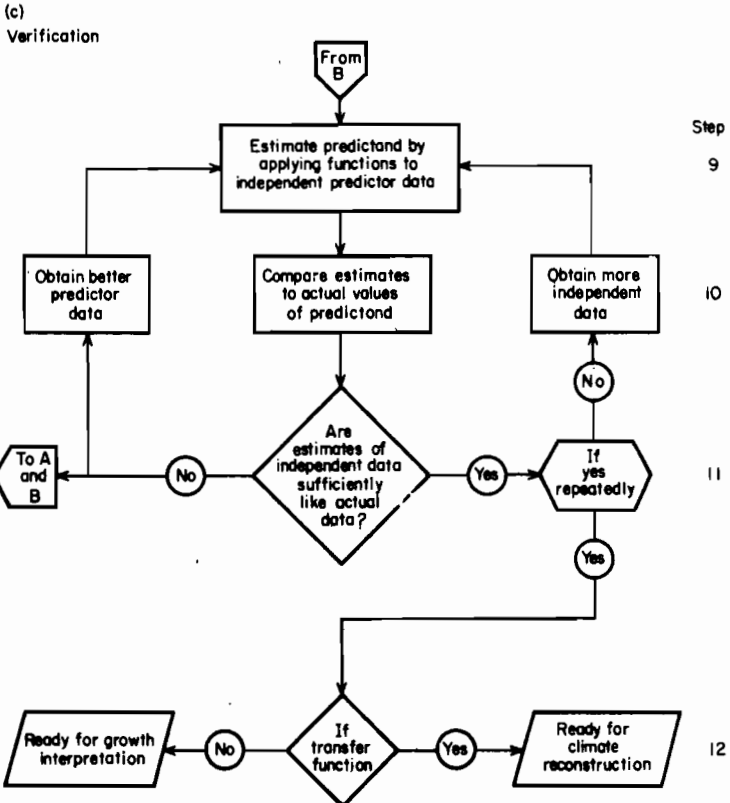
FIG. 7.1c

appropriate number of months. The amounts of monthly precipitation recorded at a nearby weather station are summed for each year and compared to yearly growth measurements. In the example using temperature records, the accumulated number of hours in each day above a chosen critical threshold are calculated and compared to the corresponding amounts of growth.

The calculated values represent the statistical estimates of growth. In these examples the climatic data are the *predictors*, and the actual growth the *predictand* (Fig. 7.1b, steps 6, 7, and 8). Some object to the term *prediction* because it implies the making of estimates forward in time. The term *retrodiction* has been proposed by Lawson (1972) to avoid this implication and is applied to statistical predictions involving estimates made backward in time. However, for the purposes of this volume the term

reconstruction appears more appropriate. The terms *predictors* and *estimates* are used in their statistical sense to refer to the statistical input data and the statistical output results, while the *predictand* will refer to the actual data to which the estimates are compared. The differences between the predictand and the estimates are the *residuals* representing the noise of the system and any signal not accounted for by the statistical relationship.

The weightings given to the predictor variables and the statistical manner in which these variables are combined to make the estimates is referred to as a *response function* or *transfer function* (Fig. 7.1b, step 5). The term *response function*, introduced in Chapter 5, refers to weights or coefficients used to estimate growth from variables of climate. The weights describe how the tree "responds" to climate. The term *transfer function* refers to a different set of weights used to estimate climate from ring-width values. Growth records are "transferred" into reconstructions of climate.

The estimated values are computed by applying the predictor data to the model coefficients (step 6), and the resulting values are compared with those of the predictand (Fig. 7.2). If the values that are estimated via a straight-line relationship differ from the actual values more at the low extremes than at the high extremes, one may conclude that a curvilinear model is more appropriate. In such cases converting the data to logarithms, powers, square roots, or reciprocals may lead to improved results. If estimates differ markedly for particular cases, close examination may suggest how the model may be altered to fit the divergent cases more adequately. A variety of models may be constructed which weight and transform the predictor variables differently.

A simple method for comparing the predictand and estimates is to plot the year-by-year values one above the other or to plot one as a function of the other using a horizontal and vertical axis to represent the abscissa and the ordinate (Fig. 7.2). In the latter, the data points fall along a straight line if the relationship is linear, and they fall along a curve if the relationship is curvilinear (see plots on the right of Fig. 7.3). For the best-fitting linear relationships the cluster of plotted points on such a graph

FIG. 7.2. After calibration the estimated values can be compared to actual data by plotting the two, one above the other, as a function of time (left) or plotting the actual value as the ordinate (vertical axis) and the estimated values as the abscissa (horizontal axis) (right). If there is a linear relationship between the two series, the plotted points fall along a diagonal line. The data represent actual and reconstructed flow of the Colorado River estimated for Lee's Ferry, Arizona, using ring-width chronologies from the upper Colorado River Basin. Note that the left graph has two ordinate scales. (Redrawn and reprinted by permission from "Long-term Streamflow Records Reconstructed from Tree Rings", Paper of the Laboratory of Tree-Ring Research at the University of Arizona, No. 5, by C. W. Stockton, Tucson: University of Arizona Press, © 1975.)
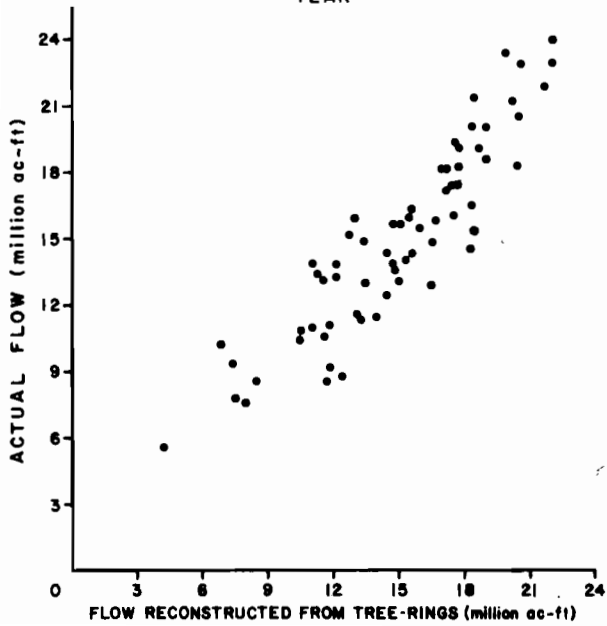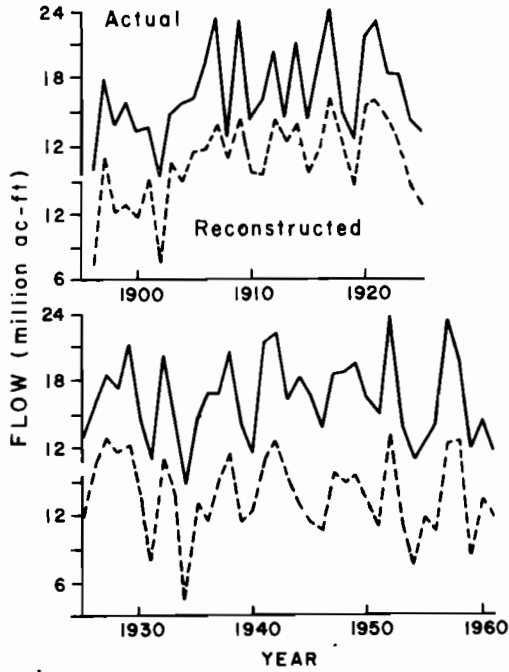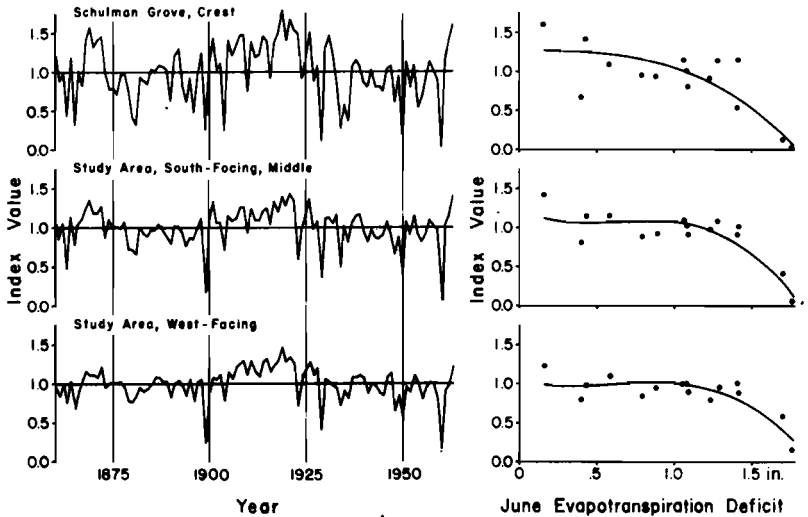
FIG. 7.3. Data from 1860 through 1963 from three ring-width chronologies for *Pinus longaeva* plotted against time on the left and against June evapotranspiration deficit on the right. In the latter only data for 1949–1963 are used. Growth is low for the years of most extreme evapotranspiration deficit, so that a curvilinear relationship results. The top chronology represents a limited site where the relationship is closest to being linear. The lower two are from more moist sites in which growth is limited by evapotranspiration deficit only for two extreme years. (Reprinted by permission from "Bristlecone Pine in the White Mountains of California, Growth and Ring-width Characteristics", Paper of the Laboratory of Tree-Ring Research at the University of Arizona, No. 4, by H. C. Fritts, Tucson: University of Arizona Press, © 1969.)

will resemble a narrow ellipse (Fig. 7.2). If the relationship is a weak one the data points will resemble a wider ellipse.

If the agreement between the estimates and the actual values is insufficient (Fig. 7.1b, step 8), the calibration is rejected and the statistical model, the biological model, or both, are reexamined. If the agreement is judged to be sufficient, the calibration is accepted and verification is then attempted (part C of Fig. 7.1).

C. *Verification*

Verification is obtained using data withheld from the calibration analysis. The coefficients of the calibration equation are applied to a set of predictor data for a different time period, for a different climatic station, or for different trees than those used to derive the calibration relationship. The data used in the original calibration are referred to as the *dependent set*,

while those used for verification are the *independent set*. Verification is established when the estimates derived from the independent predictor set resemble the independent predictand set. The operation may be repeated several times, depending upon what data are available for the independent check (Fig. 7.1c, step 11). If the relationship repeatedly holds up when testing against independent sets the calibration is accepted as appropriate for the particular relationship (step 12).

In the past there have been few dendroclimatic verifications attempted. However, verification is as important as the reconstruction, especially when complex calibration equations are utilized and the size of the dependent data set is limited. As the number of variables in the model approaches the number of observations used for calibration, the more likely it is that the calibration will degenerate into "number matching" rather than quantification of a real relationship. Such calibrations often provide good estimates of those observations of the predictand variable which are included in the calibration set, but fail miserably when tested on observations from an independent data set. Also, autocorrelation reduces the number of truly independent observations in most tree-ring chronologies (see Chapter 6), and thus the likelihood of obtaining a relationship purely by chance is greater than one would expect from a randomly distributed data set.

Repeated verification on independent data is the most rigorous statistical proof that a particular relationship is not the result of pure chance, and that the reconstructions do in fact represent conditions that actually did exist. Verification is more commonly applied to transfer functions than to response functions, because the primary objective for the former is to obtain valid reconstructions while for the latter it is to examine the structural relationships. However, in certain cases response function analysis can be applied to an independent data set. For example, Ashby and Fritts (1972) tested a particular hypothesis about climatic variation and air pollution by applying a response function to an independent climatic data set.

III. The Role of Statistics and Sample Size

Certain statistical tests and procedures are described in the following pages which can help the researcher to sort through possible growth–climatic relationships and to decide whether his calibrations are significantly different from those occurring by chance. However, these statistical methods should never be accepted blindly, as they cannot substitute for clear analytical thinking, nor should statistical methods be distrusted unduly to the extent that they are resorted to after all other

techniques have failed. Wallis and Roberts warn that, "He who accepts statistics indiscriminately will often be duped unnecessarily. But he who distrusts statistics indiscriminately will often be ignorant unnecessarily" (*Statistics: A New Approach.* Copyright, 1956, by the Free Press, a corporation). They go on to point out that "statistical interpretation depends not only on statistical ideas, but also on 'ordinary' clear thinking." They itemize several ways in which statistics can be misused. It is assumed that the reader is already familiar with such misuses, although it may be instructive to independently review examples described in their text. Included among other statistical texts which examine possible misuses concerning time-series analysis such as those dealing with tree-ring chronologies and climatic records are Mitchell *et al.* (1966) and Jenkins and Watts (1968).

Many statistical tests involve statements of probability and are therefore affected by sample size. The success or failure of a particular calibration can be expressed in terms of how much variance in the dependent variable is expressed by predictor variables and the probability that a particular result could have occurred solely by chance. Sometimes this is referred to as the "*goodness of fit*", percent *variance calibrated*, or the *variance reduced* in a particular analysis. The tests usually involve a comparison of how good the fit is relative to the *residual variance*, a term including any noise plus relationships not accounted for in the analysis.

The *goodness of fit* is dependent upon the strength of the signal in the data set as well as the adequacy of the model in describing the relationship. For example, growth data from a single tree may include a signal of climate amounting to only 25% of the total variance, the remaining 75% representing randomly varying statistical noise which results from nonclimatic site factors and internal differences in controlling factors within the tree. In such a case, the maximum possible goodness of fit using only the single tree data in a valid model would be no more than 25%.

If several trees are sampled and the mean growth is obtained for each year, the variations in the yearly averages are less than the variations of ring widths from any one individual, because some of the noise in individual tree variation is canceled in the averaging process (see Chapter 6). The variance of the signal which is the same in every tree is not lost by averaging, so the potential variance attributable to the signal grows with increasing sample size while the total variance of the mean chronology is reduced. This relationship is described as the *Law of Large Numbers* (see Roberts, 1960). It is expressed in dendroclimatological terms as follows: As the number of individual trees sampled in a mean chronology increases, and as the number of radii used from each

individual tree increases, the amount of variability due to noise in the mean chronology will decrease because there is less error in the means of the larger sample. At the same time there is an increase in the percentage of variation due to the climatic signal, the maximum possible "goodness of fit" attributable to climatic variation, and the ratio of signal to noise.

Another way to express the Law of Large Numbers is that the larger the sample, the less it is likely to differ from the statistical universe or from the true value for the mean. *True* is used here as the mean value of all trees and all radii in those trees available on a particular site. Of course, it is never possible to know the true value in this sense, so a portion of every chronology must include some statistical error or noise.

However, as was shown in Chapter 6, an increase in sample size from 5 to 10 trees will result in a far greater increase in signal and reduction in noise than an increase in sample size from 15 to 20 trees. Therefore, the relative improvement in a mean chronology resulting from adding one individual to the sample is greater the smaller the sample size.

No strict rule can be stated as to what is an adequate sample size for climatic analysis, since adequacy depends upon the degree of reliability one desires. Thus, the adequacy of 10 trees for a sample on arid sites is based upon a subjective decision that the error in such a chronology is tolerable for a particular study. However, as dendroclimatic analysis becomes more and more precise and is applied with greater frequency to trees in less extreme environments, it will probably become necessary to obtain larger sample sizes.

The investigator should evaluate the reliability that is necessary and then budget sufficient time and money for collecting and processing enough data to obtain that reliability. Analysis of variance described in Chapter 6 is especially useful for evaluating chronology reliability. If too few samples are available, it may be necessary to pool data from several sources or to resample before the results become statistically significant or before the error is reduced to acceptable limits. As a general rule, this writer prefers to collect too large a sample than to risk collecting too small a sample. This is especially important if it is difficult or expensive to reach the site. If the sample turns out to be excessively large, the longest records with the most ring-width sensitivity can be selected, which will maintain the greatest amount of signal per individual tree and preserve the maximum ratio of signal to noise.

IV. Degrees of Freedom and the Effective Sample Size

A truly random sample of *n* observations also has *n degrees of freedom*, that

is, any one value could vary without affecting the values of the others in the time series. However, if the mean is specified for the random sample, there is one less $(n-1)$ degree of freedom (see Barry and Perry, 1973). This is best seen by considering a sample of two observations. If the mean and one value of this sample are specified, the other value is automatically determined. In a case of 10 observations, if the mean and nine values are given, the 10th value is automatically determined. In these cases the last value is constrained or has no "freedom" because the mean has been specified. For example, if the mean is 1·0 and one observation has a value of 0·9, the other value must be 1·1. If the observation is 0·8, the other must be 1·2, etc. A population with both a given mean and a given standard deviation has $n-2$ degrees of freedom because the standard deviation adds another constraint to the population. In other words, a degree of freedom is lost for each statistic used to define a particular population. A response or transfer function with 10 regression coefficients defining a relationship would use up one degree of freedom for each of the 10 coefficients, one for the mean, and one for the standard deviation.

The number of degrees of freedom are also fewer than the number of observations whenever the values are not randomly distributed through time. That is, one value is dependent on, or to some extent constrained by, the other values. For example, the elements of a series which has been smoothed by a filter or which exhibits autoregression are only partly independent, because a certain amount of their variance is affected by the values of other observations. Consequently, the effective sample size of a time series of standardized ring widths is inversely related to the amount of significant autocorrelation or persistence that is present. All tests of significance must take into account this reduction in sample size. Mitchell et al. (1966) propose that the effective sample size (n') may be approximated by using the first-order autocorrelation as defined in Chapter 6. The calculation is performed as follows:

$$n' = n\frac{1-r_1}{1+r_1} \tag{7.1}$$

where n is the number of observations and r_1 is the first-order autocorrelation which always is assumed to be positive in the equation. For example, the n' for a series of 100 ring-width width indices with a first-order autocorrelation of 0·5 is

$$n' = 100\frac{1-0·5}{1+0·5} = 100\frac{0·5}{1·5} = 33 \tag{7.2}$$

This indicates that a 100-year-long ring-width chronology with a first-order autocorrelation of 0·5 instead of having 100 degrees of freedom, has

33 degrees of freedom or about one-third the number of the actual sample size. Any significance testing of this sample must be based upon a sample number of 33 even though there are 100 ring-width indices.

This method of calculating n' from r_1 is only an approximate one and assumes that r_1 is truly representative of the persistence and is relatively independent of other types of non-randomness that are present. It is not uncommon for dendroclimatological investigators to misjudge statistical significance by overlooking the reduction in degrees of freedom which results from persistence in the ring-width measurements.

If a time series with autocorrelation is smoothed by running means or moving averages, additional persistence is effectively introduced and there is further reduction in the effective sample size. For example, a two-year moving average applied to a set of 100 random data points reduces the effective number in the series to one-half, because only every second value in the moving average series is independent. Weighting by using a three-year moving average with weights 1–2–1 has approximately the same effect.

It is interesting to note that some early workers justified smoothing as a means of attaining higher correlations. It is possible that if some of them had realized how much of the increased correlation was due to the technique of smoothing, they might have been less enthusiastic about using such procedures. Smoothing before calibration with climate is no longer a recommended practice, except in cases where the trees themselves appear to be smoothing the effect of a particular year's climate over a large number of subsequent annual rings (LaMarche, 1974a; LaMarche and Stockton, 1974). In such cases the growth model used may include some sort of averaging of climatic data over a period of several years, but if such smoothing is used, the degrees of freedom for tests of significance must be adjusted appropriately.

V. Selecting the Statistical Model

The statistical model for a response function includes a number of weights associated with variables of monthly or seasonally averaged climatic data. Each statistical weight of the response function is usually multiplied by the appropriate climatic data, and the resulting products are summed to obtain the growth estimates. If the response function is a good one, the summed products will be large for years when climatic conditions were favorable and small when climatic conditions were unfavorable. For cases when climatic conditions are near average, the sum of the products will be near the growth average.

Common practice in the past has dictated a reliance on *a priori* models

using predictor variables such as monthly precipitation or temperature, the total annual water balance, the number of hours that temperatures are above a critical value, the number of days in the growing season, or some other expression of the growth-controlling conditions that can be derived from available data. Traditionally, a variety of models are tested until one or more are found which produce the best growth estimates. The success of such *a priori* analysis can depend in large part upon the cleverness and insights of the investigator as he constructs the models for analysis. If he has the wrong notions about the growth model, he may never obtain a satisfactory analysis except where he tries so many possibilities that one becomes statistically significant by chance.

This *a priori* approach to modeling has the advantage of being relatively easy to apply since it does not require statistical training and availability of a large computer. Many workers start out with simple *a priori* methods and gradually increase the complexity of their models until they obtain satisfactory growth estimates.

As was pointed out in Chapter 5, there can be a variety of possible linkages between the macroclimate and the growth-controlling factors. It was also shown that trees of varying species and of varying microhabitats can respond differently from one month to the next to the same climatic factors. During certain months growth can be directly correlated with a climatic factor, and during other months it can be inversely correlated with the same factor, depending upon which processes are most limiting to growth at that time. Models A, B, and C diagrammed in Figs. 5.8, 5.9, and 5.10 describe some of the most important biological and physical pathways by which the climatic factors of precipitation and temperature can be linked with plant processes to affect ring widths. The implication is that the more flexible multivariate methods are superior to *a priori* techniques because they let the data themselves determine the coefficients of the response function, and the investigator does not have to anticipate the particular weight given to each variable.

Nevertheless, a great deal of research has involved *a priori* modeling and the averaging of variables over periods of time. Climatic factors, such as precipitation, temperature, sunlight, humidity, and wind are utilized, or transformations are obtained to represent biological conditions such as water stress, evapotranspiration deficit, or number of days with temperatures above a particular threshold. The researcher may try various combinations of climatic data for summed intervals from one-half month to a period of 12 or more months to see which best fits the tree response. The following sections describe a number of examples found in the literature which utilize different variables and apply various degrees of *a priori* modeling.

VI. The Diversity in Variable Selection

The interval of time chosen in *a priori* modeling studies involves a variety of periods throughout the year and a variety of climatic factors. Glock (1950), in a study of arid-site trees, chose the following monthly intervals over which the precipitation was summed:

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

Estes (1970), in a study of oak and pine in the central Missouri valley, used a variety of periods within the interval from April through August from which he averaged precipitation. In a study of *Pinus longaeva*, Fritts (1969) totaled precipitation and averaged temperatures for July–November, December–March, and April–June. Tryon and True (1958), in a study on *Quercus* in West Virginia, used precipitation periods as follows:

Current growing season: May–June, May–July, May–August
Preceding season: July–August, July–September

Slåstad (1957), working in Norway, used both precipitation and temperature with annual values calculated for September 1 through August 31. Seasonal values included the periods September 1 through April 30, September 1 through May 31, May 1 through July 31, May 1 through June 30, and June 1 through July 31. Hustich (1945) used temperature, precipitation, and cloudiness for the three-month interval of June through August and for single months within that period. Eklund (1957) utilized half-monthly units from May 1 through August 31 and calculated mean temperatures and precipitation for various intervals within this period. He also calculated the number of days when temperatures were above a chosen threshold and compared these to growth. Schulman (1956) chose precipitation data for 16 intervals from a duration of three months to two years, all representing a continuous time sequence.

Sundry factors have been averaged over a variety of other interesting time intervals, presumably to represent ecologically sound parameters. For example, when working on ring widths of *Pinus halepensis* in southern France, Serre *et al.* (1966) calculated the following variables which were used in subsequent analysis:

(1) The sequence number of the year from 1 to 21.

(2) The number of days after January 1 when the dry summer period started.

(3) The number of days after January 1 when the dry summer period ended

(4) The number of days of frost from November to March.

(5) The last day of frost numbered from January 1.

(6) The total precipitation of the dry period.

(7) The total precipitation of the wet period.

(8) The exposure of the tree.

(9) The exposure of the cores with regard to slope.

(10) The number of the tree.

These 10 variables were used to estimate the natural logarithm of the width of each ring in each radius of each tree. Variables 1, 8, 9, and 10 were required to assess the nonclimatic variability in their sample.

Jonsson (1969) describes a very complex system for computing and representing environmental data which were thought to control growth: The range of a given climatic factor (temperature, light, or soil moisture) was divided into several classes, and the number of days falling into each class was tabulated. Variations among seasons were analyzed as different growth phases defined as a function of the seasonal regime of temperature.

LaMarche and Fritts (1971b), in their study of *Pinus cembra* in the Alps, relate ring-width variations to percentages of advancing glaciers which were known to be associated with growing-season temperatures. Stockton and Fritts (1973) associated the growth of *Picea glauca* located on natural levees along stream channels to fluctuations in levels of a nearby lake, which in turn were related to flooding at the tree sites.

Some of the variables used in analyses are soil–water deficits (Smith and Wilsie, 1961), calculated monthly soil–moisture storage and monthly evapotranspiration deficits (Fritts, 1962b, 1969), evaporation stress and sunshine (Schulman and Bryson, 1965), and moisture surplus (Scott, 1972).

Sometimes the growth data are transformed into logarithms (Serre *et al.*, 1966; Jonsson, 1969). Stockton and Fritts (1971b) used nine equally probable classes to subdivide frequencies of occurrence of growth. Serre (1973) uses frequency of occurrence of arbitrary growth classes. Sometimes smoothing operations are performed beforehand on ring-width data. Glock (1950), Keen (1937), and Schulman (1947, 1956) employed such a scheme, using three-year means in which the central

year was weighted twice as much as the end weights. Fahn *et al.* (1963) used 21-year running means.

Although the growth data usually represent the means of many trees, some workers have analyzed ring widths in individual trees. For example, Phipps (1972) listed extremes of growth for each tree and compared the occurrences with extremes in climate. Mitchell (1967) used sophisticated multivariate statistical techniques on chronologies from single trees that were not on climatic stress sites and, as might be expected, he obtained so much variability that results were difficult to interpret.

While many of these studies have used values for climatic factors summed over intervals ranging from half-months to one or more years, a large number of the results have turned out to be inconclusive because the sums do not satisfactorily portray the way the tree responds to climatic factors. High values of factors may be limiting in certain months, while low values may be limiting in other months. Thus, when climatic data are summarized for intervals which include both direct and inverse relationships, the two effects cancel one another and no statistical relationship is evident. In reality, the climatic factor was important but acted differently for different times in the year. In other cases the relationship was nonlinear, or the effects varied in their relative importance throughout the year. Because of many complicating factors of the climate–growth system, dendroclimatic literature is full of conflicting reports as well as genuine disagreements among investigators. (See Glock, 1941, and Agerter and Glock, 1965.)

VII. Testing the Association between Variables

A. The Sign Test

There are a number of ways to test whether or not sufficient similarity exists between the actual and estimated data. A simple and nonparametric procedure is to count the number of agreements and disagreements in the two series and to apply a measure of association known as a *sign test*.

One way to employ the test is to tabulate the direction of change in ring widths and climate from one year to the next (the first difference; see Chapter 6) as either an increase (+) or a decrease (−). No consideration is given to the magnitude of the change. Large differences receive the same weight as small ones. A second way to employ the test is to use the signs of departures from the sample mean. As in the first differences, small departures from the mean are weighted the same as large ones, and the similarity or dissimilarity of these signs is tested. The application

involving the direction of change (signs of the first difference) is relatively unaffected by trends and persistence and can be applied to un-standardized ring widths.

All cases in which the changes or departures in growth and climate are the same sign (either $+$ or $-$) are tabulated as similar. Those cases in which the changes or departures are in opposite directions ($+$ and $-$, or $-$ and $+$) are tabulated as dissimilar. Where no difference in either the tree-ring or climatic data occurs, the case is tabulated as 0 and it is eliminated from the particular comparison. If there is no association between the two variables, about half the occurrences will be similar and half dissimilar. The hypothesis that there is a significant association is accepted if the number of similarities is significantly larger than the number of dissimilarities.

TABLE 7.1 Number of agreements or disagreements in signs[a] required to obtain two significance levels[b]

Total number of cases (N)	Level of significance[c] 0·95	0·99	Total number of cases (N)	Level of significance 0·95	0·99
6	0	–	31	9	7
7	0	–	32	9	8
8	0	0	33	10	8
9	1	0	34	10	9
10	1	0	35	11	9
11	1	0	36	11	9
12	2	1	37	12	10
13	2	1	38	12	10
14	2	1	39	12	11
15	3	2	40	13	11
16	3	2	41	13	11
17	4	2	42	14	12
18	4	3	43	14	12
19	4	3	44	15	13
20	5	3	45	15	13
21	5	4	46	15	13
22	5	4	47	16	14
23	6	4	48	16	14
24	6	5	49	17	15
25	7	5	50	17	15
26	7	6	55	19	17
27	7	6	60	21	19
28	8	6	65	24	21
29	8	7	70	26	23
30	9	7	75	28	25

[a]Whichever is smaller. [b]Using two-tailed test, adapted from Tate and Clelland (1957). [c]When $N > 50$, the number required is $(N-1-z\sqrt{N})/2$ where z is 1·96 and 2·58 at the 0·95 and 0·99 levels respectively.

One procedure for testing the significance of such a relationship is shown in Table 7.I (Siegel, 1956; Tate and Clelland, 1957). The number of agreements or disagreements necessary to obtain significance is presented as a function of the total number of cases. It can be seen from the table that in the case of 10 observations all occurrences must fall into one of the two classes for the relationship to be significant at the 0·99 probability level, while all but one occurrence must fall in a particular class to be significant at the 0·95 probability level. For a sample size of 20, one class must include three or fewer cases to be significant at the 0·99 probability level and five or fewer cases to be significant at the 0·95 probability level. In other applications the critical limits may be derived from comparing many cases of improperly matched data sets (Eckstein and Bauch, 1969). The advantages of the sign test are that (1) it is not affected by extremely anomalous data, and (2) it does not require heavy computation. The sign test does not provide a rigorous analysis of significance because it does not take into account the degree of correspondence among individual cases.

The sign test has been used most extensively in European works (Ermich, 1955) where ring widths are converted to logarithms, and decreasing ring width due to tree age is present in the data. Some early North American studies using the signs of the first differences were undertaken by Friesner and Friesner (1941), Friesner (1950), Miller (1950a, b), Lyon (1936, 1943), and McInteer (1947). With the accessibility of computing facilities and programs involving rigorous statistical procedures, analysis by means of the sign test will be used mostly for preliminary probing, early model development, and for independent verification tests. In the last case the sign test is useful in that it measures the direction of the reconstruction either as a first difference or a departure from the calibration mean, without being unduly affected when the climatic reconstruction is extreme or incorrect.

B. Product Means

Another statistic, referred to as *product mean*, takes into account both the sign and magnitude of the departure from the calibration average. It is computed from the product of the actual and estimated yearly departures from the mean value, with the positive and negative products summed separately. If the departure sign is correctly estimated, the product is positive; if the sign is incorrectly estimated, the product is negative. For random guessing the means of the positive and negative products (neglecting their signs) have approximately the same values and for correct reconstruction the mean for the positive products is larger. The

difference between the mean of the positive products, m_1, and the mean of the negative products, m_2, (disregarding the sign) is tested with the t statistic as

$$t = \frac{m_1 - m_2}{\sqrt{\dfrac{s_1^{\,2}}{n_1} + \dfrac{s_2^{\,2}}{n_2}}} \tag{7.3}$$

where $s_1^{\,2}$ and $s_2^{\,2}$ are the corresponding sample variances (which may be unequal), and n_1 and n_2 are the number of items in each sum. If the value of t is higher than the expected value at the appropriate confidence level, then the difference is considered to be statistically significant. (See Parzen, 1967; Freund, 1962; Snedecor, 1956; or other general statistics texts.) A significantly larger mean positive product indicates a tendency for both actual and estimated departures from the average value to be large when the sign is correctly estimated and to be small when the sign is incorrectly estimated. In the latter case approximately average conditions both occurred and were estimated, so the reconstruction can be regarded as essentially correct even though its sign was incorrect.

C. Simple Correlation and Reduction of Error

The correlation coefficient is the most common method for measuring the association between tree rings and climate (Keen, 1937; Weakly, 1943; Hustich and Elfving, 1944; Hustich, 1945; Schulman, 1947, 1956; Holmsgaard, 1955; Eklund, 1957; Slåstad, 1957; Tryon *et al.*, 1957; Tryon and True, 1958; Daubenmire, 1960; Gagnon, 1961; Sirén, 1961; Bray and Struik, 1963; Serre *et al.*, 1966; McGinnies, 1967; Estes, 1970; Parker and Henoch, 1971; Scott, 1972). The computations of this parameter are given in Equation 6.4. The numerator of the equation is the cross product or covariance, a term which takes into account not only the number of cases of agreement and disagreement between variables, but also the relative degree of correspondence. The product emphasizes large deviations from the mean relative to small ones.

Glock (1942) describes what he refers to as the "trend method" of obtaining correlation, which can be used on ring-width data containing growth trends. It incorporates the idea of a sign test of year-to-year differences, taking into account the degree as well as the direction of the correspondence. The first differences are obtained from one value to the next, after which the sums and cross products of the differences are obtained. Although some early workers used this method, it is no better than standard statistics which can be readily tested for significance.

A statistic, referred to as the *Reduction in Error* (R. E.), is described by

Lorenz (1956) and can be applied to independent data to measure association between a series of actual values and their estimates. If it is applied to the dependent data set, the result is equivalent to the square of the correlation coefficient and measures the percent variance calibrated by the relationship.

The computations are as follows

$$RE = 1 - SSR/SSM \qquad (7.4)$$

where SSR is the sum of the squares of the differences between actual data and the statistical estimates (the residuals) and SSM is the sum of the squares of the differences of the actual data from the mean of the dependent data set used for calibration. The theoretical limits for the values of this statistic range from a maximum of $+1$, which indicates perfect agreement to minus infinity. A minus value is treated as zero and indicates no agreement. A major disadvantage of this statistic is that one extremely bad estimate can completely offset the effect of several very good estimates. The R. E. statistic provides a rigorous test of association on independent data and any positive value can be considered as encouraging. Statistical tests for positive values of the R. E. statistic are the same as for the square of the correlation coefficient. The interested reader should consult statistics texts for a more thorough discussion of the correlation coefficient, its interpretations, uses, and limitations (Ezekiel and Fox, 1959; Freund, 1962; Baggaley, 1964).

D. Conditional Probability

A somewhat specialized approach to calibration and the measurement of association between ring widths and climate involves the utilization of contingency tables to assess agreement or disagreement between two data sets. This is accomplished by dividing the tree-ring and climatic data sets into several *equally probable classes* (that is, groups of equal size) and by estimating joint occurrence using chi square (χ^2) and coefficient of contingency statistics. Data from Arizona described by Stockton and Fritts (1971b) offer a good example of this application and are summarized in this section.

The climatic data used in the example are seasonally averaged temperatures and precipitation where each of the four seasons represents three months beginning with winter as December–February, and so forth. If the data are close to a normal distribution, the averages for each year for each season can be placed into three equally probable classes. This is accomplished by calculating the mean and standard deviations of the climatic data and examining a table of the cumulative normal

frequency distribution published in most statistical texts to select the value (expressed in standard deviation units) which divides the normal curve into the desired classes. In the above case a distance of 0·43 standard deviation on each side of the mean separates the normal curve into the three desired classes where one-third of the data classed as near normal are within ±0·43 standard deviation from the mean, one-third of the data classed as below normal are less than −0·43 standard deviation and one-third classed as above normal are greater than +0·43 standard deviation from the sample mean. Nine climatic classes can be obtained by combining the three precipitation and three temperature classes (Fig. 7.4). The data are treated separately for each of four seasons, so that analyses include both individual seasons and their combinations.
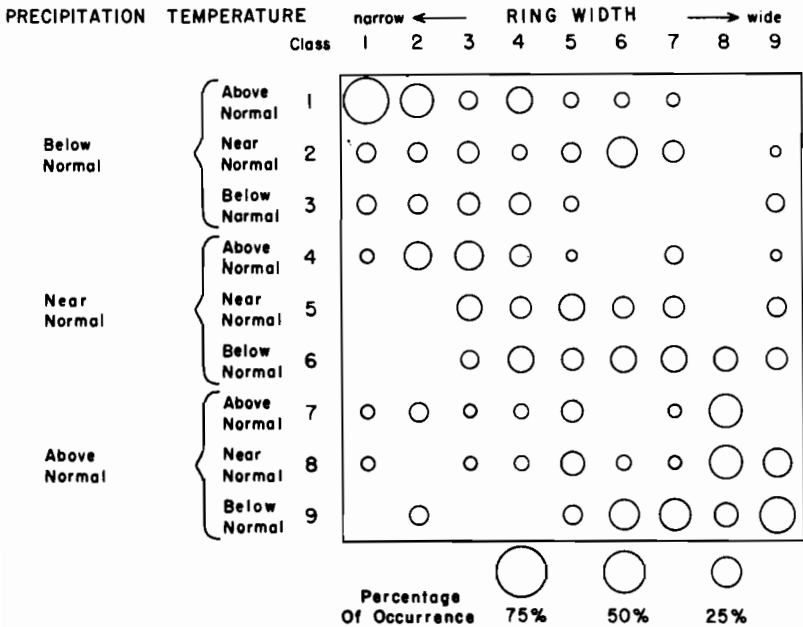
FIG. 7.4. The percentage of occurrences, represented diagrammatically by the size of the circles shown in each cell, between nine combined precipitation and temperature classes shown on the left and nine ring-width classes shown at the top. Data are pooled for autumn, winter, and spring seasons. The larger circles clustered along the diagonal of the table indicate a linkage of below-normal precipitation and above-normal temperature with narrow rings, and above-normal precipitation and below-normal temperatures with wide rings. The circle sizes express the percentages of occurrence of each climate class given the particular ring-width class indicated at the top of each column. (Stockton and Fritts, 1971b)

Normally distributed ring-width indices can be placed into equally probable classes by averaging all data from several sites and transforming them to *standard normal variates* (sometimes called *normalized data*) (z_t) in the following manner:

$$z_t = \frac{x_t - m_x}{s_x} \tag{7.5}$$

where m_x is the mean and s_x the standard deviation of the mean ring-width indices (x_t) in this example for the calibration period 1900–1957 (Equations 6.1, 6.2). These standard variates of ring-width data can then be separated into nine equally probable classes (Table 7.II) as derived from the cumulative normal frequency distribution. The classes range from 1 (very narrow rings) to 9 (very wide rings).

TABLE 7.II Upper class limits used to separate normalized
data into 9 equally probable classes[a]

Class Number	Value $\leq$[b]
1	−1·2200
2	−0·7643
3	−0·4306
4	−0·1395
5	0·1395
6	0·4306
7	0·7643
8	1·2200
9	∞

[a]From Stockton and Fritts (1971b). [b]Units are expressed as standard normal variates (Equation 7.5).

The data for each climatic class for each season were matched with the corresponding ring-width classes, and the number of joint occurrences was tabulated for (a) five seasons including the summer prior to and the summer concurrent with the growing season, (b) four seasons including the summer, autumn, winter, and spring prior to the growing season, (c) four seasons including the autumn, winter, and spring prior to growth as well as the summer concurrent with the growth season, and (d) three seasons including the autumn, winter, and spring (Table 7.III). The numbers of occurrences in each class are entered in the various *cells* or boxes of a contingency table, and the percentages or joint occurrences between tree-ring and climatic classes are obtained (Fig. 7.4, Table 7.IV).

Of interest is the hypothesis that the percentage occurrences are more frequent in certain classes and less frequent in others than would be

TABLE 7.III Contingency analysis of ring-width indices and Arizona climate[a]

Seasons	Computed χ^2 [b]	Occurrences	Coefficient of contingency[c]
Previous summer climate	65·8	58	---
Autumn climate	72·9	58	---
Winter climate	100·0	58	0·80
Spring climate	74·2	58	0·75
Concurrent summer climate	6·3	58	---
Five seasons combined	132·9	290	0·56
Four seasons combined using prior summer	132·4	232	0·60
Four seasons combined using concurrent summer	123·1	232	0·59
Three seasons combined without summers	124·7	174	0·64

[a]From Stockton and Fritts (1971b). [b]The theoretical χ^2 at 95 percent confidence limit for 64 degrees of freedom is 73·6. [c]Only seasons with significant chi square values above 73·6 are calculated.

expected by pure chance given no suppositions as to which classes are involved. A test of this hypothesis is accomplished using the occurrences in the contingency table similarly portrayed in Fig. 7.4 and Table 7.IV. A chi square (χ^2), statistic is calculated for joint occurrences of the nine climatic classes with the nine ring-width classes as follows:

$$\chi^2 = \sum^{kr} \frac{(f_{mn} - h_{mn})^2}{h_{mn}} \qquad (7.6)$$

where the term f_{mn} is the observed number of occurrences in a particular cell of the table $(k_m r_n)$ representing ring-width class k_m and climatic class r_n. The term h_{mn} is the hypothetical frequency computed as

$$h_{mn} = k_m \frac{r_n}{\Sigma_r} \qquad (7.7)$$

where k_m is the number of occurrences in all nine climatic classes within a particular ring-width class, r_n is the occurrence of all nine ring-width classes within a particular climatic class, and Σ_r is the total of all cells for all classes.

If the computed statistic exceeds the 95% confidence level of the chi-square distribution, it may be concluded that particular climatic classes are significantly linked with particular ring-width classes (Table 7.III), and statements regarding probabilities of occurrence of climatic classes given particular ring-width classes may be obtained from them (Table 7.IV).

TABLE 7.IV Conditional probability for each climatic class for previous summer, autumn, winter, and spring given a ring-width class[a]

Climatic class	Ring-width class								
	1	2	3	4	5	6	7	8	9
1	0·583	0·292	0·179	0·200	0·100	0·050	0·036	0·125	0·000
2	0·083	0·125	0·179	0·050	0·100	0·200	0·143	0·000	0·025
3	0·083	0·083	0·143	0·100	0·075	0·050	0·036	0·J00	0·075
4	0·042	0·250	0·179	0·100	0·075	0·000	0·107	0·000	0·025
5	0·042	0·083	0·179	0·150	0·225	0·150	0·107	0·000	0·075
6	0·042	0·000	0·071	0·200	0·100	0·150	0·179	0·125	0·150
7	0·042	0·083	0·036	0·050	0·100	0·000	0·036	0·250	0·025
8	0·042	0·000	0·036	0·100	0·150	0·100	0·107	0·250	0·200
9	0·042	U·083	0·000	0·050	0·075	0·300	0·250	0·250	0·425

[a]Using the joint occurrence of ring-width and seasonal climatic classes from Stockton and Fritts ('971b).

The coefficient of contingency (C), which measures the degree of linkage or dependence, can be calculated in the following manner:

$$C = \left[\frac{\chi^2}{\chi^2 + \Sigma_r} \right]^{\frac{1}{2}} \tag{7.8}$$

where χ^2 is the chi square computed from Equation 7.6 and Σ_r is the total of all cells for all classes as used in Equation 7.7.

The value of C (Table 7.III) can be calculated only if the chi-square value is significant. The higher the value, the greater the association between the two classes.

The highest coefficient of contingency for a single season as shown in Table 7.III was for ring width and winter climate (0·80). The only other significant single-season relationship was for ring width and spring climate (0·75). Of the calculations using pooled data, the combination of autumn, winter, and spring gave the highest coefficient. The values of the coefficient were lower when summer was combined with autumn, winter, and spring climate. This result is consistent with the statement made in earlier chapters that the trees respond in this semiarid area more consistently with the autumn, winter, and spring climate than with the summer climate.

The occurrences within the individual cells or boxes of the contingency table are converted to percentages by dividing the number of occurrences in each cell by the sum of occurrences for that particular column representing a ring-width class (Fig. 7.4, Table 7.IV). If there had been no relationship between tree growth and climate, the percentages would be similar in all cells of the table, and all circles in Figure 7.4 would be

approximately the same size; that is, each ring-width class would have all climatic classes associated with it. However, there was a direct relationship between the two data sets so that the cells with highest frequency of occurrence (the largest circles and largest probabilities) occur along the diagonal line extending from cell 1,1 to cell 9,9. The climate class most likely to be associated with a narrow ring is the dry–warm class while that most likely to be associated with a wide ring is the cool–moist class.

A major disadvantage of the conditional probability technique is that the data of different seasons can be pooled only if the effects of the climatic factors are the same. If they are different the significance of the pooled data is less than for the individual seasons. Two advantages of the technique are (1) the relationship between variables does not have to be linear; that is, the largest values need not be in the cells along the diagonals of the table, and (2) it is possible to make statements about the probability of climatic classes in the past, given the occurrence in a particular ring-width class. The class is read from the normalized values of tree growth (Fig. 7.5) for a particular year in the past as defined by the dashed horizontal lines. The column in Table 7.III for the appropriate ring-width class is entered, and the conditional probabilities for each climatic class given the particular tree-ring class is read from the table.

For example, the ring width for 1872 shown in Fig. 7.5 is narrow and falls in class 1. Entering Table 7.IV under ring-width class 1, the probabilities for an occurrence of climatic classes 1, 2, . . .,9 for the climate of summer, autumn, winter, or spring seasons are $0 \cdot 583, 0 \cdot 083, \ldots, 0 \cdot 042$. These data are interpreted in the following manner: Any one of the four seasons for that year has a $0 \cdot 583$ probability of being in climatic class 1 (below normal precipitation and above normal temperature), a $0 \cdot 083$ probability of being in climatic class 2, and a $0 \cdot 042$ probability of being in climatic class 4.

The probabilities may be combined for several classes to make statements about precipitation, or temperature alone, or statements like the following: The probability that climate for 1872 was in either climatic class 1 or 2 is $0 \cdot 583 + 0 \cdot 083$, or $0 \cdot 666$, and the probability that it was in a class 3 or higher is $1 - 0 \cdot 666$, or $0 \cdot 334$. Also, the probability of occurrence for a particular climatic class during a particular interval of time may be calculated from the table using the growth classes for each year of the interval as follows:

$$Pr(E_n) = \frac{N_n}{\Sigma N} \qquad (7.9)$$

where $Pr(E_n)$ is the probability of occurrence for one of the nine ring-
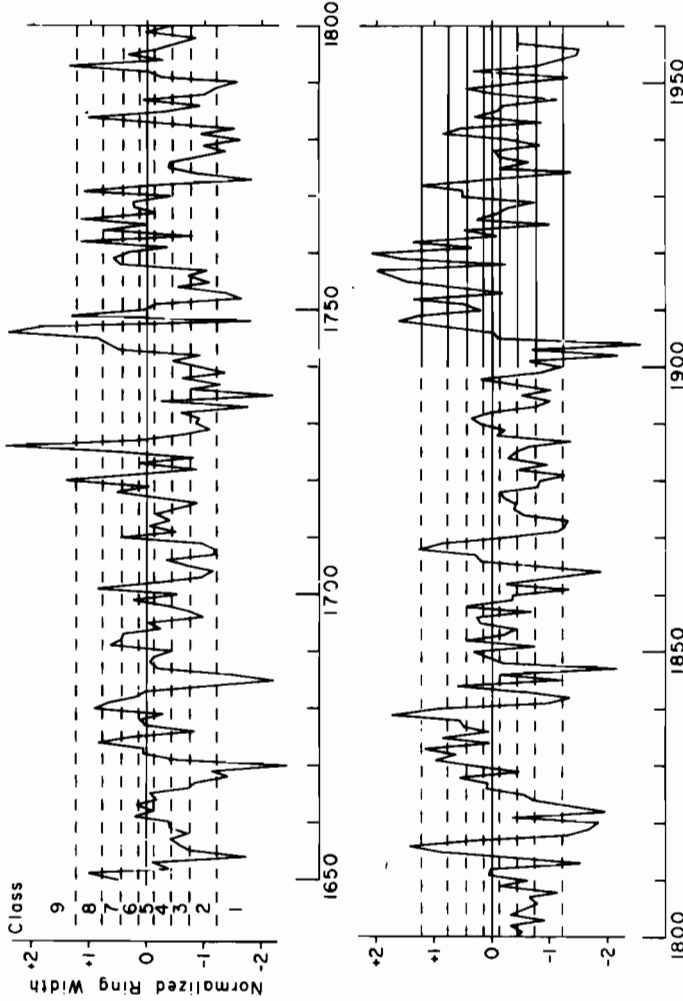
FIG. 7.5. Yearly ring-width values for the state of Arizona are used to make statements of conditional probability concerning climate. The data are the average of four area chronologies expressed as standard normal variates (Equation 7.5). The equally probable ring-width class limits for the calibration period are shown as solid horizontal lines and these are extrapolated for the earlier record as dashed lines. Statements concerning past climate are obtained by identifying the tree-ring class for a year in the earlier record, finding the appropriate column for the growth class in Table 7.III, and reading the conditional probabilities for the climate classes from the rows in the column. (Stockton and Fritts, 1971b)

width classes occurring within the interval which must be a period substantially less than the entire length of record. N_n is the number of yearly occurrences of the ring-width class being considered, and ΣN is the total number of occurrences (years) within the time interval being considered.

Applying the tree-ring data in Fig. 7.5 for a decade of low growth such as 1730–1739 to Equation 7.9 using the data in Table 7.IV, the probabilities for occurrences for class 1, 2, 3, . . ., 9 during the decade are calculated to be 0·365, 0·117, 0·103, . . ., 0·038. The probability of below-normal precipitation for any of the four seasons during these 10 years is the sum of the probability of the first three classes, or 0·585. The ring-width class for a high-growth decade indicates a probability of occurrence for a season of above normal precipitation such as 1831–1840 to be 0·547. It can be seen from comparing these results and from examining the data in Table 7.IV that in general there is more certainty about drought years than there is about wet years. This observation is consistent with statements made in Chapter 6 about the greater reliability of narrow rings than wide rings from arid-site trees as estimators of climate. For further discussion of the technique refer to Spiegel (1961), Li (1964), and Stockton and Fritts (1971b). Attention will now be directed to techniques for handling limiting effects of factors that vary from one month to the next throughout the year.

VIII. Multivariate Techniques

As shown by the growth models in Chapter 5, ring-width variations are rarely caused by single limiting factors, though one can be markedly more important than others, and a single factor can vary in its importance at different times throughout the year. For example, the relative effect on growth of a particular amount of precipitation in winter is usually different from the effect of the same amount in summer because the two seasons offer different limiting environmental conditions and there are different growth-controlling processes in operation (see Chapters 2, 3, and 4).

Also, the effect of a climatic factor such as precipitation may be conditioned by other climatic factors occurring during the year. For example, temperature determines whether precipitation falls as rain or snow, and temperature governs the rate at which water evaporates from the soil. Therefore, the tree-growth and climatic relationship is best represented as a system with different variables entering into the relationship. In fact, there are so many possibilities for variations in limiting factors, that it is surprising that a priori modeling by summing one

variable during different periods of time has worked at all. A more logical but complex approach would be to include many variables as growth predictors, to utilize statistical techniques which ascertain the variables that are most important, and to scale the variables in a way to obtain the best results.

A straightforward approach to the problem of analyzing such a multiple variable system is to calculate simple correlations (Equation 6.4) between several variables and ring widths and to select all variables with which growth is significantly correlated as predictors (Hustich and Elfving, 1944; Hustich, 1945; Eklund, 1957; Tryon *et al.*, 1957; Elling, 1966; Serre *et al.* 1966; Julian and Fritts, 1968; Scott, 1972; and many others). The use of simple correlation has one major limitation, however. Variables of the climatic system are usually highly correlated with each other as well as with growth. Positive intercorrelation within the climatic system can inflate the simple correlations between some noncausal factors and growth, and negative intercorrelation can deflate the simple correlation between important causal factors and growth.

One way to deal with this difference in intercorrelation is to use a statistical technique referred to as *multiple regression* or *multiple correlation* (Hustich and Elfving, 1944; Hustich, 1945; Holmsgaard, 1955; Eklund, 1957; Tryon *et al.*, 1957; Sirén, 1961; Fritts, 1962a, 1962b, 1965, 1969; Schulman and Bryson, 1965; Elling, 1966; Serre *et al.*, 1966; Julian and Fritts, 1968; Scott, 1972).

A. Multiple Regression and Correlation

Multiple regression and correlation employs statistical procedures to resolve variable intercorrelation so that one equation is obtained expressing the relative effect of each variable upon the amount of growth. The statistical model assumes that the variations in some predictands, which in this case are growth, are related in a linear fashion to variations in several predictors, which in this case are the intercorrelated variables of climate. The statistical equation is

$$\hat{y}_t = b_o + b_1 x_{1t} + b_2 x_{2t} \cdots b_m x_{mt} \qquad (7.10)$$

where $\hat{y}_t$ is the estimate of the predictand, which varies each year (t) depending upon the values of the predictors; b_1 through b_m are regression *coefficients*, sometimes called partial regression coefficients, associated with each of the m predictor variables x_1 through x_m, and b_o scales the equation to the mean of the predictand. The calculation of the multiple regression equation is a complex statistical procedure derived from the statistical theory of *least squares* which is beyond the scope of this text. The

interested reader may consult Ezekiel and Fox (1959), Draper and Smith (1966), Bendat and Piersol (1966), Simpson *et al.* (1960), or some other standard statistical text.

The effect of each variable on growth is scaled by the coefficient and the scaled values are added to obtain the growth estimate. Significance tests assume that the variables are distributed normally. The partial regression coefficients express the relative effect of each variable on the predictand, and the coefficients can be tested using standard errors that are associated with them. Also, a multiple correlation coefficient is obtained which is analogous to the simple correlation in that it is a measure of the linear statistical relationship that exists between the set of predictors and the predictand. The percentage of variance in the dependent variable explained (accounted for or reduced) by the equation is calculated by squaring the multiple correlation and multiplying by 100. The multiple correlation generally increases with the addition of a predictor variable, partly because it may reduce additional variance and partly because an additional degree of freedom is lost.

Multiple regression has been used most often to describe, test, and measure those climatic variables that are related to variations in growth. Only recently has it been applied to climatic reconstruction or growth estimation. For example, Eklund (1957) calculated an index of ring widths for *Picea excelsa* in northern Sweden with reference to the mean growth for 1900–1944. The following regression equation was obtained by selecting only those coefficients that were statistically significant:

$$\hat{y}_t = 99{\cdot}41 + 0{\cdot}9188x_1 - 3{\cdot}129x_2 - 2{\cdot}405x_3 - 0{\cdot}4282x_4 \quad (7.11)$$

Variable x_1 was the number of days during May 16 through July 31 for year t in which the maximum temperature reached at least 16 C. Variable x_2 was cone yield, expressed in cone point numbers for the year t, and variable x_3 is the cone yield expressed in cone points for the year $t-1$. Variable x_4 is the accumulated daily maximum temperatures for the period July 16 through August 31 of year $t-1$. For simplicity, the subscripts t for the predictor variables are not listed. Precipitation was included in early analyses, but the regression coefficient for precipitation did not significantly differ from zero.

It may be inferred from these results that the widest rings were formed when (1) maximum temperatures for many days during the period from May 16 through July 31 were equal to or greater than 16 C, (2) when the cone yield of both the current season and the previous season were low, and (3) when the accumulated daily maximum temperature for the period July 16 through August 31 of the prior year was low.

Another example is from the work of Serre *et al.* (1966) in which the following equation for estimating the logarithm of ring width of *Pinus halepensis* was obtained:

$$\hat{y}_t = 3 \cdot 070 - 0 \cdot 5965x_1 - 0 \cdot 01811x_4 + 0 \cdot 00208x_6 - 0 \cdot 00018x_7 \quad (7.12)$$
$$- 0 \cdot 23392x_9 + 0 \cdot 06936x_{10}$$

where x_1 through x_{10} are the variables listed in section VI of this chapter. The interpretation of these results is listed in the order of the variables entered into the equation as follows: (1) Each successive ring width decreases at an average of 64 microns for each year; (2) the width of the ring decreases by 19 microns for each day of frost during November through March; (3) the width of the ring increases by 30 microns for each 10mm of rain falling during the specified dry season; (4) the width of the ring increases by 5 microns for each 10mm of rain falling during the winter wet period; (5) the rings in the upslope sides of the stem are on average 231 microns wider than those of the downslope sides; and (6) ring widths vary from one tree to the next by an average of 79 microns.

Schulman and Bryson (1965) obtained equations for predicting ring widths of eight deciduous species growing in Wisconsin, the largest sample being from *Quercus rubra*. The equation for estimating ring-width ($\hat{y}_t$) was

$$\hat{y}_t = -0 \cdot 01967x_{18} + 0 \cdot 003151x_{41} + 0 \cdot 002606x_{39} - 0 \cdot 001102x_{11} \quad (7.13)$$
$$+ 0 \cdot 01199x_{22}$$

where x_{18} is evaporative stress for June of year t (expressed in miles per hour times inches of mercury); x_{39} and x_{41} are total precipitation for May and July respectively of year t; x_{11} is mean temperature for May of year $t-1$; and x_{22} is evaporative stress for April of year $t-1$. It may be inferred from the equation that rings in *Quercus rubra* are wide for seasons (1) when evaporative stress in June is low, (2) when total precipitation for both May and July is high, (3) when mean temperature for May of the prior year is low, and (4) when evaporative stress for April of the prior year is high.

The multiple correlation and the regression coefficients may be tested for significance to ascertain whether they could have arisen solely by chance. The appropriate tests which are described in most statistical texts require that the number of degrees of freedom be obtained. The computations for degrees of freedom cannot be made in the usual manner, however, because high autocorrelation in ring-width chronologies reduces their effective sample size. Equation 7.1 is therefore used to obtain n', which is then entered in the following equation along

with the number of regression coefficients (k) to calculate the degrees of freedom (d.f.) that apply.

$$d.f. = n' - k - 2 \qquad (7.14)$$

A more efficient method of handling autocorrelation in multiple regression analysis was suggested by Quenouille (1952) and applied to tree-ring work by Fritts (1962a). Variables for prior growth at lags of 1, 2, and 3 years are used as predictor variables along with the variables of climate. If this procedure adequately removes the effects of autocorrelation, the variance of the residual is random with respect to time and the usual tests of significance and degrees of freedom apply. The value for n' in Equation 7.14 then becomes the number of yearly observations, and as above, k is the number of regression coefficients including those for prior growth.

Some workers have used sequential numbers, their squares, and cubes as statistical predictor variables to express systematic variations due to increasing tree age or changes in the site. For example, the value of t is used as a variable along with its square and cube, and the regression coefficients associated with these three variables describe a curve that statistically assesses the variance associated with most trend in growth (Fritts, 1962b; Schulman and Bryson, 1965; Serre *et al.*, 1966). However, it is usually better to remove these systematic variations beforehand by standardization procedures, because the variance represented by trends is usually large and masks the variance related to climatic factors.

Often there is a large number of possible variables from which a smaller number of predictor variables must be selected. Each one that is entered into regression consumes one degree of freedom, so that the number of observations (or the effective sample size) limits the number of variables that can be entered in regression and still be significant. Whenever degrees of freedom (as calculated by Equation 7.14) are less than 10, there is a high likelihood of obtaining large coefficients purely by chance.

For example, a multiple-regression equation with 20 coefficients and 24 independent observations will have two degrees of freedom in the residual variance (Equation 7.14). In such a case, only the largest regression coefficients, those that are greater than 4·3 times the standard error, will exceed the 0·95 level of significance. However, if there had been 31 independent observations, the degrees of freedom would be 9, and all coefficients that are greater than 2·3 times their standard errors would exceed the 0·95 level of significance. [See the t distribution in Ezekiel and Fox (1959), Draper and Smith (1966), or a general statistics

text.] It is desirable to retain 20 or more degrees of freedom in the residual variance. Under this condition a record with at least 42 independent observations is necessary to retain 20 degrees of freedom in a multiple regression relationship involving 20 predictor variables; while 30 independent observations are needed to retain 20 degrees of freedom in a relationship involving 8 predictor variables.

Fritts (1962a) proposes that the procedure of stepwise multiple regression be used when it is necessary to select a small number of variables from a large number of possibilities. The stepwise procedure starts with a calculation of simple correlations for all combinations of variables under consideration, including intercorrelations among predictor variables, as well as correlations between predictors and the predictand. The procedure then examines all of the simple correlation coefficients and first selects the variable that is best correlated with the predictand. A regression using that variable to estimate growth is obtained, and all variables excluding the one in the regression are correlated with the residual variance. The one that is best correlated is added to the regression and a new two-variable equation is obtained. Additional variables are added as long as the residual variance is reduced by a significant amount.

Stepwise multiple-regression analysis does lead to certain technical difficulties, since high intercorrelations among the independent variables create instability in the results. Some variables that are entered early in the stepwise process become insignificant when other variables highly correlated with them are entered in regression at a later step. Therefore, the significance of each regression coefficient is tested at each step, and whenever it drops below a level specified beforehand, the insignificant variable is removed and a new regression equation is computed. At each step the regression procedure adjusts for intercorrelations with only the variables already in regression. A large correlation of a variable entered into regression with one that has not entered can prohibit the latter from being selected in the stepwise process, even though it may be well correlated with growth.

Figures 7.6 and 7.7 include examples of several stepwise multiple regression analyses. The former includes the results of four analyses of two stands of *Fagus grandifolia*, one on a well-drained site and one on a poorly-drained site (see soil profiles in Fig. 3.11). The latter includes the results of eight different stepwise multiple regression analyses for two stands of *Quercus alba*, one on a north-facing slope and one on a south-facing slope. In the case of *Quercus* the earlywood and latewood portions of the ring were analyzed rather than total ring width.

The stepwise analysis selected from variables of mean temperature,
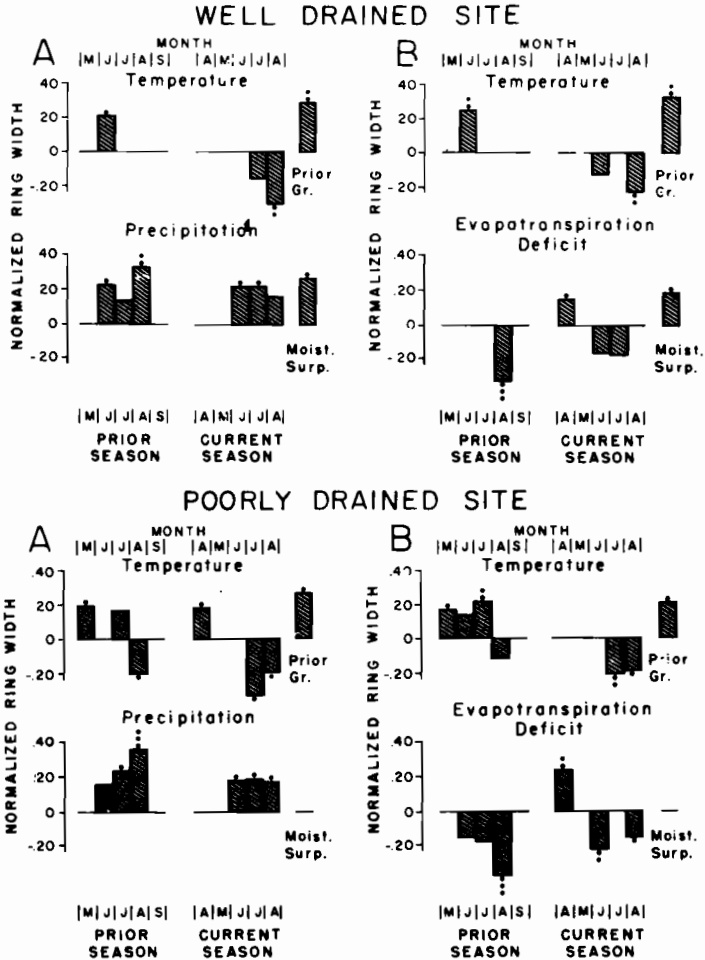
FIG. 7.6. Results of stepwise multiple regression analysis of variations in ring widths for two stands of *Fagus grandifolia* in an Ohio swamp forest. Potential predictor variables available to the stepwise selection process are monthly temperature and precipitation (*A*), or monthly temperature and evapotranspiration deficits (*B*) (Thornthwaite and Mather, 1957), for May–September prior to the season of growth and for April–August during the season concurrent with growth. Soil moisture surplus of the winter, spring, and the ring width of the prior year were included as potential predictor variables. The bars represent the standardized regression coefficients for all variables entered into the regression equation with F ratios greater than 1, and the number of dots indicates their significance level: $\cdot \geq 0.95$ $\cdot\cdot \geq 0.99$, $\cdot\cdot\cdot \geq 0.999$. The percent variance reduced ranged from 64% to 72%. (Redrawn from Fritts, 1962b, by M. Huggins)

total monthly precipitation, and evapotranspiration deficits for months May, June, July, August, and September during the year prior to growth and for months April, May, June, July, and August, of the year concurrent with growth. Other variables that were available for selection were moisture surplus and values of prior ring width. Set A shown in each of the figures utilized only precipitation as the moisture variable while set B utilized evapotranspiration deficits. The same temperature variables were available in both cases. The length and direction of the bars portray the magnitude and sign of the regression coefficients for variables that were selected in the stepwise process, and the number of dots indicates the level of significance.

It is notable from these figures that less than half the number of available variables were selected in the stepwise process, and sometimes the particular variables selected varied markedly from one analysis to the next. Nevertheless, the most significant regression coefficients do appear reasonable and are relatively consistent.

For example, most coefficients for precipitation are positive, indicating a direct relationship between precipitation and ring width. Also, precipitation in the middle or latter part of the growing season is most highly correlated with growth. Temperature and evapotranspiration deficits during July and August are most often inversely correlated with ring widths, but earlier in the season and during the prior year coefficients for these variables are both positive and negative, indicating the presence of both direct and inverse relationships.

The significant temperature variables that were entered into the equations differ between analyses using precipitation and analyses using evapotranspiration deficits. Small differences in the intercorrelations among these variables affected the sequence of selection and influenced which variables were included in the final result. Ring widths of *Fagus grandifolia* and earlywood widths of *Quercus alba* are about as highly correlated with the climate of the prior season as with the climate during the season of growth. Latewood of *Quercus alba*, however, is best correlated with moisture and temperature during the season of growth.

All analyses show highly significant first-order autocorrelation; that is, ring width is significantly correlated with the prior ring width, earlywood with the width of the prior season's latewood, and latewood with the width of earlywood produced during the same year.

Sometimes there are a number of ways of representing various limiting factors and it is not certain ahead of time which representation will be the best for statistically predicting growth. For example, temperature may be represented by average, maximum, or minimum daily temperatures; moisture by precipitation or evapotranspiration deficits; air humidity by
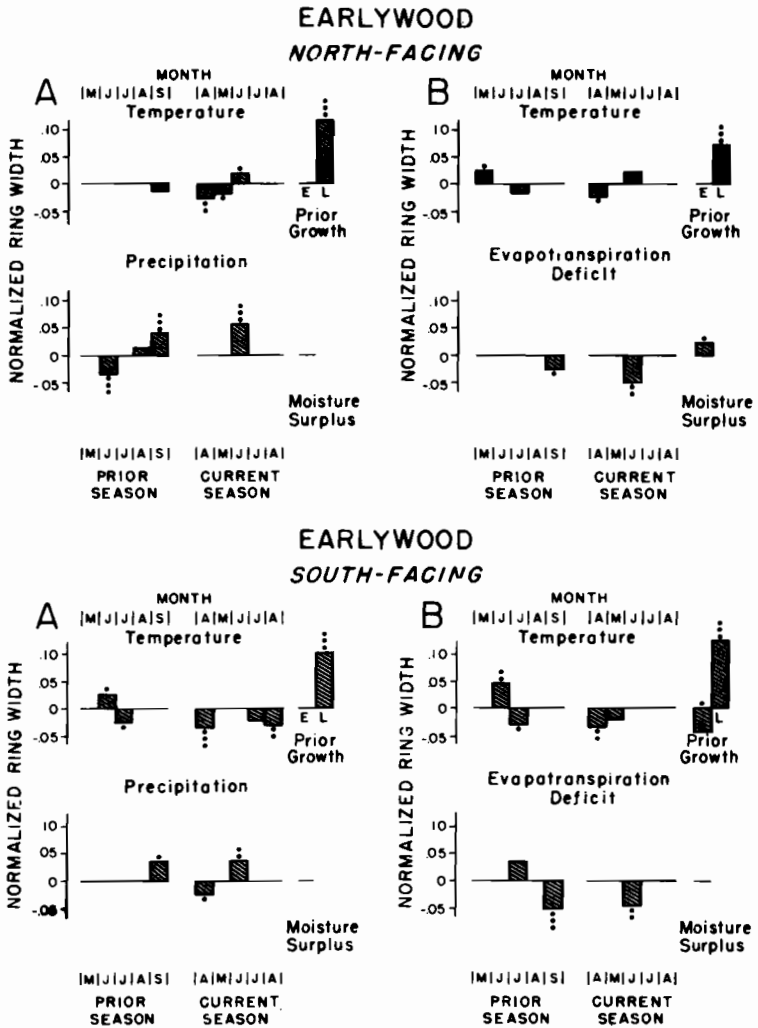
FIG. 7.7. Results of stepwise multiple regression analysis of earlywood and latewood of *Quercus alba* on two opposing slopes in central Illinois. The potential predictor variables are the same as in Fig. 7.6, except that the width of earlywood was included as a predictor variable as well as the width of the earlywood and latewood during the prior year. The analysis and symbols are the same as in Fig. 7.6. The percent variance reduced ranged from 73% to 83% for earlywood and 70% to 81% for latewood. (Redrawn from Fritts, 1962b, by M. Huggins)
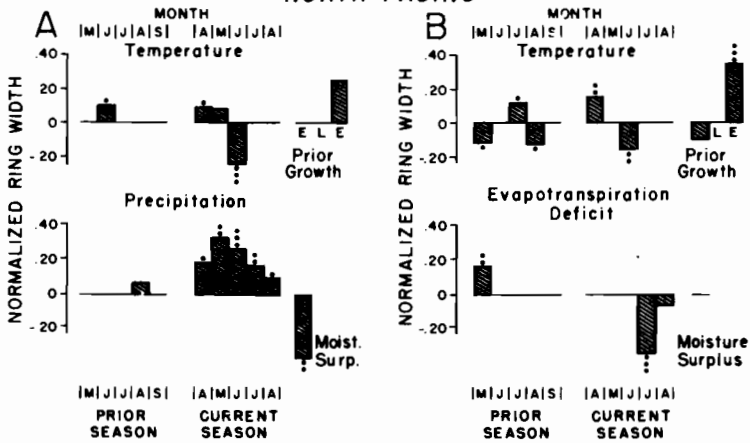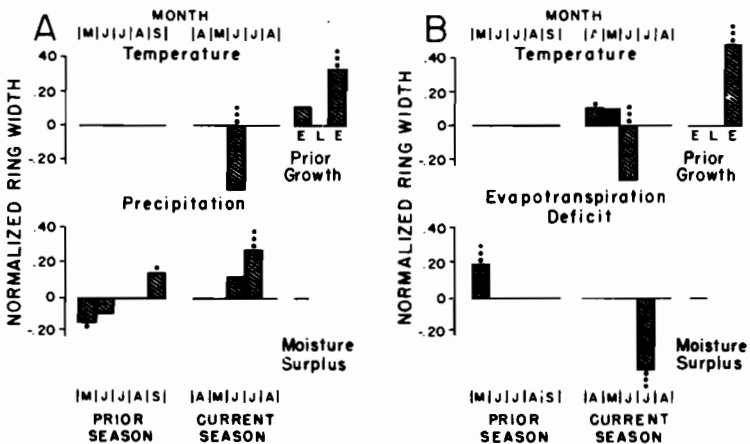
relative humidity or vapor pressure; and solar radiation by Langley units or hours of sunshine. It may also be uncertain as to how many different variables may be analyzed at once or whether relationships are nonlinear or multiplicative, thereby requiring some transformation to be made.

Fritts *et al.* (1956c) ran stepwise regression a number of ways. First, variables of total precipitation and average mean, average maximum,

and average minimum temperatures were calculated and grouped into the following eight intervals of time with respect to the particular growing season:

1. June of the previous year
2. July of the previous year
3. August through September of the previous year
4. October through November of the previous year
5. December through February of the current year
6. March through May of the current year
7. June of the current year
8. July of the current year

The variables for regression were selected from the above intervals, and seven different analyses were run using the following combinations of data:

1. Total precipitation
2. Average maximum temperature
3. Average mean temperature
4. Average minimum temperature

5. Total precipitation, average maximum temperature, and the product of these two

6. Total precipitation, average mean temperature, and the product of these two

7. Total precipitation, average minimum temperature, and the product of these two

Eight climatic variables,' representing the eight time intervals, were used in analyses 1 through 4, while 24 climatic variables were used in analyses 5 through 7. Stepwise multiple-regression analyses were obtained in the above systematic order, using the tree-ring chronology from each statistical sample as the dependent variable. Multiple regressions were obtained for predicting the ring indices as a function of only the climatic data and then as a function of the climatic data along with variables representing the three preceding ring indices. Thus, 14 separate regression analyses were required to evaluate each tree-ring sample, and in each of these, five to 10 different steps were employed to arrive at the final equation. The final multiple correlations adjusted for degrees of freedom lost (Ezekiel and Fox, 1959), that were obtained with each set of climatic variables (Table 7.V), were multiplied by 100 to obtain percent variance explained by the relationship.

TABLE 7.V The square of multiple correlation coefficients adjusted for sample size for regression analysis of three tree species[a]

Climatic variables used[c]	Sites and Species[b]			
	Wetherill Mesa		Navajo Canyon	
	Juniperus osteosperma 400-year trees	Pinus edulis 200-year trees	Pseudotsuga menziesii	
			260-year trees	500–800-year trees
Total monthly precipitation	0·78	0·66	0·79	0·75
Average maximum temperatures	0·45	0·64	0·42	0·53
Average mean temperatures	0·39	0·50	0·37	0·47
Average minimum temperatures	0·20	0·38	0·17	0·00
Precipitation and average maximum temperatures	0·87	0·78	0·80	0·79
Precipitation and average mean temperatures	0·87	0·76	0·78	0·82
Precipitation and average minimum temperatures	0·83	0·72	0·85	0·82

[a]Fritts *et al.* (1965c), see also Table 7.VI. [b]Mesa Verde National Park, Colorado. [c]Including variables for indices of 3 prior rings.

Sometimes the values of variables can be squared or converted to logarithms to allow for nonlinear relationships (Fritts, 1969; also see Fig. 7.3), and cross products between variables can be utilized to allow for multiplicative effects (Table 7.VI). Since the square of the multiple correlation adjusted for sample size increased with the complexity of the analysis, it was concluded by Fritts *et al.* (1965c) that the percentage of variance did indeed increase for the more complex models and that the complexity was required to handle some of the variable interactions. However, final selection of results depended not only on the significance and variance calibrated by the regression but also on the biological reasonableness of the results (Table 7.VI).

For example, the data in Table 7.V indicate that ring widths of *Juniperus osteosperma* at Wetherill Mesa are more markedly affected by precipitation ($R^2 = 0.78$) than temperature ($R^2 = 0.45$). When both variables are used, significant interaction of these two variables appears during the autumn, winter, and spring months from October to May (Table 7.VI). That is, the product of temperature and precipitation was chosen as a significant predictor. The square of multiple correlation for this case was 0·87. Combinations of precipitation and temperature gave

TABLE 7.VI Climatic conditions which produce narrow rings in three species of trees[a]

	Site and species[b]			
	Wetherill Mesa		Navajo Canyon	
	Juniperus osteosperma 400-year	*Pinus edulis* 250-year	*Pseudotsuga menziesii*	
			260-year	500–800-year
Interval summed	trees	trees	trees	trees
Prior June, July	no effect	no effect	6 warm, dry[d]	6 warm, dry
Prior Aug., Sept.	no effect	no effect	3 dry[c]	3 dry[c]
Prior Oct., Nov.[c]	3 dry, warm[c]	1 dry[c]	1 dry[c]	2 dry[c]
Prior Dec.–Feb.	1 dry, cool[c]	2 dry[c]	2 dry[c]	5 dry[d]
Current Mar.–May	2 dry, warm[c]	4 dry(cool)[d]	4 dry(cool)[c]	1 dry cool[c]
Current June	no effect	no effect	5 dry[d]	4 warm[c]
Current July	no effect	3 warm[c]	no effect	no effect

[a]Fritts *et al.* (1965c), also see Table 7.V. [b]Mesa Verde National Park, Colorado. [c]Numbers 1 to 6 indicate rank of variable importance from high to low. Comma between variables indicates variable interaction with cross products entered into the regression. Parentheses indicate second variable entered but no cross product term involved. [d]Significant $P > 0.95$. [e]Significant $P > 0.99$.

the highest multiple correlations for *Pinus edulis* at Wetherill Mesa and for *Pseudotsuga menziesii* at both Navajo Canyon sites listed in Table 7.VI, but variable interaction was evident for the latter species only during June and July of the summer prior to growth.

Stepwise multiple-regression analysis cannot handle all variable intercorrelations. As was mentioned earlier, certain variables which are important to growth are prevented from entering regression because of their correlation with variables already in regression. This produces differences and inconsistencies which limit the usefulness of stepwise multiple regression for evaluating the effect of intercorrelated climatic variables on ring-width growth.

There are two regression procedures that may be suitable alternatives to the stepwise analysis because they are more efficient for handling the intercorrelations among predictors. One method begins by solving for all variables in regression and then deletes each one in a stepwise fashion. Those that are most insignificant are deleted first. The other approach uses principal components combined with regression. The first alternative has not been used by the writer, since the second seemed to have more advantages. This second method is described in the following sections.

B. Regression after Extracting The Principal Components

Problems due to variable intercorrelation can be circumvented by transforming the predictor variables into a new set of orthogonal or

uncorrelated variables called *eigenvectors* or *principal components*. When these new variables are used as predictors in a stepwise multiple-regression analysis, the selection process occurs in a systematic and efficient manner. In addition, a smaller number of transformed variables may be required to obtain the regression relationships, thereby reducing the amount of error as well as the number of degrees of freedom consumed in the stepwise process. Lastly, the transformation ranks the new orthogonal variables in order of their importance allowing the investigator to select the most important variables and to discard the least important ones. Once the regression coefficients for the selected set of orthogonal variables have been calculated, they may be mathematically transformed into a new set of coefficients which correspond to the original correlated set of variables. These new coefficients (sometimes referred to as *weights* or *elements* of the response function) are analogous to the stepwise regression coefficients described in the previous section, except that a coefficient is associated with each original climatic variable, there are usually more degrees of freedom, and there is less error to contend with because of variable orthogonality and because some of the principal components are left out. As a result, the equations derived by means of this method are more reliable than those obtained by the usual stepwise multiple-regression process. Since the procedure is a relatively new and complicated one, the details are described in the following subsections. For background reading of these multivariate techniques see Cooley and Lohnes (1971), Dempster (1969), Morrison (1967), Press (1972), and Seal (1968).

1. Some Matrix Notations

It is necessary and easier for the remaining portions of this volume to describe the computations in terms of matrices and simple algebraic manipulations. The reader already familiar with this terminology may go on to the next subsection.

Matrix notation facilitates the mathematics involved in large grids of data where there are a number of variables and a number of observations of each variable. Probably the most obvious dendroclimatological example of a data matrix is a sequence of measurements taken from a spatial grid of tree-ring or climatic stations. A *matrix* is defined as simply an array of data ordered in columns and rows. Each data matrix can be identified by a letter assigned to it, such as A, B, or C. Portions of three matrices are shown diagrammatically in Fig. 7.8 as blocks divided into rows and columns, which are referred to as *elements*. It is convenient to designate the size of each matrix, that is, the number of rows and columns, by using subscripts. In the examples shown in Fig. 7.8, matrix A

indicated by a in each element has m rows and n columns. This is written in matrix notation as $_mA_n$, where the subscripts refer to the total number of rows and columns of the matrix. The elements of A are also subscripted, where the first subscript refers to the number of the row in the matrix and the second to the number of the column in the matrix. The rows might represent different variables used as growth predictors, such as monthly precipitation and temperature, and the columns might represent the individual years for which the precipitation and temperature data are recorded.

$_1B_mA_n = {}_1C_n$

	a_{11}	a_{12}	a_{13}	$\cdots$	a_{1n}
	a_{21}	a_{22}	a_{23}	$\cdots$	a_{2n}
	$\cdot$	$\cdot$	$\cdot$		$\cdot$

b_{11}	b_{12}	$\cdots$	b_{1m}

| a_{m1} | a_{m2} | a_{m3} | $\cdots$ | a_{mn} |

$=$

$b_{11}a_{11}$	$b_{11}a_{12}$	$b_{11}a_{13}$	$\cdots$	$b_{11}a_{1n}$
$+$	$+$	$+$		$+$
$b_{12}a_{21}$	$b_{12}a_{22}$	$b_{12}a_{23}$	$\cdots$	$b_{12}a_{2n}$
$+$	$+$	$+$		$+$
$b_{1m}a_{m1}$	$b_{1m}a_{m2}$	$b_{1m}a_{m3}$	$\cdots$	$b_{1m}a_{mn}$

$=$

c_{11}	c_{12}	c_{13}	$\cdots$	c_{1n}
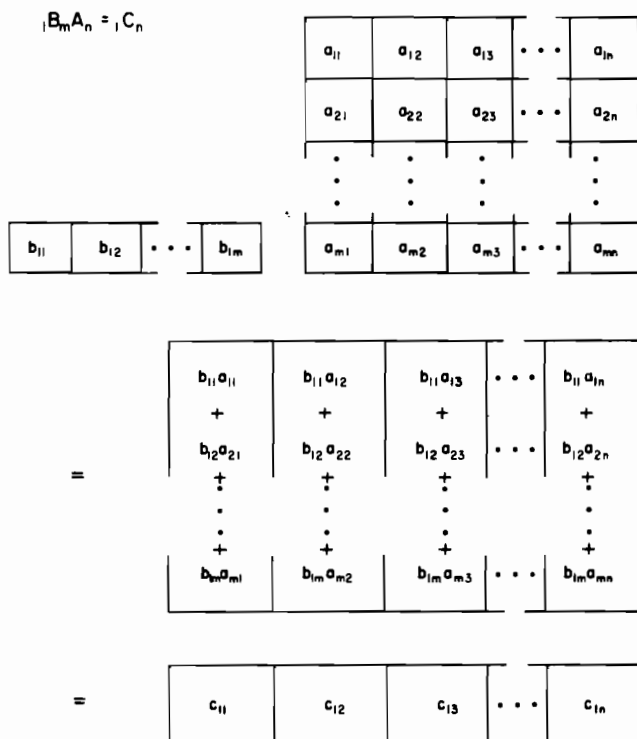
FIG. 7.8. A diagrammatic representation of a matrix multiplication. Matrix A is multiplied by B to obtain a new matrix C. Subscripts designate the number of rows and columns in each matrix. The elements of the matrices are shown as boxes at the top and bottom of the figure. The vertically oriented boxes show the algebraic multiplication of the elements before the columns are summed to obtain the C matrix. See text for explanation.

Matrix B in Fig 7.8 is also a matrix but it has 1 row and m columns. This matrix may be written as $_1B_m$. Thus, the elements b_{1t} are arranged in one row with m columns in the figure. This matrix might represent a set of multiple regression coefficients obtained for use with the variable stored in the rows of matrix A to estimate another variable such as ring width. Matrix C, shown at the bottom of the figure, has 1 row and n columns and may be written as $_1C_n$, the elements c_{1j} arranged in one row and n columns.

Only two matrix manipulations are of importance to this discussion. The first is multiplication which can be accomplished between two matrices if the number of columns in the first is the same as the number of rows in the second. In the aforementioned example (Fig. 7.8), matrix B and A can be multiplied since B has m columns and A has m rows. The algebraic representation of this multiplication is shown in the figure and can be written as follows:

$$_1B_mA_n = {}_1C_n \tag{7.15}$$

The subscripts for the columns of B and the rows of A are the same and need not be written twice. Multiplication as shown in Fig. 7.8 involves a particular element in each row of A which is multiplied by the corresponding column element in B: $b_{11} \times a_{11}$, $b_{11} \times a_{12}$, $b_{11} \times a_{13} \ldots$ $b_{11} \times a_{1n}$; and $b_{12} \times a_{21}, b_{12} \times a_{22}, b_{12} \times a_{23} \ldots b_{12} \times a_{2n}$. The products of the elements B and A are then summed in the direction of the columns of A as shown in the lower portion of Fig. 7.8 to become a new matrix, $_1C_n$, with the same number of columns as A and the same number of rows as B (see Equation 7.15).

Using the example cited above, where the elements of $_mA_n$ are observations of climatic data on m variables for n years and the elements of $_1B_m$ are the corresponding regression weights, matrix $_1C_n$ contains the solutions or estimates obtained by applying the regression equation to the data. Thus the multiple regression equation is very conveniently written in matrix notation as in Equation 7.15.

If the same operation were written using summation notation, the elements in matrix C, c_{1j}, are obtained as follows:

$$c_{1j} = \sum_{i=1}^{m} b_{1i}a_{ij}; \quad j = 1, n \tag{7.16}$$

If there had been q rows rather than one row in matrix B, there would have been q rows in matrix C, and the operation would have been repeated as in Fig. 7.8 q times using a different row of B to obtain a different row in C.

The only other matrix operation that is required in the following pages

involves obtaining the transpose of a matrix in which the columns and rows are interchanged. The transpose of A is written as A' and the elements of row 1 become the elements of column 1, while the elements of row 2 become the elements of column 2, etc. A transpose is sometimes necessary to arrange the rows and columns properly to make a multiplication. See Searles (1966) for additional discussion of matrix algebra techniques.

2. Principal Components

The *principal components*, which are also referred to as *eigenvectors*, are a set of variables which are derived from a data set to be *orthogonal* to (uncorrelated with) each other. In dendroclimatic studies, the principal components may be derived from a set of climatic data or a set of tree-ring data. For example, the climatic data may be mean monthly temperature and a total monthly precipitation. In the example shown below, the data for each month are considered as separate variables, and the variables are arranged in a 28-variable array consisting of 14 months of temperature and the same 14 months of precipitation preceding and concurrent with each growing season from 1924 to 1962. The first variable is the average temperature of June for the year prior to the season of growth and the 14th is the average temperature for July during the period of growth. The 15th variable is precipitation for the prior June, and variable 28 is precipitation for July of the growing season. Although this 14-month interval has been found in prior analyses to include the most important climatic factors thought to affect ring width, other periods of time could be used.

The eigenvectors are representations of the original climatic variables; that is, they include the same information as the original data. There are usually as many eigenvectors as there are variables but the most important eigenvectors, as the name *principal component* implies, account for a large portion of the data variance. The least important eigenvectors express only minor variations in the original data, some of which result from errors, noise, and residual variation imposed by the mathematical constraints in deriving the eigenvectors. It is customary to order these eigenvectors from greatest to least importance (those that express the most to the least variance) and to select a subset which concentrates the climatic data into a smaller number of variables than the original data set.

For the sake of clarity, an actual example is helpful. It will include climatic data from Mesa Verde in southwestern Colorado for 1923–1962. The temperature and precipitation data are designated as matrix $_mF_n$, which is a set of observations for n years on m climatic variables. In the

example n is 39 years and m is 28 climatic variables, so that matrix F has 39 columns and 28 rows. The lower part of Fig. 7.9 shows the data for two columns (growth-years) of the matrix.

The first step in extracting the eigenvectors of such a data set is to obtain the simple correlation coefficients (Equation 6.4) for each variable with all other variables. If there are m variables, the set of correlations can be defined as an $m - by - m$ matrix, C, in which the element of the first row and first column is the correlation coefficient for variable 1 with itself, and the second element of the first row is the correlation coefficient for variable 1 and variable 2, and the ith row and the jth column is the correlation between the ith and jth variables.

If the data are normalized beforehand (Equation 7.5) to standard units (see lower half of Fig. 7.9) the correlation matrix can be calculated as

$$ _mC_m = \left(\frac{1}{n}\right)_mF_n F'_m \qquad (7.17) $$

where $_mF_n$ is the set of climatic data described above and the symbol $(')$ designates the transpose.

The matrix of principal components (eigenvectors) $_mE_m$ is obtained from the correlation matrix $_mC_m$ by a complicated mathematical procedure. The relationship between the correlation matrix and the eigenvectors is

$$ _mC_mE_m = \ _mE_mL_m \qquad (7.18) $$

where $_mL_m$ is a set of scaling factors referred to as *eigenvalues*. These scalars represent the importance of each eigenvector and are arranged in order of descending value in the diagonal elements of matrix L, with zeroes in the off-diagonal elements. Such a diagonal matrix is a technical construction necessary to multiply a set of scalars with another matrix. Each diagonal element of the eigenvalue matrix is proportional to the variance reduced by one of the eigenvectors. The percent variance reduced by the eigenvector corresponding to a particular eigenvalue is obtained by dividing that eigenvalue by the sum of all eigenvalues and multiplying by 100.

Each column $_mE_m$ contains an eigenvector consisting of m elements. The eigenvector elements are weights or scalars associated with each of the m variables of matrix F so that the magnitude of each element is proportional to the importance of the corresponding variable in the particular eigenvector. The complete matrix of eigenvectors contains the same information as was in the original correlation matrix. In mathematical terms, the axes have been rotated and the data are

expressed in terms of a new set of coordinates, with each eigenvector representing one orthogonal mode of behavior in the original data set. The following illustrates the relationships between the data and the eigenvectors.

The data for the 28 variables during two years at Mesa Verde, one ending in 1936 and the second ending in 1924, are shown at the top of Fig.
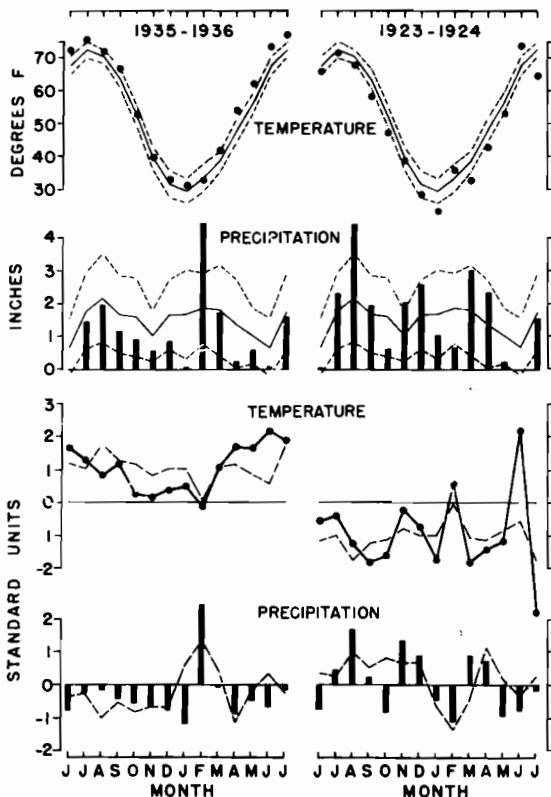
FIG. 7.9. The values for average monthly precipitation and monthly temperature at Mesa Verde for two 14-month periods, one for 1935-1936 and one for 1923-1924, which are arranged as 28 variables for calculating the principal components. The points and bars in the upper half of the figure represent the actual values for temperature and precipitation, respectively. The solid lines indicate the mean for the entire record for 1923-1962; the dashed lines designate distances of plus and minus one standard deviation from the means. The data in the lower half of the figure are normalized and plotted as standard units (z, Equation 7.5). The lines in the lower portion of the figure represent the values for the elements of eigenvector 1 in its positive and negative representations. See text for explanation.

7.9. The values for the mean temperatures and total precipitation are plotted as points and bars respectively. The solid lines behind these data connect the means for each variable for the entire period of record, 1923–62. The dashed lines connect the points representing plus and minus one standard deviation from the mean. The normalized form of the data (see Equation 7.5), expressed as standard units, are shown in the lower half of Fig. 7.9. The values for temperature for 1935–36 were generally above average, and those for precipitation were below average for June through January and March through July. For February the signs of the standard units for both variables were reversed. Comparable data for the year 1923–1924 are shown in Fig. 7.9 on the right.

A plot of the first principal component (eigenvector 1) for the sample data is shown at the top of Fig. 7.10. Since this eigenvector is the first one, it represents the most important pattern or mode of behavior of the original 28 climatic variables. It reduces 13% of the total variance in the original data set of $_mF_n$. Each element of the eigenvector shown in Fig. 7.10 corresponds to one of the 28 variables shown in Fig. 7.9. The magnitudes of the elements for the 14 temperature variables are plotted at the top, and the magnitudes of the elements for the 14 precipitation variables are plotted immediately below them. The pattern formed by the elements of the eigenvectors is of importance—not the signs. That is to say that all monthly weights could have been multiplied by −1 giving the opposite signs, and the elements in Fig. 7.10 could be plotted as the reverse.

The climatic mode expressed by the positive representation of eigenvector 1 represents years in which monthly temperatures (variables 1–14 plotted at the top of Fig. 7.10), with the exception of those in February, are all above average, while those for 10 of the 14 precipitation variables (plotted below those for temperature) are below average. Only values for precipitation of January through March and June are above average in this mode. The climatic mode for the negative representation consists of years when temperatures below average precipitation for the 10 months are above average, and precipitation amounts for the four months are below average.

When the eigenvector matrix (Fig. 7.10) is multiplied by the normalized climatic data shown in Fig. 7.9, a new matrix is obtained called the *amplitudes* or *factor scores*$(_mX_n)$.

$$_mX_n = {}_mE'_m F_n \tag{7.19}$$

The values of the first row of the amplitude matrix corresponding to eigenvector 1 are plotted at the bottom of Fig. 7.10. The years of the growing seasons are substituted for the subscripts 1 to n. The variance of
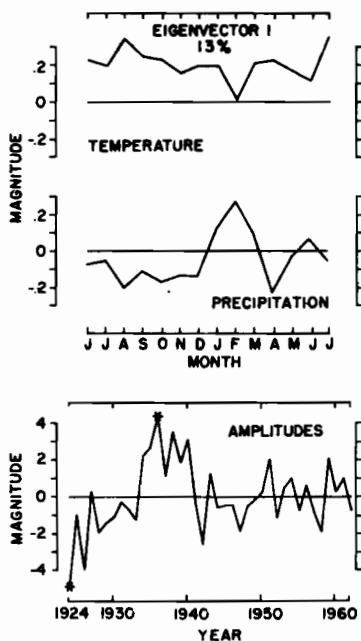
FIG. 7.10. Plot of the magnitudes of the elements of the first and most important eigenvector of Mesa Verde climate, which reduces 13% of the climatic variance, and the corresponding amplitude set. The eigenvector elements for temperature are all the same sign, and the corresponding signs for 10 elements for precipitation have the opposite sign. This arises because temperatures throughout the 14-month period are somewhat positively correlated with each other, but they are negatively correlated with precipitation for 10 out of 14 months. The eigenvector is multiplied with normalized climatic data to obtain the amplitude set. Asterisks mark those elements with the largest positive and negative values indicating the most resemblance of the climatic regime for the year to that particular eigenvector (see Fig. 7.9).

this new time series represents the 13% of the original variance reduced by the first eigenvector.

It may be helpful to mentally carry out one multiplication for one row and column. Refer to Fig. 7.8 and consider the 28 elements of eigenvector 1 shown in Fig. 7.10 as if they are the terms in the boxes of matrix B arranged in one row with 28 columns; and consider the normalized climatic data for 1935–1936, shown in the lower left of Fig. 7.9, as if they are the items of a column in matrix A with 28 rows. The items in the row are individually multiplied by the corresponding item in the column. To help visualize the operation, the corresponding elements of the first

eigenvector are plotted as dashed lines behind the normalized data in the lower left of Fig. 7.9. It may be noted from the figure that the individual products are generally positive because the data and the elements of the eigenvector both tend to be above average and below average together. When the products (Fig. 7.8) are summed, the result is large and positive so that the element of X, the amplitude for 1935–1936, has a large positive value (see the large positive value with star in Fig. 7.10).

For the year 1923–24 the data are like the negative representation of eigenvector 1 (Fig. 7.9) so that individual products tend to be large and negative and the amplitude for the year (starred in Fig. 7.10) has a large negative value. Eigenvector 1 is plotted in the lower right of Fig. 7.9 with signs of the elements reversed along with the normalized data to facilitate comparison.

Thus the amplitude matrix is a time series which expresses how well the data for each year resemble the particular eigenvector. If the amplitude is large and positive, the climatic data resemble the eigenvector in a direct manner; if it is large in magnitude but is negative, the climatic data resemble the eigenvector in a negative or inverse manner. If the amplitude value is zero, the eigenvector is uncorrelated with the climatic data for that year. Usually a number of eigenvectors are necessary to characterize the climatic regime represented by a particular year, although one or two eigenvectors may be by far the most important.

The upper portion of Fig. 7.11 is a plot of the second most important principal component (eigenvector 2) in this example, which reduces 11°₀ of the variance. The plot of the elements for this eigenvector represents a mode of climate in which the first six months of the 14-month period are either warmer and dryer or cooler and wetter than average, while the eight following months are the opposite; that is, cooler and wetter or warmer and drier than average. As in eigenvector 1, high temperatures usually go with low precipitation and low temperatures with high precipitation. The amplitudes for this eigenvector are plotted at the bottom of the figure and the stars mark those elements with most extreme values.

The climatic data corresponding to the starred amplitudes are shown in Fig. 7.12 and the elements of eigenvector 2 are plotted as dashed lines with the normalized climatic data to facilitate comparison. As noted in Fig. 7.9, the climatic regimes of years with large positive or large negative amplitude again resemble the positive or negative mode of the particular eigenvector, though as before the values for individual eigenvector elements and variables do not match perfectly.

If all 28 eigenvectors are used, the information contained in the complete matrix of amplitudes describes all the original data. In other
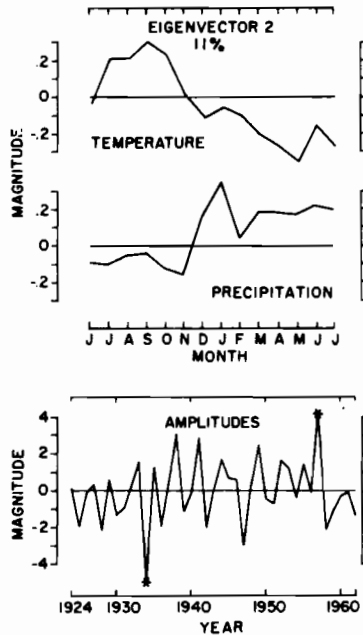
FIG. 7.11. The magnitude of the elements of the second eigenvector of Mesa Verde climate, which reduces 11% of the climatic variance, and the corresponding amplitude set. This eigenvector expresses a mode of climate in which the departures of temperatures for July–November are opposite of the sign for those of temperature during December–July. All elements for precipitation have signs opposite those for temperature, indicating a generally inverse relationship. The eigenvector is multiplied with normalized climatic data to obtain the amplitude set. Asterisks mark those elements with the largest positive and negative values indicating the most resemblence of the climatic regime for the year to that particular eigenvector (see Fig. 7.12).

words, the amplitude matrix contains exactly the same information as the original normalized data set, except that the data are arranged into a set of new variables which are completely uncorrelated with one another and which can be ordered in terms of their importance from those reducing the greatest amount of variance to those reducing the least.

Thus, the extraction of the principal components or eigenvectors actually transforms data representing a number of correlated variables into a new set of uncorrelated variables. The investigator can examine the eigenvalues and discard the least important eigenvectors with the smallest eigenvalues, thus removing unwanted noise and small-scale variability and reducing the total number of variables with which he must deal. This concentrates the information into a small number of
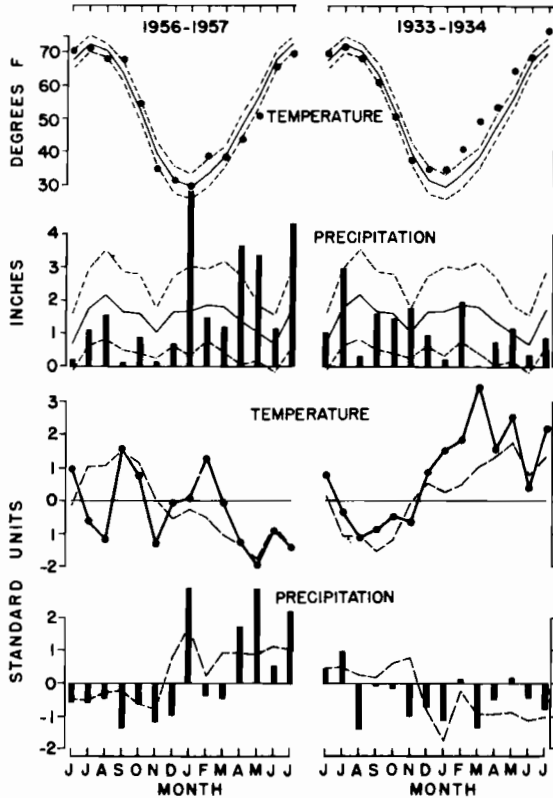
FIG. 7.12. The values for average monthly precipitation and monthly temperature at Mesa Verde for 14 months during 1956–1957 and 1933–1934 which are arranged as the 28 variables used in calculating the principal components. The lines with long dashes in the lower half of the figure represent the values for the elements of eigenvector 2 in its positive and negative representations. See Fig. 7.9 and text for additional explanation.

principal components. Often the first 20 of the 28 possible eigenvectors of climatic data handled in the above manner reduce 90% to 95% of the variance in the original data set. The reduced set of amplitudes is then used as predictor variables in a stepwise multiple regression analysis in place of the original climatic data as described in the next subsection.

3. Response Functions

Since the amplitude matrix represents the original climatic data, the amplitudes may be used to statistically predict a ring-width chronology,

$_1P_n$, using a stepwise multiple regression analysis. The multiple regression equation (7.10) may be rewritten in matrix notation as

$$_1\hat{P}_n = {}_1R_pX_n \tag{7.20}$$

where $_1\hat{P}_n$ includes the estimated ring-width indices for n years and $_1R_p$ are the significant partial multiple regression coefficients associated with each of the amplitudes of the selected set of p eigenvector amplitudes (all values for insignificant regression coefficients are assigned a value of zero). As for regression using actual climatic data, the particular values assigned to the regression coefficients can be interpreted as expressing the relative importance of each eigenvector amplitude in predicting growth $(_1P_n)$. The interpretation of the eigenvector amplitude is considerably more difficult because the real world does not behave like the eigenvectors, as uncorrelated modes of climatic behavior. However, these regression coefficients associated with the eigenvector amplitude can be converted into a new set of coefficients, $_1T_m$, which express the same relationships but in terms of the original variables rather than the eigenvector amplitudes. The equation for the transformation is obtained by substituting Equation 7.19 into 7.20:

$$_1\hat{P}_n = {}_1R_pE_mF_n = {}_1T_mF_n \tag{7.21}$$

The same statistical estimates of ring-width indices $_1\hat{P}_n$ are obtained by either multiplying normalized climatic data, $_mF_n$, and the response function, $_1T_m$ or by multiplying the amplitudes $_pX_n$ by the regression coefficients, $_1R_p$. Since the elements of the response function, $_1T_m$, are associated with the original climatic variables, not the eigenvector amplitudes, each element can be directly interpreted in terms of an anomaly in the particular variable—monthly temperature or monthly precipitation. Growth is expressed as a response to variations in particular climatic variables.

As was pointed out earlier, the presence of interdependence in ring-width indices measured by the first-, second-, and third-order autocorrelation can affect the tests of significance. Therefore the ring-width indices for three prior years must be included as three additional predictor variables $(_3Z_n)$ in the stepwise analysis. The regression coefficients for these three variables are handled in matrix notation as $_1R_3^*$ where the estimations of $_1P_n$ made with this enlarged set of predictors is accomplished by adding $_1R_3^*Z_n$ to the original estimates $(_1\hat{P}_n)$.

The same eigenvector amplitudes may be used to derive response functions for several chronologies from a given climatic region, though

the regression coefficients will be different for each chronology. The orthogonality of the eigenvectors and their amplitudes allows efficient and orderly use of stepwise multiple-regression analysis. The variables in regression are more likely to remain in the same order of importance as they were when they entered regression, but exceptions to this occur when the autocorrelations in the ring-width indices complicate the relationships.

When estimating $_1P_n$ using the response function $(_1T_m)$, the variance reduced is a direct measure of the amount of climatic information expressed by the chronology. A second estimation of $_1P_n$ can be made using the above response function $(_1T_m)$ and the correction for prior growth $(_1R_3^*Z_n)$ which usually accounts for more variance in $_1P_n$ if autocorrelation in the ring-width chronology is significant. The difference in the variance reduced in the above two calculations provides a measure of the variance attributed to autocorrelation of indices at a lag of one to three years. A check for the residuals is made to ensure that they are randomly distributed with respect to time and that the usual tests for significance are valid.

The confidence limits for each element of the response function, $_1T_m$, are calculated from the respective standard errors (see Draper and Smith, 1966). These standard errors are in turn obtained from the standard errors of the elements of $_1R_p$ as defined in Equation 7.20. The required transformation is

$$_mS_m = {}_mE_pU_pU_pE'_m \tag{7.22}$$

where $_pU_p$ is a *diagonal matrix* of the standard errors of the elements of $_1R_p$, and $_mS_m$ is a symmetric matrix, the diagonal elements of which are the square of the standard errors of the elements of $_1T_m$. This operation simply distributes the square of the errors to each standard error in proportion to the squares of the elements of the eigenvector.

The desired confidence limits are obtained by multiplying each diagonal element of $_mS_m$ by the appropriate F value with v_1/v_2 degrees of freedom and then taking the square root. Here v_1 has a value of 1 and v_2 is the effective sample size less the number of nonzero regression coefficients in matrices $_1R_p$ and $_1R_3^*$ and less two more degrees of freedom (Equation 7.14). The residuals of the regression are almost always sequentially independent (having no significant autocorrelation), so the effective sample size is the same as the number of years of observations.

Figure 7.13 includes several response functions obtained for a chronology representing the mean of six sites along the eastern slope of the Rocky Mountains (Julian and Fritts, 1968; Fritts et al., 1971). Stepwise multiple regression was run using the amplitudes of climatic eigenvectors

to estimate growth. Each successive step utilizes an increased number of eigenvector amplitudes. The regression weights at five different steps were multiplied by the eigenvectors (as in Equation 7.21) to obtain five different response functions $(_1 T_m)$. The first response function included only one regression coefficient associated with the amplitude set which is best correlated with the ring-width chronology. In the example it was the amplitude of the first and most important eigenvector. The regression coefficient is multiplied by the weights of eigenvector 1 to obtain a response function that reduces 36% of the growth variance (Fig. 7.13). This response function can be interpreted as representing the condition of yearly climate which leads to above average growth, characterized by below average temperature for any month and above average precipitation for any month.

The vertical lines in Fig. 7.13 indicate the 0·95 confidence intervals used to test variable significance. In the above example all but two variables (elements of the response function) have a 0·95 or higher probability of being significant from zero.

The second response function shown in Fig. 7.13 is the result of stepwise multiple regression analysis of the same climatic amplitudes using the three most significant regression coefficients. The three coefficients were multiplied by the appropriate three eigenvectors, and the three products were summed for each of the 28 elements of the response function $_1 T_m$. This response function assumes a more complicated shape and the variance reduced is 67·3% of the total growth variance. It can be interpreted by the significant elements to indicate that temperatures in May are the only temperature variables that are directly related to growth, while temperatures in seven of the 14 months are significant and inversely related to growth. Variables for precipitation are significant and directly related to growth in nine of the 14 months. Precipitation for the July prior to growth is the only precipitation variable that is inversely related to growth at this step.

The stepwise multiple-regression procedure was continued, and the response functions which were obtained for steps with 7, 12, and 20 amplitude variables are included in Fig. 7.13. Since the last response function reduces 97·7% of the ring-width index variance, the elements of the last response function may be considered to most resemble the actual manner in which the trees on the particular sites are responding to fluctuations in climate.

The response function with 20 variables can be interpreted as showing significant inverse correlation of growth with temperatures in July of the prior summer, November, April, and July during the year of growth. The elements for September, March, and May suggest the presence of a direct

relationship between growth and temperatures during these three months. The results for precipitation indicate an inverse and significant relationship for January, and a direct and significant relationship for the prior June, October, February, April, May, and June. The prior growth
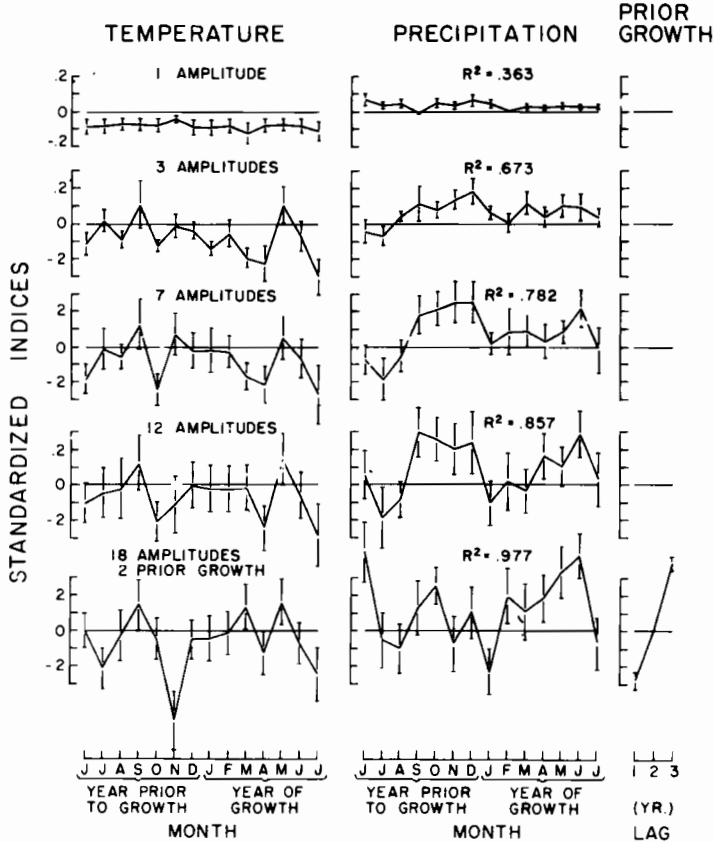
FIG. 7.13. Response functions obtained from a stepwise regression analysis using amplitudes of eigenvectors and prior growth to estimate a ring-width chronology representing six *Pinus ponderosa* sites along the lower slopes of the Rocky Mountains, Colorado. Steps with 1, 3, 7, 12, and 20 predictor variables are shown. The regression coefficients for amplitudes, $_1R_1$, are converted to response functions, $_1T_m$, (Equation 7.21), along with the approximate $\pm$ 0.95 confidence limits (Equation 7.22). When response functions are complex, as in this example, a linear combination of many eigenvectors is needed to obtain the best-fitting relationship. Prior growth was entered into regression after the step with 12 variables. The percent variance reduced can be calculated by multiplying the R^2 by 100.

at a lag of one year is inversely correlated with the ring width, although at a lag of three years a direct correlation exists.

The changing shapes of the response functions in Fig. 7.13 illustrate how the regressions on increasing numbers of eigenvector amplitudes can be used to describe the manner in which climatic factors affect growth. At first the amplitudes that are most highly correlated with the tree-ring chronology are entered into regression, and the linear combination of the eigenvectors express the general pattern of growth response to climate. As more and more steps are added, the finer details of the response of growth to climate begin to take shape. The method implies that the more an amplitude series resembles the ring-width chronology, the more the corresponding eigenvector resembles the manner in which the trees respond to climate.

The stepwise multiple-regression analysis is terminated when the F ratio for the variable entering regression is $< 1 \cdot 0$. In this type of analysis the F ratio for entering variables is used not as a test of significance, but rather as a measure of the ratio between the variance reduced and the error variance. When the variance due to the addition of a variable is less than the error of variance (F is $< 1 \cdot 0$) there is nothing gained by including it as a predictor in the regression equation. But as long as the variance added by regression is greater than the error variance, some improvement can be made. If a large number of confidence intervals begin to intersect the zero line of the response function indicating they are insignificant, however, it may be desirable to choose a response function for an earlier step. Also, a higher F level for termination of analysis can be chosen if the response function is to be used for some sort of statistical estimation.

The results of stepwise multiple regression on the amplitudes of the eigenvectors are different from stepwise multiple regression on the actual climatic variables. For example, Fig. 7.14 includes the results of a stepwise multiple-regression analysis using the same climatic and tree-growth data as in Fig. 7.13 except that the actual climatic data rather than amplitudes of eigenvectors are used as predictor variables. The plotted bars represent the regression coefficients for the climatic variables, R^2 is the square of the multiple correlation coefficient, and the response functions for comparable steps to those in Fig. 7.13 are shown without the confidence intervals.

At step 1, the regression coefficient for June precipitation is entered which reduced $39 \cdot 8\%$ of the variance; while in the response function for step 1, 26 of the 28 elements of the response function are significant—reducing $36 \cdot 3\%$ of the variance. At step 3, temperature of July, precipitation of October, and precipitation of June are entered as

significant, reducing 67.2% of the variance. The response function
exhibits a complicated pattern with 18 elements out of 28 significant,
reducing 67·3% of the variance.
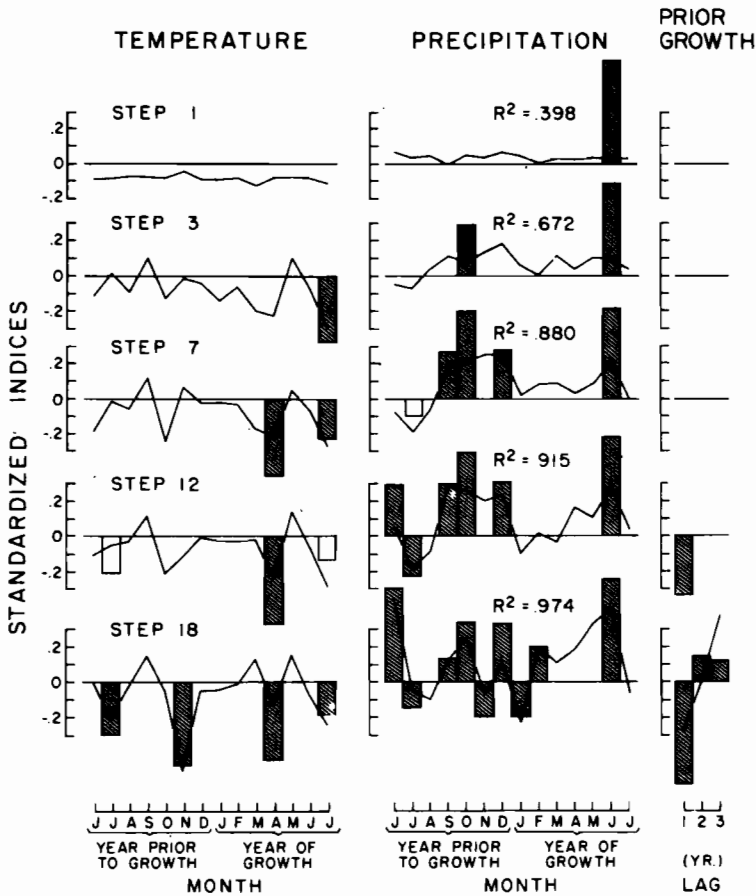
FIG. 7.14. The regression coefficients for stepwise multiple regression on the same
climatic and tree-growth data utilized in Fig. 7.13. The comparable response functions as
shown in Fig. 7.13 are drawn at each step to facilitate comparison. The shading indicates
those partial regression coefficients that are significant at the 95% level of confidence. The
percent variance reduced can be calculated in the same manner as in Fig. 7.13.

At step 7, the regression analysis entered seven variables, six of which are significant, reducing 88·0% of the variance. The comparable step in the response function included 13 significant elements. At step 12 there are only 10 regression coefficients entered, because a coefficient for November precipitation, entered at step 8, is deleted at step 12, probably as a result of its intercorrelation with other variables entered into the regression. Prior growth for a lag of one year is entered as a significant predictor variable. Only eight of the coefficients are significant and the equation reduces 91·5% of the variance. The response function for the comparable step has 10 elements which are significant.

Step 18 was the final step as the F ratio at higher order steps dropped below values of 1. A total of 16 variables are entered and are significant, including partial regression coefficients for prior growth at all three lags and reducing 97·4% of the variance. The last step for the response function utilized 20 amplitude variables and reduced 97·7% of the tree-growth variance; and 14 of the elements plus two coefficients for prior growth are significant.

It is evident from these results that the regression coefficients at the various steps often, but not always, coincide with the larger elements of the response function. However, there are important differences. For example, at step 18 the significant regression coefficients are associated with four variables of temperature and are negative, indicating the predominance of a general inverse effect of temperature on growth. Yet the response function indicates that the weights for temperatures are significant and positive for three additional months. The regression coefficients for precipitation stress several apparent relationships from month to month, but the large positive weights for precipitation in April and May are not represented by the coefficients of the stepwise analysis of the untransformed climatic variables. Apparently, intercorrelation among predictor variables prevents variables for April and May precipitation from entering the equation, although the variables may have been limiting to growth. Three prior growth variables are entered by the stepwise analysis while only two variables for prior growth are utilized in the response function analysis.

In general, there are usually more significant items in the response function results than in the straightforward stepwise multiple regression analysis. The response functions also have a weight for all variables which is sometimes helpful in visualizing the growth response. Lastly, as in the case of spring precipitation for step 18, the results from the response function seem more reasonable and consistent than the results from the straightforward regression analysis.

4. Transfer Functions

Transfer functions are obtained in a manner similar to response functions, the primary difference being that transfer functions are obtained by performing regression analysis using the ring-width chronologies as predictors and the climatic data as the predictands. Thus, the data $_{\blacksquare}F_{\blacksquare}$ in Equation 7.17 would be ring-width chronologies which are obtained from sites differing in geographic location, in species, or in microenvironments.

The principal components, $_{\blacksquare}E_{\blacksquare}$ (eigenvectors of ring-widths, Equation 7.18), express modes of growth behavior (Fig. 7.15). The examples shown include the seven most important eigenvectors derived from chronologies at the 26 sites described by Fritts (1965). The first eigenvector accounts for 27% of the tree-growth variance and is characterized by a marked resemblance among the chronologies of the Colorado River Basin and surrounding areas. This pattern can be observed as a positive growth anomaly during the decades 1616–1625 and as a negative growth anomaly during 1896–1905 (see Fig. 1.13). The second principal component (Fig. 7.15) represents anomalies in which higher-than-average growth occurs over northwestern United States, while an area of lower-than-normal growth is centered over New Mexico. The growth for the decade 1521–1530 resembles this pattern in a positive sense, and the growth for 1626–1635 and 1931–1940 resembles the pattern in an inverse sense (see Fig. 1.13).

The remaining five patterns each reduce a decreasing amount of variance and express smaller and smaller scale variations in growth. The anomalies expressed by the fourth principal component can be observed in the growth anomalies for the decade 1806–1815; those of the sixth resemble in an inverse sense the growth anomalies during 1776–1785 (see Fig. 1.13). The first seven principal components representing the largest scale growth anomalies reduce a total of 67% of the growth variance. As in the case of eigenvectors of climate, the higher-order principal components may be discarded to eliminate the small-scale variations, since the smallest ones are likely to represent errors, noise, the least important features of growth, or growth anomalies that are not related to macroclimatic variations.

In order to appreciate what the spatial eigenvectors of growth can tell us, consider the following theoretical situations. If all the chronologies of a region represent exactly the same information, only one principal component, with elements of the eigenvector weighting all chronologies equally, would reduce all the variance. On the other hand, if all growth chronologies are independent of every other chronology, theoretically there would be the same number of eigenvectors as chronologies and they

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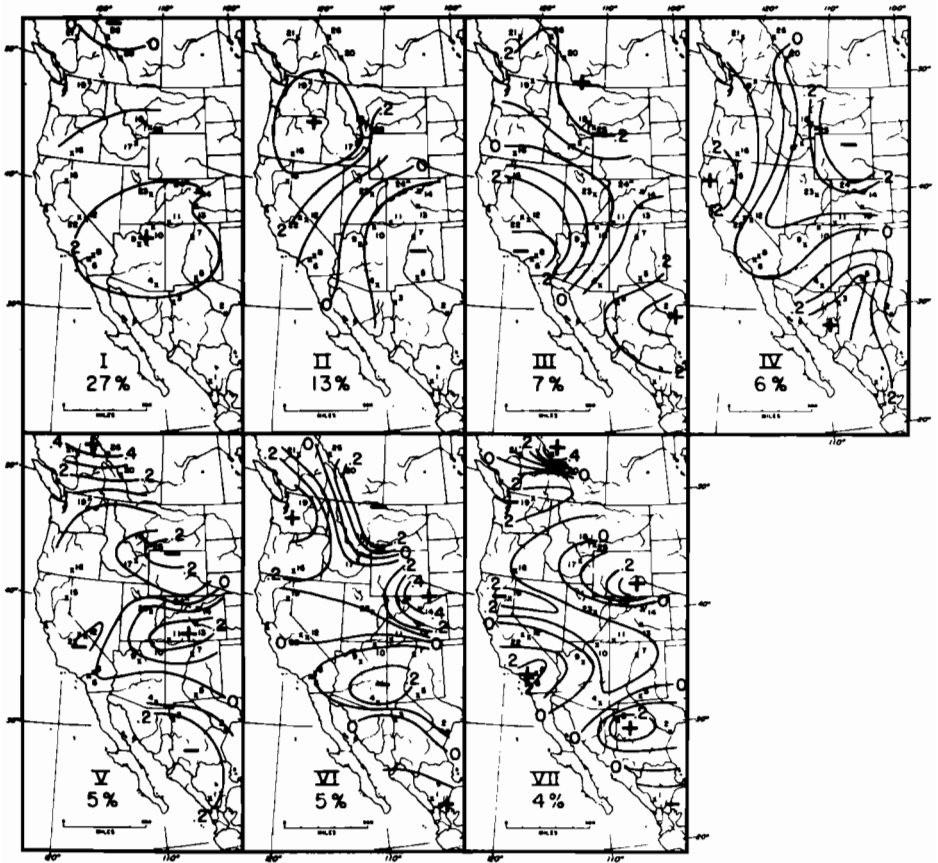
FIG. 7.15. The first seven eigenvectors of tree growth from 26 sites throughout western North America (Fritts, 1965). The percentage growth variance reduced by each eigenvector is shown.

would all reduce about the same variance. However, the real world is somewhere between these two extremes. If there is a large amount of redundancy in the several variables, most of the variance is reduced by a small number of eigenvectors. As more and more of the data sets behave independently, more and more eigenvectors are required to reduce the variance.

The growth eigenvectors and the normalized growth data for each year are multiplied (Equation 7.19) to obtain the amplitudes which express the amount of similarity of growth patterns during each year to

each eigenvector pattern. These amplitudes can then be used as predictors of climate in a multiple regression equation (Equation 7.20) as in the response function analysis. Such regressions on the amplitudes of growth eigenvectors utilize the spatial variability of the chronologies to statistically reconstruct the anomalies in the macroclimate that had originally produced the corresponding anomalies in the growth.

The similarity between spatial anomalies of growth and climate were noted by LaMarche and Fritts (1971a). They examined the most important eigenvectors for the ring-width indices from western North America and found that they resembled eigenvectors of precipitation for the same region described by Sellers (1968). Fig. 7.16 includes selected principal components of monthly precipitation that occurred during 1931–1966 which matched the first four principal components of growth for A.D. 1700–1930. The first principal component exhibits large-scale anomalies over the Colorado Plateau for both precipitation and tree growth. The second component expresses opposite anomalies between northwestern United States and New Mexico and southwestern Texas. The third component for precipitation in October and for tree growth exhibits high values over the east slope of the Rocky Mountains and low values over California and the extreme Southwest. The third component for March precipitation and the fourth component for tree growth exhibit positive areas over the Pacific Southwest, the northern Rocky Mountains, and the northern Great Plains, while negative areas can be noted over the southwestern Plains and the extreme Northwest.

One way to obtain the actual transfer function is to calculate a multiple regression equation ($_1R_p$, Equation 7.20) which uses the eigenvector amplitudes of tree growth as predictor variables to estimate a climatic variable in a particular region or site. Since there is sometimes a lag of growth for one or more years behind the occurrence of certain climatic variables, the statistical calibration model may include growth predictors which lag one or more years behind the climatic occurrence. Also, autocorrelation may exist in the tree growth data, and it may be necessary in some cases to include growth for prior years so that the constraint due to prior growth is separated from the signal of climate (see Figs. 1.10 and 1.11).

In general, transfer functions are derived in the same manner as response functions, only the variables used for predictor and predictand sets vary. However, the model for transfer functions can be simple, utilizing only a small number of predictor variables, or it can be extremely complex. While the complex models can potentially reduce a large amount of the variance in the predictand for the dependent period, the simpler models using only the large-scale principal components may
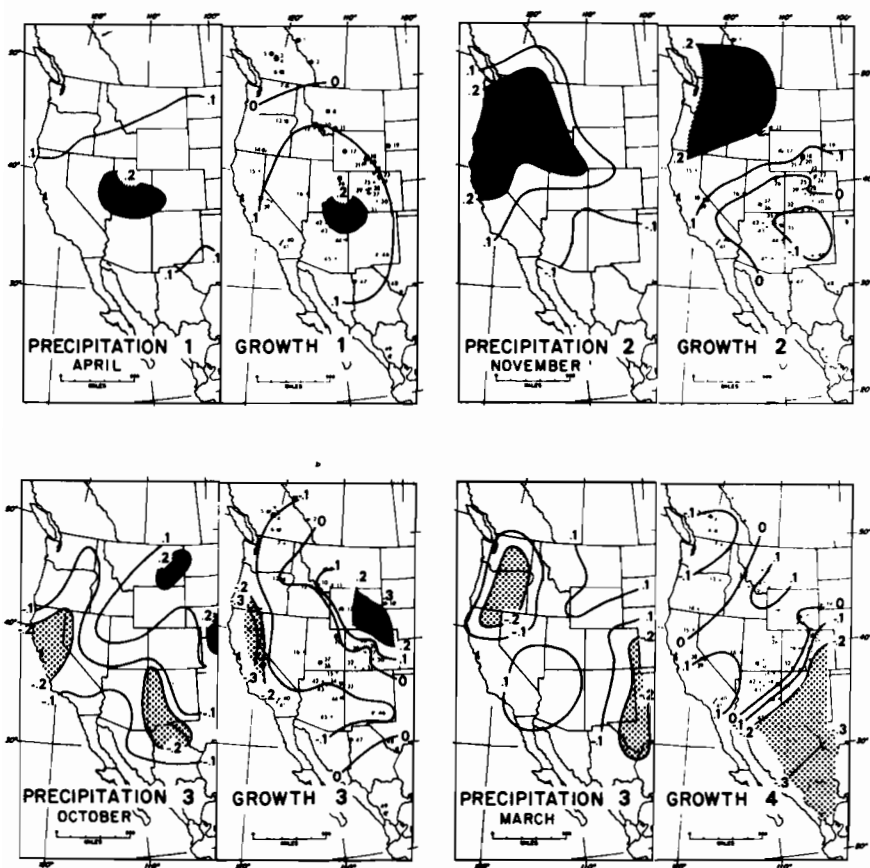
FIG. 7.16. Similar patterns in the spatial anomalies of precipitation and growth occur over western North America. The precipitation data (Sellers, 1968) were obtained by principal component analysis of monthly precipitation data for selected climatic regions of the United States from 1931–1966. The growth data were obtained by analysis of 49 tree-ring stations over western North America for 1700–1930. Examples are selected from the first three principal components of monthly precipitation and are matched with similar principal components of tree growth. (Redrawn from LaMarche and Fritts, 1971a)

hold up better, as seems to be the case when they are tested against independent predictard sets.

Now that the working tools of dendroclimatic analysis have been described, attention will be directed to analyzing the relationships and

reconstructing past climate. The first portion of Chapter 8 deals with examples of response function analyses. Examples of various models used to obtain transfer functions and their applications will be described more fully in the latter portion of Chapter 8 and in Chapter 9 of this book.

Chapter 8

Interpretation of Climatic Calibrations, Reconstruction, and Verification

I. Introduction

A variety of techniques have been described for calibrating ring-width variations with variations in climate and for reconstructing past variations in climate. The simplest calibrations usually involve few statistics and rely upon biological insight for recognition and documentation of some type of relationship. Climatic data are converted to growth estimates and compared to the actual growth measurements. Ring-width variation is then utilized to infer past variations in climate.

Most dendroclimatic studies include some quantitative analysis. At the end of Chapter 7 two recent innovations in quantitative methods were described. The two which will be further discussed here are (1) the

multivariate response function, which is used to describe the ring-width response to variations in climate, and (2) the multivariate transfer function, which transforms values of ring width into estimates of climate.

The first portion of this chapter describes the details of six different response functions and then summarizes an analysis of 127 North American response functions. Differences are examined in terms of seasonal variations in the environments and their effect on the growth-controlling processes. The last portion draws upon recent studies to illustrate the variety of approaches to dendroclimatology, ranging from the use of simple logical inference to the use of rigorous calibration, reconstruction, and verification. This chapter focuses on single station and local climatic reconstructions, while the last chapter describes regional and synoptic studies employing spatial analysis.

II. Response Functions

A. Examples of Response Functions

Response functions like those described in Chapter 7 have been calculated for a large number of North American tree sites (Fritts, 1974) and more recently for a number of European study sites. All response functions described here include 14 weights (coefficients or elements) associated with variables of monthly mean temperature and 14 weights with variables of total monthly precipitation. Three additional weights are included to allow assessment of growth on the relationships during prior years. Other climatic factors and monthly intervals can be used instead if the data are available and if there is a reason to believe the factors are important in the growth–climatic relationship.

The three plots in Fig. 8.1 represent response functions for semiarid conifers showing weights for temperature on the left, weights for precipitation on the center right, and weights for prior growth on the extreme right. The vertical bars which delimit the 95% confidence limits are used to test for significance.

The uppermost plot for Quartz Mountain *Pinus ponderosa* illustrates a weakly linked relationship, since most elements of the response function have confidence limits intersecting zero and therefore must be considered insignificant. A total of 46% of the variance is accounted for by climate and 39% by prior growth so that climate and prior growth together explain a total of 85% of the ring-width variance.

Although no temperature weight is significant, those for summer are generally negative and those for winter are positive. Weights corresponding to precipitation are more often positive, but only the one
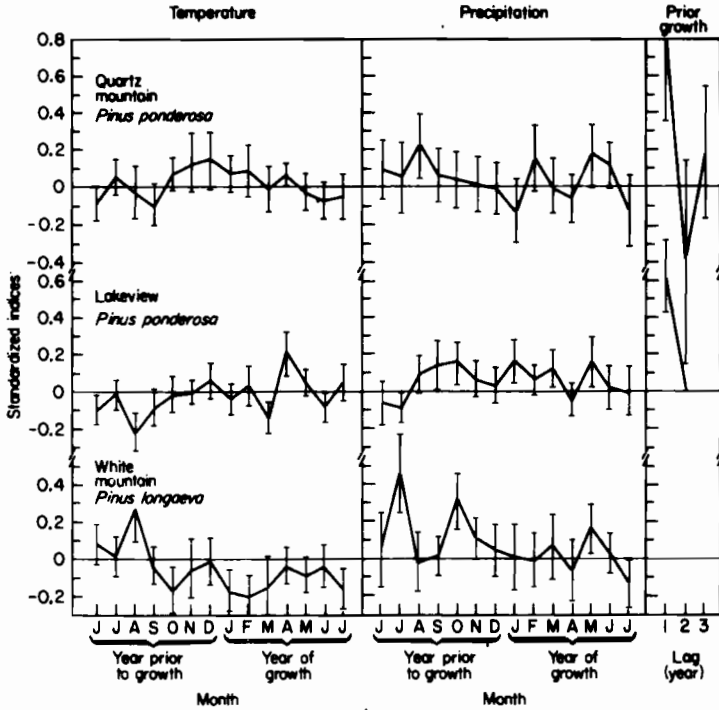
FIG. 8.1. Three response functions for ring-width indices of *Pinus ponderosa* on Quartz Mountain, Washington, and Lakeview, Oregon, and *Pinus longaeva* in the White Mountains of California. Each response function includes 14 weights for average monthly temperatures and 14 weights for total monthly precipitation from June of the year prior to the season of growth through the July concurrent with growth. Three additional weights are associated with prior ring-width index at lags of 1, 2, and 3 years. A positive weight indicates a direct relationship of the climatic variable or prior growth variable to ring width, and a negative weight indicates an inverse relationship. The vertical lines designate the 0·95 confidence level.

for August is significant. The weight for prior growth at a lag of one year is positive and significant, indicating an important direct relationship, but at lags of two and three years the respective weights are negative and positive, both being insignificant.

The excessively wide spread of the confidence limits indicates that any one element of this response function provides information of questionable reliability. However, the predominance of water stress can be inferred from the large number of negative weights for temperatures during summer, and low temperature limitations can be inferred from

the large number of positive weights for winter temperature. In addition, the positive weights for precipitation suggests that moisture is limiting, especially in late summer of the preceding year and May through June of the growing year, while the positive weight for prior growth at a lag of one year indicates the presence of first-order autocorrelation.

The plot for Lakeview *Pinus ponderosa* (Fig. 8.1) is more typical of arid sites as it represents a stronger climate–growth linkage. It is similar to the response function for the Quartz Mountain site in that climate accounts for about the same amount of ring-width variance. A total of 48% is accounted for by climate and 39% by prior growth, giving a total of 87%. It differs, however, in that more weights for climate are significant. This occurs because fewer eigenvectors are used in deriving the response function, so that the error terms for fewer eigenvectors are included in the confidence limits.

Weights for variables of temperature are negative and significant for the prior June, August, and March, and the current June. Only the weight for April is significantly positive. For precipitation, the only significant negative weight is for the July prior to growth, while significant positive weights for precipitation are those for September, October, January, March, and May. The weight for growth at a lag of one year is the only prior growth variable that was entered into the response function equation, and its positive sign indicates the presence of first-order positive autocorrelation.

The four negative weights for temperatures imply that water stress is limiting for at least four months during the year. However, the positive weight for temperature in April indicates that higher than average temperatures at that time are favorable to growth, perhaps as they influence the breaking of dormancy and the resumption of physiological activity in the tree. The weights for precipitation indicate that above-average precipitation during September, October, January, March, and May are beneficial to growth, undoubtedly as they affect the water balance of the trees. However, lower than average precipitation in the prior July is significant, perhaps because it interacts with the growth which is occurring at that time. In short, annual rings in the Lakeview trees are shown to be wide when the autumn, winter, and spring are wetter than average, and when late summer of the prior season and early spring are cooler than average, changing to warmer than average by April.

The plot in the lower part of Fig. 8.1 is typical for arid-site *Pinus longaeva* from the White Mountains of California. Climate accounts for 63% of the growth variance, and the effect of prior growth is not significant. The weights for temperature of the prior August are

significantly positive, and those for October, January, February, and the current July are significantly negative. The weights for precipitation are generally positive, with those for the prior July, October, and May being significant. The weight for precipitation during the current July is negative and significant.

It may be inferred from this response function that rings are wider than average in White Mountain *Pinus longaeva* when temperatures are (1) higher than average in ·the prior summer favoring prior growth conditions, and (2) lower than average in late autumn, winter, and spring maintaining low respiration rates within the trees. Wide rings also result when precipitation is (1) higher than average in the prior July and October and the current May, which helps to maintain a favorable water balance, and (2) is lower than average in the July concurrent with the growing season, a result with no clear-cut explanation.

The plots in Fig. 8.2 are response functions for *Quercus alba* from eastern North America and for two conifer species in Western Europe. In the first example, climate accounts for 59% of the ring-width variance and prior growth accounts for 2%. The significant positive temperature weights are for the prior July, November, and February, the latter two being months when the tree is leafless and apparently dormant. In June the temperature relationship is inverse and significant. The significant weights for precipitation all are positive and include the months of the prior August, May, June, and July, all times when the tree is physiologically active. The weight for prior ring width is insignificant.

It can be inferred from this response function that rings are widest when (1) precipitation is higher than average and (2) temperatures are lower than average during the growing season, both of which are factors that help maintain a favorable water balance in the trees. Above-average temperatures and moisture prior to the growing season can also favor growth since they promote rapid physiological activity within the trees.

The variance explained by climate for *Pinus halepensis* near Marseille, France, is 42%, and that explained by prior growth is 26%, making a total of 68%. The negative weights for temperatures in October, February, and April are significant. All weights for precipitation are positive for the period from August through May except for October. The predominant effect of winter moisture on growth is likely an effect of high precipitation on soil moisture recharge and winter photosynthesis. Temperature is apparently less important to growth, although the inverse relationships are probably due to water stress, and the direct relationships due to respiration and preconditioning phenomena occurring in October, February, and April.

The variance explained by climate in the third response function (Fig.

8.2) for *Pinus sylvestris* in northern Sweden accounts for 44%, while prior growth accounts for 20%. The weights for temperature in the prior June and the concurrent July are positive and highly significant, and this is inferred to indicate the major control of growing season temperatures on ring width. The positive temperature weights for September and April are smaller but also significant; those for the prior July and August are negative and significant. As might be expected for the northern tree line, fewer weights for precipitation are significant. Those for June of the year prior to growth and for March and April are positive, while those for May and July are inverse. Ring width at a lag of one year is the only prior
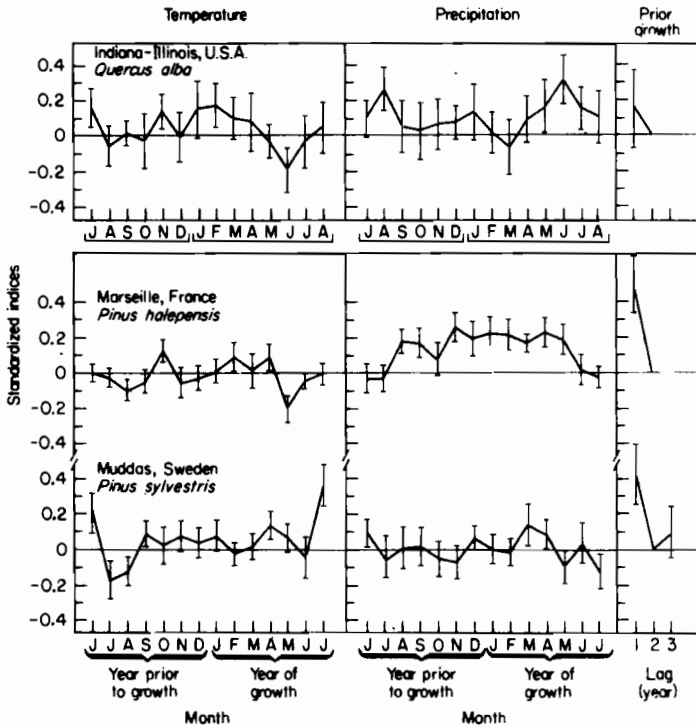
FIG. 8.2. Response functions for ring-width indices of *Quercus alba* in Indiana and Illinois (Ashby and Fritts, 1972), *Pinus halepensis* in Marseille, France (courtesy of Françoise Serre), and *Pinus sylvestris* from northern Sweden (courtesy of B. Jonsson and T P. Harlan). The 14-month interval for the first differs from the latter two by one month. See Fig. 8.1 and text for further explanation.

growth variable that is significant and its weight is positive. It is inferred from positive response to temperature and inverse response to precipitation that on this site Model Part C (Fig. 5.10) is dominant.

The varying signs of the six response functions in Figs 8.1 and 8.2 indicate the presence of both direct and inverse relationships; the confidence limits indicate varying significance; and the presence or absence of prior growth variables indicate varying autocorrelation relationships. Such relationships with prior growth can be visualized as climatic phenomena, for they incorporate effects of climate on growth in prior years which are transmitted to a later growing season through the autocorrelation phenomenon.

Because of the statistical interaction of prior growth values with the prior summer climate, the weights for prior summer climate must be interpreted with caution if ring width at a lag of one year has been entered as a part of the statistical relationship. The regression portions out the growth and climatic effects as it attempts statistically to reconcile their intercorrelations. If climate and growth are highly correlated with one another, their individual weights in the response function may be diminished or be of opposite sign.

The Muddas site response function (Fig. 8.2) provides a good example of this kind of interaction. July temperature and concurrent ring width are directly correlated. From this fact it is concluded that temperature of the prior July and prior growth are also directly correlated. However, the weight for the response function for July temperatures in the prior summer is negative, while the weight for prior growth is positive. The equation has separated the effects of the two directly correlated variables statistically holding all but one variable constant. Thus, when prior growth is held constant the statistical effect of temperature with prior growth held constant is inverse. If prior growth had not been used as a variable, the strong positive linkage between prior temperature, prior growth, and ring width would have prevailed, and the weight for temperature of the prior July would likely have been positive and significant.

B. Analyzing Variations among Response Functions

Response functions have been obtained for a large number of coniferous species and sites in western North America. The smoothed response functions shown in Fig. 5.12 are the means for five different species or species complexes. An analysis of these same data including response functions for 127 individual ring-width chronologies (Fritts, 1974), is presented below. Most of the response functions were calculated

using monthly mean temperatures and total monthly precipitation for homogeneous climatic regions within state boundaries. In a few cases climatic data for single stations were utilized, but the results for regional climatic data usually surpassed those for single-station data in explaining a greater percent of ring-width variance.

The weights or elements in each response function (excluding variables for prior growth) were transformed to the same variance by dividing each element of the response function by the standard deviation of all 28 elements, then multiplying by a constant. A multivariate procedure referred to as cluster analysis as described by Tryon and Bailey (1970)
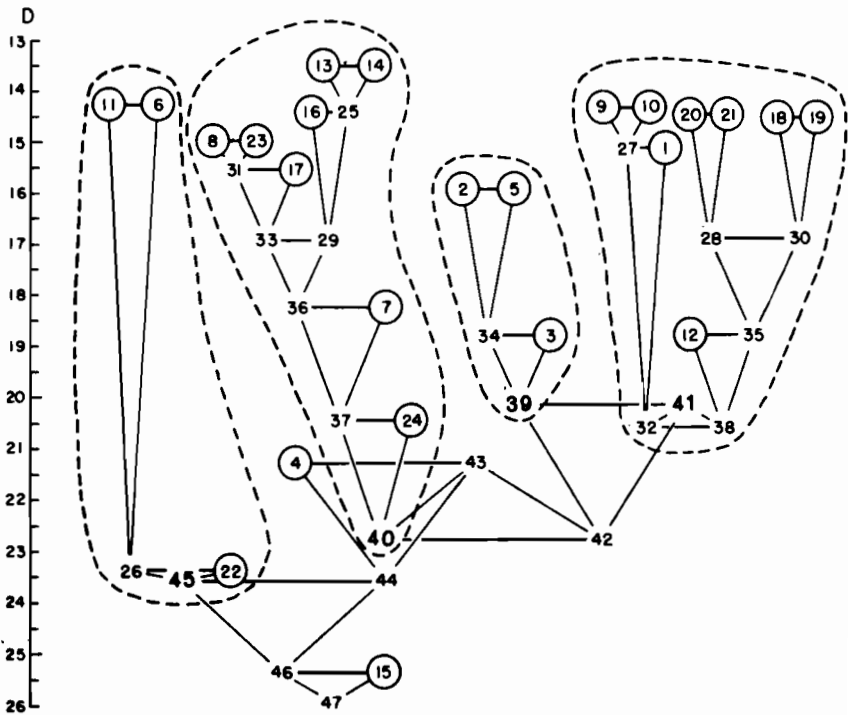
FIG. 8.3. A diagrammatic representation of the relationships among the clustered groups of response functions. The circled numbers represent the basic clusters of three or more response functions. Each cluster is paired with another which most resembles it as indicated by solid horizontal lines joining numbers, and the pairs are plotted as a function of their similarity. The most similar have low values of D and are plotted near the top of the figure. The dashed lines enclose four distinct sets of response functions as described in the text. (From Fritts, 1974)

was used to sort the response functions and to classify them into meaningful groups and subgroups. The cluster analysis was necessary because the differences among the 127 response functions were often subtle and difficult to sort and classify by visual inspection. The dashed lines shown in Fig. 8.3 encircle four categories of response functions which are merged into four large clusters shown near the bottom of each encircled set as numbers 41, 39, 40, and 45. Five relatively independent features of the response functions were identified as differentiating factors in the process of clustering (Fritts, 1974), and these factors were used to sort and group the 127 response functions into their respective classes.

Figure 8.3 is a diagram representing the clustering response function hierarchy, where the ends of the branches terminate in 24 distinct groups, each of which includes three or more similar response functions. These 24 groups are represented by the circled numbers 1 to 24 and are referred to in the following discussion as the basic clusters. Each is paired with the cluster it most resembles and the pairs are indicated by a horizontal line drawn between them (Fig. 8.3). The vertical position of each pair in the figure expresses the dissimilarity as measured by the scale marked D on the left margin of the figure. Pairs at the bottom are the least similar while those at the top are most similar. The most similar pair is identified first in the clustering process and the two clusters are merged into a single cluster group. The next most similar pair is then identified and these clusters merged. Pairing and merging continues until finally all the clusters are merged into a single group, shown as number 47 at the bottom of the figure. The cluster groups to be merged become less and less similar as more response functions are included.

The elements of the mean response function for all 127 sites represented by cluster 47 are shown in Fig. 8.4. The average weight for each of the 14 elements for temperature is shown in the upper portion of the plot; the average for each of the 14 elements for precipitation is shown in the lower portion. The average for prior growth at each of the three lags is also shown, even though these elements were not utilized in the clustering procedure. This mean response function for all sites has mostly positive weights for precipitation, representing the generally positive association of arid-site tree growth with precipitation. The means for elements of the response function associated with temperature are nearer to zero than those for precipitation, because the temperature elements for individual response functions exhibit both positive and negative signs. The average elements of temperature that depart most markedly from zero and are most often negative, are those for the months of October, March, May, and June.

This averaged response function confirms the generally stated
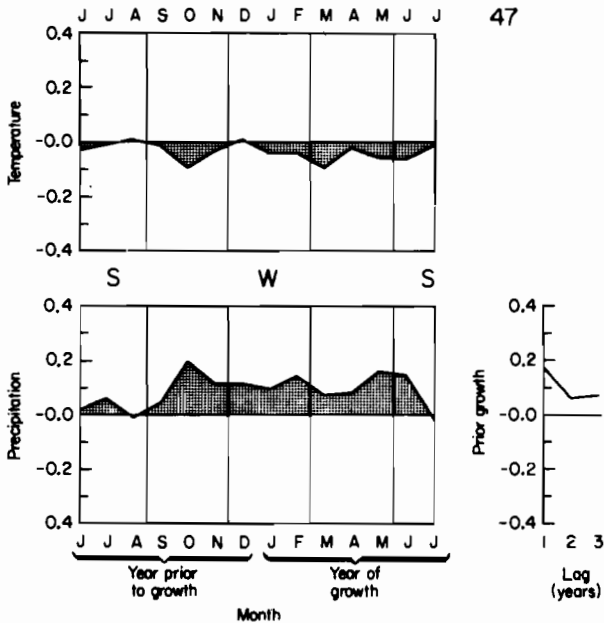
FIG. 8.4. The mean values for the 31 elements of all 127 response functions representing the 28 climatic variables and the three variables for prior growth (cluster 47, Fig. 8.3). The magnitude of the averaged elements and the sign indicate the average importance and the average direction of the relationship that exists. Vertical lines divide the seasons: S, W, and S designate prior summer, prior winter, and the summer concurrent with growth. (From Fritts, 1974) ·

conclusion of many of the early studies that tree rings from arid-site conifers are narrowest when precipitation during the year is low and when temperatures during certain months of the year are high with respect to normal conditions at each site.

It is apparent from the study that certain clusters exhibit a relatively high degree of resemblance and others do not. The largest differences revealed by clustering appear to result from varying site factors, such as exposure, elevation, slope, and geographic location. Species differences are present (see Fig. 5.12), but interestingly enough they are not as marked as the differences due to site characteristics.

The mean response function for any one of the four encircled cluster sets is different from the mean response function for the other sets (Fig. 8.5). These differences may be interpreted as the most important differences among the 127 response functions. The average response
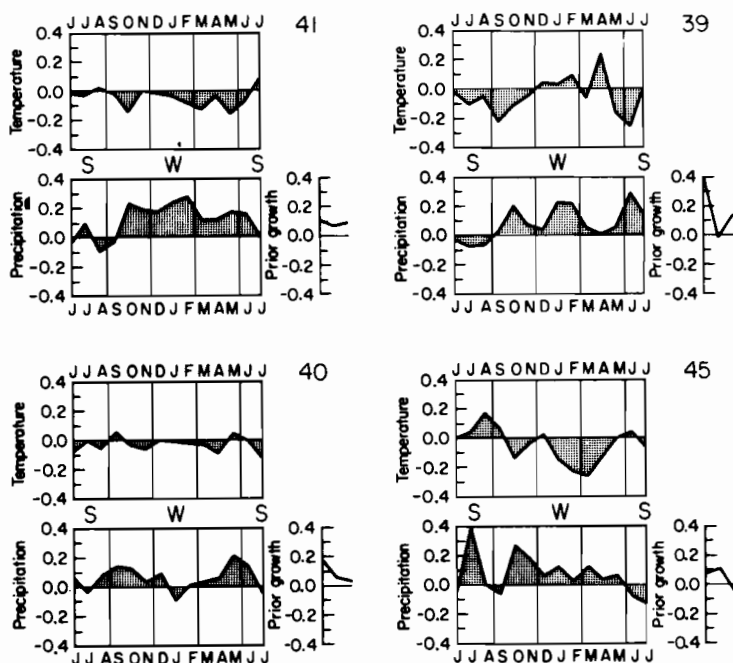
FIG. 8.5. The mean values for the 31 elements of the response functions for the four encircled groups of clusters shown in Fig. 8.3 as expressed by clusters 41, 39, 40, and 45. The magnitude of the elements and sign indicate the importance and direction of relationships that exist. Vertical lines divide seasons as in Fig. 8.4.

function of cluster set 41 (top left, Fig. 8.5) resembles that of cluster 47 (the mean of all response functions shown in Fig. 8.4). In these response functions there is generally a direct relation between growth and precipitation, especially during the latter portion of autumn, winter, spring, and the first month of summer, June. Temperature on the average is inversely related to growth for the six months of October, February, March, April, May, and June.

The branches associated with cluster set 41 shown in Fig. 8.3 terminate with eight basic clusters. One group, indicated by number circles 19, 18, 21, 20 and 12, is related to cluster set 41 through an intermediate cluster, 38, on the right. Another group, 9, 10, and 1, is related to cluster set 41 through an intermediate cluster, 32, on the left. The differences as well as the similarities within the set of basic clusters can be expressed by averaging the mean weight of response functions in each basic cluster,

then plotting all mean weights which were significantly greater or less than zero (in this case at the 85% probability level) (Fig. 8.6). The upper plots on the left of this figure include the statistically significant mean elements of the response functions in basic clusters 19, 18, 21, 20, and 12. The plots for 9, 10, and 1 are shown on the right.

All response functions in the first two groups have generally large positive values for the elements associated with precipitation for autumn, winter, and spring as is shown in the mean response function for cluster set 41 (Fig. 8.5), though certain variations among the response functions of the basic clusters are evident. Many of the elements for variables of temperature are negative, representing a predominance of inverse relationships for temperature in autumn, winter, and spring (Fig. 8.6 top). In a few cases, particularly significant elements are positive, indicating a direct relationship between temperature and growth in certain months.

Basic clusters 19, 18, 21, 20, and 12 include response functions where the elements for temperature and precipitation during the prior summer and for those at the end of the current summer (July) are frequently correlated positively with growth. However, for basic clusters 9, 10, and 1, the significant weights for summer temperatures are either negative or insignificant, while those for midspring (April) are either positive or insignificant.

Thirty-two percent of all response functions were included in the clusters associated with 41. The trees are on arid, exposed, and well-drained sites located on the mountains and mesas of Arizona, New Mexico, Colorado, and Utah (Fritts, 1974). The chronologies are most typical of arid-site trees as described by Schulman (1956) and include 73% of the *Pinus edulis* stands sampled in this particular study. *Pinus edulis* is an arid-site species restricted to low elevations and latitudes in southwestern North America (see Fig. 4.16). Also included are 43% of the sites with *Pseudotsuga menziesii* and 26% with *Pinus ponderosa*.

Three closely related basic clusters of response functions are associated with cluster set 39 (Fig. 8.3). The means for the elements of the response functions included in 39 are shown in the upper right portion of Fig. 8.5. The elements for precipitation are large and positive for certain months in the prior autumn and winter, and the summer concurrent with growth. The elements associated with temperature are, on the average, negative for the prior summer, autumn, and late spring, and early summer concurrent with growth, while the means associated with temperatures of April and the winter months are positive. The means of the significant elements of the response functions in the three basic clusters associated with 39 (basic clusters 5, 2, and 3) are shown in the left
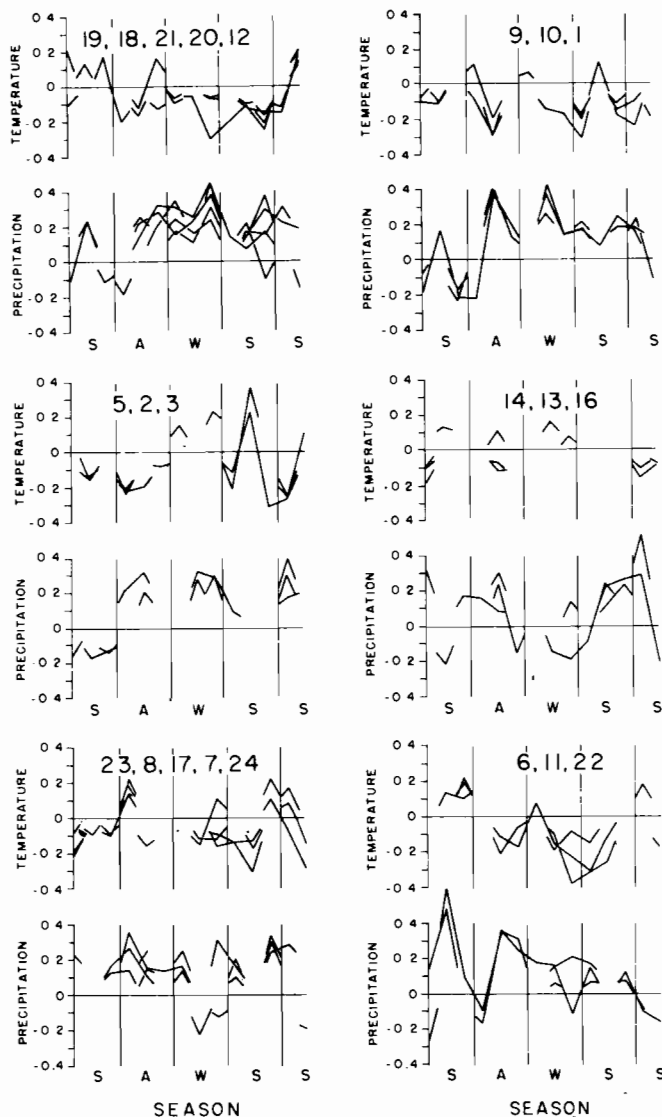
FIG. 8.6. The means of significant elements in the response functions included in each basic cluster are plotted as a function of the variable they represent. Plots of similar clusters are superimposed to show the kinds of variability that occur among the basic clusters. Numbers at the top of each set designate which of the basic clusters from Fig. 8.3 are represented. Variables are plotted as in Fig. 8.5.

middle portion of Fig. 8.6. Basic clusters 5 and 2 both emphasize direct relationships of growth with April temperatures, while for 3, the significant direct relationship is for temperatures in February.

The principal feature of this group of clusters is the direct response of growth to temperatures prior to the beginning of cambial activity. Basic clusters 5 and 2 represent response functions for 22% of the *Pinus ponderosa* and *P. jeffreyi* sites. Basic cluster 3 includes response functions for a site of *Pseudotsuga menziesii* in Montana, *Pinus edulis* in Arizona, and *P. flexilis* in Wyoming. All are on steep west-facing slopes.

The response to temperatures in another basic cluster (15) shown near the bottom of Fig. 8.3 resembles basic cluster 3 in that there is a marked direct relationship with February temperature, but it differs in that March shows a significant direct temperature effect. Therefore, basic cluster 15 was not classed with any of the four large sets and appears in the diagram in Fig. 8.3 nearest the mean cluster for the entire set (47).

Cluster set 40 (Fig. 8.5) portrays the mean for the third set of response functions encircled by dashed lines in Fig. 8.3. The means for elements associated with precipitation (especially for winter) are not as large as for those in 41 and 39. This indicates a lower importance of winter precipitation as a limiting factor on growth but still shows a similar dependency on warm-season moisture. The mean values of the weights for temperatures are small, with some indicating direct and some indicating inverse effects.

The significant elements of each basic cluster, 14, 13, 16, 23, 8, 17, 7, and 24, are shown in the middle and lower portions of Fig. 8.6. Many of the elements associated with temperature for basic clusters 14, 13, and 16 do not appear in the plot because they are statistically insignificant. In two cases where winter response is significant, a direct relationship between temperature and growth is apparent. During the warmer seasons, the elements for temperature are more often negative, indicating that growth and temperature relationships at that time of year are more commonly inverse than direct. It is difficult to generalize here because there are considerable differences among the elements for temperature in the response functions representing basic clusters 13, 14, and 16.

The elements in basic clusters 23, 8, 17, 7, and 24, as shown at the lower left of Fig. 8.6, often express a direct relationship between growth and temperature during early autumn, late spring, and summer of the growing season. Within this cluster, elements for precipitation during winter months are in some instances positive, but in other instances negative.

The response functions of set 40, in general, express a direct relationship with precipitation in autumn, late spring, and early summer,

but differ markedly in the signs and values for temperature elements. In a few cases there is an inverse or low correlation of growth with winter precipitation and a direct correlation of growth with temperatures in early autumn or late spring. The set includes 40% of the *Pseudotsuga menziesii* sites, 43% of the *Pinus ponderosa* sites, and 20% of the *Pinus edulis* sites used in the cluster analysis.

Elevations of the sites are often high and exposures are usually other than south-facing. The habitats are apparently relatively cool and moist where low temperatures in the cooler seasons would tend to be severe and hence lead to physiological inactivity or to direct temperature and growth relationships. Climatic conditions occurring during the growing season are emphasized more than those during midwinter and this suggests that models A and C, described in Chapter 5, are the most important for describing these particular climate–growth relationships.

The averages for elements of the response functions of the basic clusters associated with cluster set 45 (Fig. 8.3) are shown at the lower right portion of Fig. 8.5, and the differences among the three basic clusters are shown on the lower right portion of Fig. 8.6. Large positive values for elements of the response functions can be noted for the summer and autumn seasons prior to growth. The weights associated with precipitation in the prior July, October, and November, and for temperatures in the prior July and August are large and positive. However, the weights for elements of temperature are large and negative for autumn and late winter through early spring. Those for precipitation in June and July, the period of the growing season, are also negative.

This type of response to climate expresses a negative feedback relationship whereby a summer of extreme climate appears to favor the current growth in one direction and the following year's growth in the reverse direction. Such a negative feedback counters tendencies for positive autocorrelation, and the mean for the element associated with prior growth at a one-year lag is smaller than in the other basic clusters. However, the effects on growth of the climatic variations during winter and spring are similar to those of other groups in that precipitation is directly related and temperature is inversely related. Unlike many other response functions, the weights for temperatures during winter and early spring are larger than those for precipitation, indicating that temperature is more important than precipitation during the winter period.

These clusters include response functions for high-elevation arid sites, mostly for *Pinus longaeva* (also see Fig. 8.1). It can be noted from Fig. 8.3 that basic cluster 22 differs markedly from the mean for the other two basic clusters in this set. This particular basic cluster includes response

functions for extremely high-elevation sites near the upper tree line for *Pinus longaeva* and one for *Abies concolor*. The weights in the response functions for these sites differ in that growth is directly correlated with temperatures during the concurrent summer as well as during the summer prior to growth. This response, which is associated with cold high-elevation sites of arid regions, is consistent with the response of conifers at high northern latitudes, in that the temperatures of the growing season aré important and directly related to ring width.

LaMarche and Stockton (1974) computed response functions for eight high-elevation sites of *Pinus longaeva* and *Pinus aristata* at the upper tree line. The values of the elements they obtained for temperature during the growing season were also large and positive. The elements for precipitation in late summer of the prior year, autumn, and spring were more often positive than those for precipitation in winter, except in the case of some of the more arid sites. The weights for winter temperatures were positive as often as they were negative. LaMarche and Stockton's results confirm further the generalization that ring widths of low latitude trees at the upper tree line are often directly correlated with temperature and sometimes directly correlated with precipitation. The results differ from those of Fritts (1974) reported above, in that growth at their high-elevation sites was not as strongly coupled with winter and early spring temperatures as occurred in the more arid habitats.

C. Frequencies of Positive and Negative Response Function Elements

Certain significant features are evident from a frequency analysis of the signs of the response function elements. The occurrences of significant positive and negative elements of the 24 basic clusters were examined, weighted for the number of response functions they represented, and tabulated by season of occurrence. Table 8.I includes the percentage of response functions in which significant positive and negative weights were exhibited in each of the five seasonal periods (Fritts, 1974).

These data show that the relative importance of direct and inverse relationships differs markedly between variables for temperature and precipitation and from one season to the next. The elements associated with precipitation are more commonly positive, while those associated with temperatures are more commonly negative. During the winter period the weights for temperatures were significantly positive in 33%, significantly negative in 57%, and not significant in 10% of the cases. During the warmer seasons of the year the weights for temperature were

TABLE 8.1 Percent response functions that exhibit a significant positive or negative weight for at least one month within a particular season.[a]

| | Climatic Variable[b] | | | |
| | Temperature | | Precipitation | |
Season	Positive (%)	Negative (%)	Positive (%)	Negative (%)
Prior Summer	35	57	49	40
Autumn	31	69	87	28
Winter	33	57	90	18
Spring	22	73	93	8
June–July	36	71	46	31

[a]From Fritts, 1974. [b]If coefficients with both positive and negative signs occur for a given season (but for different months), the occurrences are tallied in both the positive and negative columns.

significantly negative from 57% to 73% of the time. The weights for elements of precipitation during the winter and spring were significantly positive 90% and 93% of the time respectively. However, in June and July concurrent with growth the weights for precipitation were significantly positive only 46% of the time.

The variability in the sign of the weights for precipitation at the time of growth in June and July may be attributed to three causes. (1) The ring may be partially formed by that time so that climate may have a limited effect, (2) only two months (June and July) comprise this season as compared to three months for the other seasons, so the probability for a significant weight is two-thirds that for the other seasons, (3) the precipitation for July is generally more weakly correlated or inversely correlated with prior climatic conditions, only partly for climatic reasons. July is positioned at the end of the 14-month period. As a result, a smaller portion of the temperature and precipitation variance for this month is reduced by the first and most important principal components than is reduced by the same principal components for variables well within the 14-month interval. With less variance reduced by the principal components, the elements for July at the end of the 14-month period are on the average lower than the elements for months well within the 14-month interval.

The last condition mentioned above may also reduce the magnitude of the elements corresponding to the June marking the beginning of the 14-month interval. As mentioned earlier, the weights for factors of the prior summer climate may also interact with prior growth, and together they share a role in the predictand variance they reduce. Hence, the response function weights for climate of the prior season are lower and

sometimes the opposite sign than if prior growth had not been entered as a ring-width predictor.

D. Interpreting Response Functions

Although response functions cannot prove cause-and-effect relationships, they should at least be explainable in the light of current knowledge of tree growth. In addition, they may indicate previously unrecognized relationships. This section will examine the elements of response functions for possible systematic and meaningful patterns associated with particular species, site conditions, or geographical regions. Details of the physiological processes and microenvironmental factors are covered in Chapters 2 through 5, and the details of the data for the particular sites are described by Fritts (1974).

It is important to keep in mind that each element of a growth response function represents the net effect of whatever correlation exists between environment and growth. The results of the response function are constrained by the year-to-year fluctuation of the climatic variables above and below their mean values for the particular season. If the mean of the tree's environment and the range of variability are near the optimum for physiological processes, the natural variations in climate may not be sufficient to limit the processes, and there is likely to be no correlation and no significant response function elements. If the mean and range of variability in the tree's environment are near the limits of one or more plant processes, there is likely to be a marked effect on these processes and subsequent correlation between climate and growth. Further, if two processes act in opposite directions, they may cancel one another's effect and result in a lack of correlation between climate and growth.

For example, during a given month, temperature at a site may range between 10°C and 15°C, which is optimal for many processes. No process would be limited by temperatures varying within this range, and the element of the response function for temperature would be insignificant. If temperatures at the site actually range from 0°C to some value such as 10°C, the high temperatures may be near the optimum for certain processes such as net photosynthesis, but those near 0°C may be limiting. Significant correlation with climate may result, and the corresponding elements in the response function would be large, positive, and significant. If, however, the site is very cool (such as on a north-facing slope), leaf temperatures on the average may be below 0°C during the winter so that chlorophyll in the leaves is deactivated. The brief periods of warm temperatures (above 0°C), unlike the very cold periods, may be

unfavorable to growth because they result in high respiration and high consumption of food. In such a case, due to the brief warm periods, the relationship between temperature and processes affecting growth would be inverse, and the element of the response function would be negative.

In other situations, temperature in winter may range between 0°C and above when temperature is positively correlated with important processes and between 0°C and below when temperature is inversely correlated with important processes. These two opposing situations can cancel one another's effects, in which case the corresponding elements would be near zero and insignificant. On the other hand, during the same time period high precipitation may occur more frequently in meteorological situations when temperatures are near 0°C than may occur when temperatures are at either the warm or cold extreme. If such were the case, precipitation rather than temperature could correlate with the growth-related processes and the response function would exhibit a significant element, when in fact temperature, not precipitation, actually is responsible for the physiological effect. While such noncausal associations may not be a particular problem to a dendroclimatologist who is interested primarily in the information on climate contained in the chronology of widths, they do cause difficulties when one attempts to speculate on the physiological basis for the result.

In addition to the statistical associations described above, a meaningful interpretation of response functions must also be based upon a knowledge of how the various plant processes are limited by environmental factors and how the microenvironmental factors are linked to the monthly temperature and precipitation. Since linkages may be different for different seasons, and since the factors limiting growth processes may vary from one month to the next, it is also important to evaluate the elements of the response function in terms of the different seasons and to consider very carefully the transitional periods between seasons when the microclimates are changing from one limiting condition to the next. Furthermore, the energy balance, the water balance, and the climatic regime may vary markedly for different exposures, latitudes, and elevations (Figs. 4.16 and 5.2). It is well also to consider the distribution of the tree species in question because trees on sites near the limits of the species may be particularly susceptible to climatic variations.

Many kinds of relationships can complicate the interpretation of growth response functions but observations on features of environments, sites, and species, and an understanding of plant processes, can be utilized to eliminate many of the problems and allow for acceptable confidence in explaining the meaning of the result. Inferences can always be made on the basis of the best available information, and hypotheses can be made

and tested as new samples are obtained. A certain amount of verification is achieved as one is able to predict the type of responses function on the basis of site and species information along with the statistical characteristics of the chronology that results.

For example, the response functions for *Pinus ponderosa* on sites near its arid and low elevation limits in northern Arizona show a more marked correlation of growth with winter precipitation than with summer precipitation, while response functions for the same species on sites at greater distances from the species' arid lower limits show a greater correlation of growth with summer precipitation than with winter precipitation. This observation can serve as a hypothesis about the importance of winter and summer moisture on arid versus moist sites or warm versus cold sites. The hypothesis may then be tested by classifying available response functions for the same and other species on the basis of nearness of the site to the arid limits and looking for differences in the mean response function of the grouped sets. Since many response functions are found to be consistent with this hypothesis, the hypothesis is accepted as a valid one. Of course, physiological evidence can provide the ultimate verification, and it may lead to a more detailed and accurate explanation of the dominant physiological cause-and-effect relationships.

Observations of differences in the response functions associated with latitude, exposure, elevation, soil type, and other factors have led to many inferences which are testable by classification of response functions and examination of the classes for significant differences in the results. The following discussion is a summary of the best inferences drawn from such classified response functions and other information. Some of the generalizations will undoubtedly be modified and improved in the future, some will remain unchanged, and others will be abandoned as they are found to be inconsistent with new research results. The items described here reflect certain inadvertent biases in that a major portion of research at the present time involves arid-site conifers from North America. Information gathered by workers in other regions has been examined for its consistency, but there are certainly many species, site factors, and situations that have not been examined adequately.

The following discussion treats the macroclimatic factors of monthly mean temperature and total monthly precipitation separately, with each divided into those relationships that are direct and those that are inverse. This classification is further divided into subgroups consisting of varying seasons, sites, and species.

1. Temperature

(a) Direct Relationship. Direct relationships between ring width and

summer temperatures are often found in response functions for trees near
the upper elevational or latitudinal limits of the species, especially for
'those on north-facing slopes or in other unusually cool microclimates.
This undoubtedly occurs because low temperatures limit respiration,
photosynthesis, and other biochemical processes essential for rapid
growth (Chapters 2 and 4). Low temperatures can further lead to
reduced ring width by delaying the beginning of the growth period and
by terminating growth before the end of the normal growing season.

Some direct correlations with temperatures in winter may result from
interacting conditions within a tree site. High temperatures in winter can
reduce snow cover, promote infiltration of moisture into the soil, cause
soil temperatures to be unusually · high, and result in high net
photosynthesis. Near sea level in northwestern United States where
cloudy weather is common, a direct correlation of ring-width growth in
conifers with winter temperature may result from the association of cool
temperatures with cloudy weather, low light intensities, and reduced net
photosynthesis (Chapter 4).

(b) *Inverse Relationships.* Ring width of conifers on semiarid sites is often
inversely correlated with variations in monthly temperatures. The most
obvious explanation for this inverse relationship is that temperature is the
driving force for diffusion of water, and anomalously high temperatures
lead to rapid evapotranspiration and accentuated conditions of water
stress (Chapter 3). Such effects of temperature are most apparent (1) in
the summer when high temperatures are common and low temperatures
are not likely to limit growth-controlling processes, (2) at low elevations
where air temperatures are most likely to be high for many months during
the year (Fig. 4.16), (3) on south-facing slopes, where there is abundant
radiant energy and plant temperatures are high, (4) in trees exposed to
wind which causes plant temperatures to approach those of the air and
steepens the leaf–air moisture gradients, (5) in trees on shallow
well-drained soils or with restricted root distributions where little
moisture is available, and (6) in individual tree sites nearest the warm
and arid limits of the particular species distribution.

An inverse relationship may be generated by the direct effect of
temperatures on respiration, causing available foods to be utilized more
rapidly and net photosynthesis and storage of food to decrease (Chapters
4 and 5). Also, high air temperatures may force plant temperatures to
exceed the optimum levels for processes of growth, assimilation, and
hormone synthesis (Chapters 2 and 4). Inverse correlations between
temperature and growth can also result when root temperatures are likely
to be low during winter periods of little snow or in the late autumn and
early spring. High air temperatures during times when the roots are cold

or frozen can lead to severe internal water stress and injury to the leaves and tissues exposed to the air (Chapter 4).

Higher than normal temperatures in the autumn can delay winter hardening, making the tissues more susceptible to frost injury and adversely influencing growth in the following spring (Chapter 4). Higher than normal temperatures late in summer or early in the autumn can prolong growth of certain tissues, which consume food reserves so that less is available for growth during the next year (Chapter 2). However, late in the growing season water is also likely to be deficient, in which case an inverse relationship between temperatures and growth might predominate (Chapter 2).

There are other interactions among plant processes which could lead to either direct or inverse correlation with temperature. Extremely high or low temperatures can reduce apical and needle growth affecting the production and movement of growth-regulating substances and the sizes and number of cells produced by the cambium (Chapters 2 and 4). At times of flooding when low amounts of oxygen in the soil may limit processes in the roots, high temperatures can enhance the further depletion of oxygen in the soil as well as induce water stress (Chapters 3 and 4). A review of Chapters 2, 3, and 4 will suggest other ways in which temperature can directly or indirectly affect ring width.

2. Precipitation

(a) *Direct Relationships.* Variations in monthly precipitation are most commonly directly correlated with ring widths in trees on semiarid sites, the most obvious explanation being the association between low precipitation, low soil moisture, and internal water stress, which limits physiological processes affecting growth (Chapter 3). The more precipitation there is, the more moisture is available in the soil, and the longer is the period of time before water stress becomes the most limiting factor to growth.

Such a model has been used frequently in tree-ring studies, as it is relatively apparent from experimental results. However, the response functions and field investigations on arid sites suggest that water stress very often limits processes other than cambial activity and creates internal conditions that at some later time affect growth (Model B, Fig. 5.9). This sequence is seen most clearly in trees nearest the arid limits, on well-drained sites, at low elevations, and on southerly exposures where the response functions often show significant and direct relationships between growth and precipitation during almost any month of the year. Some of the most important processes involved in this direct relationship between precipitation and cambial activity are net photosynthesis,

assimilation, apical growth, leaf development, root growth, and both the production and translocation of growth regulators.

Precipitation relationships can vary during the nongrowing season, depending upon whether moisture typically falls as rain or snow. If soil moisture is low and soil temperatures are above 0°C, either rain or snow can add moisture to the soil. If the soil is frozen, additional precipitation falling in the form of snow cannot penetrate the soil and may not have any significant effect on available moisture. Snow early in the season can insulate the soil and contribute to warm soil temperatures and rapid water absorption by the roots during the winter period, while an absence of early snow can lead to low soil temperatures and the freezing of roots. In addition, precipitation falling as snow may be subject to wind, blowing it away from certain exposures and depositing it as drifts in others. Variations in wind direction or intensity from one year to the next can complicate further the growth–precipitation correlations as they affect drifting snow.

(b) *Inverse Relationships.* Inverse correlation between precipitation and growth is less common than direct correlation especially in arid sites, and when it does occur it often exists because precipitation is correlated with other more limiting factors. For example, in sites where soil drainage is poor, excessive moisture may reduce soil oxygen and inhibit the growth of roots. An unusually deep snow and an increase in the length of time a particular site is covered by snow may extend the length of the photosynthetically inactive period and delay the beginning of growth (Model C, Fig. 5.10), thus leading to an inverse relationship between precipitation and ring width. Another related inverse effect of precipitation on growth can occur in autumn when unusually dry weather can lead to water stress and increase the winter hardening, which prevents destruction of plant tissues by severe winter cold (Chapter 4). Other inverse correlations with precipitation may result from the favorable effects of soil moisture on flowering, fruiting, and other phenomena that compete with cambium for the reserves of food (Chapter 5). Heavy snow, ice, hail, and lightning that are associated with high precipitation can damage the plant and occasionally lead to a reduction in growth.

3. Interactions between Climatic Variables

Precipitation may have an influence on the elements of the response via its correlation with cloud cover, air temperatures, and other factors influencing processes in the trees. At sites which are frequently limited by low temperatures, precipitation and cloud cover may considerably reduce the direct radiation and cause additional cooling of the plant

(Chapter 5). If no other factor is more limiting, the association of cloud cover with low temperatures may become more limiting to growth than either factor alone. The response function may show an inverse precipitation effect as well as a direct temperature effect, although the former may not occur frequently enough to give rise to a significant weight.

Such inverse relationships between precipitation and temperature may also lead to unexpected results. Cloud cover, increased humidity, and cooler temperatures associated with rainy periods in summer can have a favorable effect on net photosynthesis and growth in arid-site trees because of the corresponding reduction in the heat load and improved water balance (Chapters 3 and 5). This could conceivably produce a direct correlation between growth and precipitation of a region due to the frequent occurrence of afternoon clouds, even though the amounts of rainfall falling on the tree sites might be insufficient to affect growth.

Clouds in winter may prevent excessive cooling at night and maintain plant temperatures near those of the daytime (Chapter 5). At high elevations winters with little precipitation may be accompanied by warm days and very cold nights, which would contribute to high respiration in the day without any compensating photosynthesis, and would result in depletion of food reserves available for spring growth (Chapter 4).

Interactions can occur among prior growth and the concurrent climatic factors if drought is followed by more favorable conditions in late summer and early autumn (Chapter 2). The growth processes which ordinarily consume foods are checked by the drought, and all photosynthates go into food reserves which are then available for the next year's growth. Also, the moisture of the prior growing season may affect the number, size, and kind of buds produced, the amounts of leaf and root growth, and the degree of winter hardening, all of which in turn determine the functional tissues that influence the amount of growth (Chapter 5). The net effect of drought may be a reduction in present growth, but an increase in future growth if other factors are not limiting. The opposite type of interaction has already been mentioned for *Pinus longaeva* from arid sites where high precipitation during the growing season leads to low growth in that year, but high growth in the next year. This may be due to diversion of food substances to the growth of needles and roots, which in turn enable the tree in the following season to better utilize its environment for growth.

Interactions may arise from antecedent climatic conditions which affect the tree through preconditioning. An extremely cold winter can cause the tree to become completely dormant (all processes essentially inactive) for several months. Variations in precipitation and soil moisture

are then less likely to affect processes because of their inactivity. In the spring, as temperatures rise and the trees become more active, an abundant soil moisture reserve is more likely to have a beneficial effect. Also if the annual precipitation is high enough to fully recharge the soil during the winter, late winter precipitation may run off and have no physiological effect unless they influence variables such as light and temperature, which become limiting to processes affecting growth. The amount of precipitation and temperature may also be correlated with frequency of various types of destructive processes which indirectly lead to a change in the forest habitat and the variations in growth. For example, climate can be a contributing factor to the occurrence of fire, insect infestation (Fig. 5.6), ice damage, landslides, and flooding which in turn can lead to variations in growth.

III. Strengths and Weaknesses of Response Function Analysis

It can be seen from the above discussion that response function analysis provides an exceptionally precise tool for identifying tree-growth and climatic relationships. The fact that variables of monthly temperature and precipitation can account for as much variance as they do attests to the validity of the method. For example, in 80% of the response functions mentioned by Fritts et al., (1971), climatic variables reduced more than 50% of the ring-width variance. The median percentage of variance due to climate is approximately 60% to 65%, and for 20% of the response functions climatic variation accounted for more than 80% of the chronology variance. If one regards the variance due to prior growth as an effect of climate in prior years, an even larger percentage of total variance is due to climate. Considering the fact that response functions represent a linear expression of very complex biological systems responding to the microenvironments, and that the microclimates are only partially coupled to the macroclimate of a large climatic region, the percentage of variance due to climate appears to be a substantial amount.

However, the response function technique does have a number of weaknesses. The most important one is that elements in response functions need not be causally related to ring-width growth. Any factors that are correlated with temperature and precipitation inadvertently affect the response function relationships. A second limitation is that strong nonlinear interactions among variables may not be represented adequately and may not be fully taken into account.

It is possible that additional flexibility in the statistical model for the response functions could be achieved by using curvilinear regression or

other appropriate transformations (Jonsson, 1969) or by adding cross products as factors to allow for multiplicative effects. Such changes could lead to significant loss of degrees of freedom and perhaps impair the ability to analyze individual months and sites. A certain number of degrees of freedom could be added by increasing the length of the climatic record with which the ring-width chronology is analyzed. However, the quality of many early climatic records is questionable and, in the case of region-wide data, the record is likely to include fewer reporting stations so that it represents a less reliable record of variations in the macroclimate. Thus, it is not at all promising that the response function analysis can be improved markedly by adding more observations and variables to handle nonlinear effects.

Another limitation is that the response function in its present form does not allow for differentiation between climatic factors that have an immediate effect on growth (high frequencies) and those that may have a prolonged affect lasting several years to several decades (low frequencies). Such differences in tree growth and environmental relationships which involve frequency variations may be handled by filtering the data before analysis or by use of power and cross-power spectrum techniques (Chapter 6).

IV. Significance of Response Function Capability

As tree-ring analysis is applied to a wider variety of sites and climatic conditions, even more diversity in response functions is expected to result. Although the presence of such diversity appears to substantiate claims made by early critics that the tree growth climatic relationships are exceedingly complex, it does not follow that they are too complex to allow for climatic analysis. Actually the complexity is an asset, for the greater the diversity in the response to climate, the greater the information on climate.

For example, the response functions for two chronologies from trees on neighboring sites may be similar in all respects except for the weights of one climatic factor and season, such as precipitation for winter. Differences between the chronologies could occur only when winter precipitation was either higher or lower than the average. In such a case the two chronologies could be subtracted one from the other to estimate the variation in winter precipitation. To be more specific assume that:

Trees on a hypothetical site A respond to precipitation over all seasons of the year;
Trees on a hypothetical site B respond only to precipitation of the autumn, winter, and spring;
Trees on site C respond only to precipitation of autumn and spring; and
Trees on site D respond only to precipitation of spring.

Then the following can be obtained:

Annual precipitation is proportional to indices of A;
Summer precipitation is proportional to the indices of A minus the indices of B;
Winter precipitation is proportional to the indices of B minus those of C;
Autumn precipitation is proportional to indices of C minus indices of D; and
Spring precipitation is proportional to the indices of D.

Thus, it is at least theoretically possible to obtain estimates of climate for different seasons if the response functions indicate sufficient diversity in the chronologies used to estimate climate. In order to obtain as much diverse information as possible, a number of sites and species in an area should be sampled with adequate replication and each summarized separately. Each ring-width chronology may then be calibrated directly with available climatic data, and the calibrations used to ascertain what information the associated chronologies have recorded regarding past climate. Those chronologies with the most diverse set of response functions can be selected and a transfer function calculated to convert the variations in the selected chronologies to variations in climate.

The development of this multivariate procedure has substantially changed the data-collection requirements of dendroclimatological research. In the past the emphasis was placed on selecting trees from extremely arid or cold sites which responded similarly to variations in either drought or temperature. With such selection the ring-width chronologies were all inferred to represent the appropriate climatic element. Now one can somewhat relax the emphasis on collection from the extremely limiting environments, since the multivariate procedures offer convenient, objective, and rapid methods of analyzing the diversity of the response. However, the selected sites must be sufficiently stressful so that some climatic factors are limiting and there is sufficient variability in ring structure to crossdate and calibrate with climate.

V. Assessing Effects on Growth of Varying Climate

As was mentioned earlier, each element or weight of a response function is proportional to the relative effect of the calibrated climatic variable on ring width. Responses functions shown thus far are in normal form; that is, the units are expressed in units of the standard deviations of each variable. When each element of a response function is divided by the appropriate standard deviation of the climatic variable it represents, the elements are transformed to units expressing the effect of inches or millimeters of precipitation and degrees of temperature on ring width (Fritts *et al.*, 1971). It is then possible to substitute into the equation particular departure values of each climatic variable for each month and

calculate the absolute effect of climate upon ring width as measured at the climatic station. If specific departure values are applied to all weights, including substitutions of the derived growth departure for prior years, some interactions among variables and prior growth are taken into account.

Figure 8.7 is an example of the use of response functions for a number of relatively arid-site trees from the western United States to assess the effects on tree growth of hypothesized changes in global climate which could result from the operation of a fleet of supersonic transport aircraft (Cooper *et al.*, 1974). A reduction in temperature of 2°C (3°C for sites north of latitude 40°N) for each of the 14 variables for monthly temperature was multiplied with each element of the response function, which had itself been divided by the appropriate standard deviation. Calculations also included precipitation changes of +5% and −5% (10% for sites north of latitude 40°N). The calculations were carried out for five successive years, and estimated anomalies in growth were multiplied by the elements of prior growth for lags of up to three years. The result represents an estimate of the percentage change in ring-width growth that would be expected from the proposed climatic anomaly operating over a period of five years (Fig. 8.7). This of course does not take into account community changes which may alter competition and affect growth.

Growth increased in nine out of the 12 cases shown in Fig. 8.7, a result attributable to the lowering of temperatures, which reduces both water stress and respiration (Models A and B, Figs. 5.8 and 5.9) and hence augments the available water and food supplies. In the three sites where growth was reduced, it was hypothesized that the lowering of temperatures caused a reduction in physiological processes that directly govern ring-width (Model C, Fig. 5.10).

The effect of both a 5% decrease and 5% increase in precipitation (solid line and dashed line) indicates that the specified changes in precipitation would have a much smaller effect than temperature on growth. A decrease in precipitation consistently reduces growth. The differences in the shapes of the curves are due to varying effects of prior growth.

These results differed from computations for other forest sites using simulation models of productivity developed for certain forest biomes (Cooper *et al.*, 1974). The simulation of some models was based on measurements of actual plant processes on cool and moist sites. Consequently, those models predicted a reduction in growth due to the lowering of temperatures, while the response functions derived from more arid-site trees indicated that the detrimental effects of water stress due to high temperatures would be most limiting to growth.

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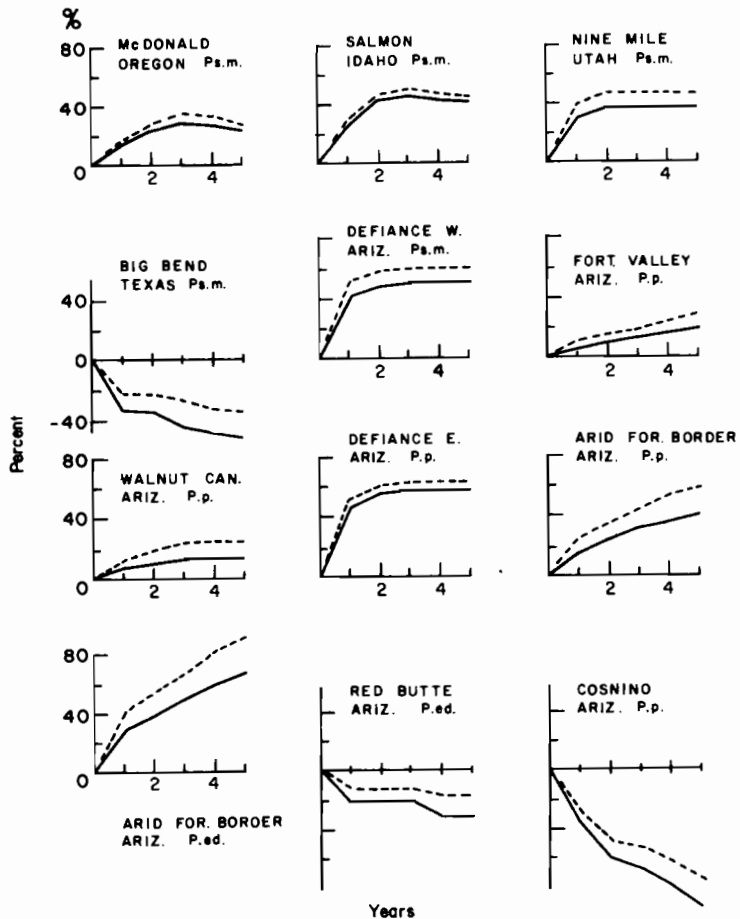
FIG. 8.7. The calculated ring-width response to the most extreme climatic changes suggested to result from operation of a fleet of supersonic transport aircraft, shown for 12 sites. Calculations included a 2°C decrease in temperatures and a 5% increase (dashed lines) or decrease (solid lines) in precipitation for each month throughout the year, which were multiplied with the appropriate element of the response function for sites south of 40 N. (For sites north of 40°N, the specified change in temperature was 3°C and in precipitation ± 10%.) The calculations were carried out for a succession of five years and the estimated growth applied to the elements of the response function for prior growth at lags up to three years. Ordinate values are in terms of percentage of present normal ring width at each site. Response functions and site data are published from Fritts (1974). Ps.m., P.p., and P.ed. indicate species *Pseudotsuga menziesii*, *Pinus ponderosa*, and *Pinus edulis* respectively.

The response function analysis described by Fritts (1974) demonstrates the existence of a wide variety of climatic factors that can affect ring width. This suggests that more physiological studies on extreme sites may reveal new growth–environmental relationships not encountered in more optimal environments.

Since the response functions can be used to ascertain the effects of climatic variations on growth over a wide area and a variety of sites, they may be used to test the appropriateness of extrapolating information gathered from areas intensively studied for ecosystem analysis to other locations, especially to those representing stress sites near the natural limits of the forest.

VI. Climatic Reconstruction and Verification

The primary goal of dendroclimatology is the reconstruction of past climate. A typical approach to reconstruction has been to identify what climatic parameters correspond to particular variations in ring width, to examine the ring-width record for anomalous variations in growth, and then to deduce the appropriate variations in the climatic parameters from the anomalies in growth (Schulman, 1956; Sirén, 1963).

Figure 8.8 is an example of such a study in which past variations in growth at Mesa Verde, Colorado, were used to infer variations in past climate (Fritts, et al., 1965c). The study was made to test a hypothesis which asserted that a so-called "great drought" apparent from tree rings for A.D. 1276-1289 was of sufficient severity to force abandonment of the cliff dwellings at about the same time.

Ring widths in living trees of *Pseudotsuga menziesii* were examined and were found to be directly related to variations in precipitation and, to a limited extent, inversely related to variations in temperature for a 13-month period extending from June of one year through June of the next (see Table 7.VI). The climate for particular monthly intervals that were significantly related to growth are listed as follows in order of decreasing importance: (1) precipitation and temperature for March through May, (2) precipitation for October and November, (3) precipitation for August and September, (4) temperature for the June concurrent with growth, (5) precipitation for December through February, and (6) temperature and precipitation for June and July of the year prior to growth (Fritts et al., 1965c). Fritts (1974) confirmed these generalities by calculating the response function for the same data and sites.

There was also a direct relationship between yearly ring-width index values and the index for the ring formed three years earlier. The standardized ring-width chronology was corrected for this third-order

autocorrelation by subtracting the normalized value for prior growth
after it had been multiplied by the appropriate regression coefficient and
the result denormalized. A five-year moving average of the corrected
indices was plotted for every even-numbered year (Fig. 8.8). The five-
year average was chosen to bring out long-term growth variations
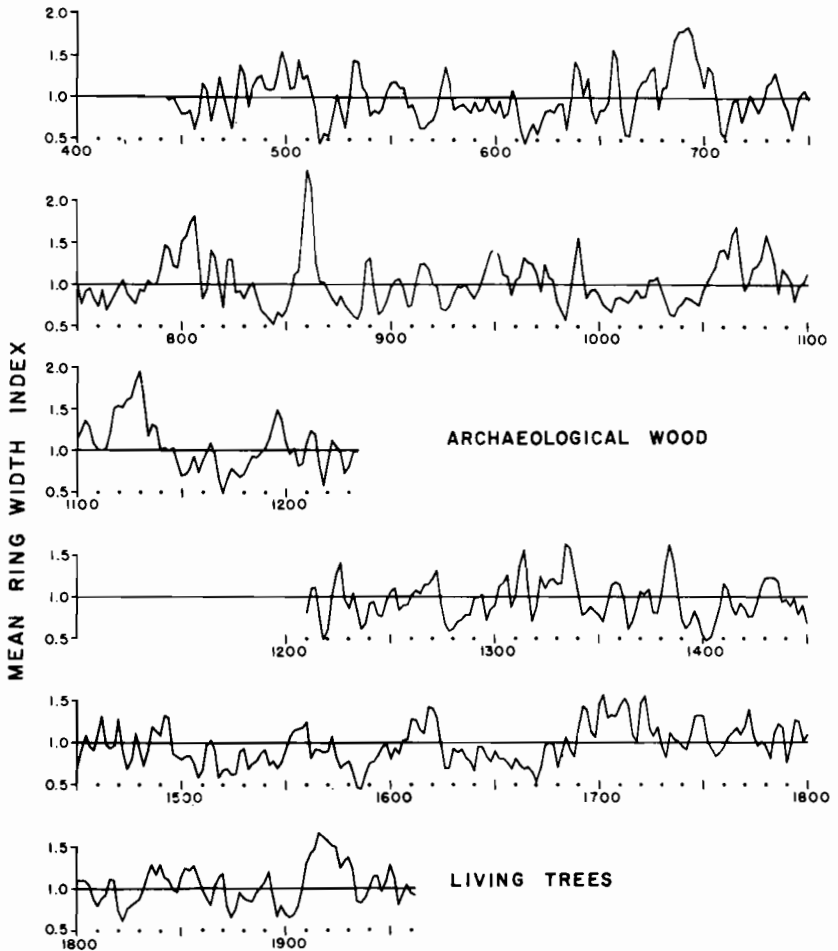
FIG. 8.8. Five-year running means of ring-width indices from *Pseudotsuga menziesii* at
Mesa Verde, Colorado, corrected for autocorrelation and plotted on every even year from
A.D. 442 through 1962. (Modified from Fritts *et al.*, 1965c)

expressing climatic conditions thought to be detrimental to agriculture and food reserves of the mesa inhabitants. An archaeological ring-width chronology obtained from the dwelling timbers was similarly treated to extend the record back in time.

It was inferred from the calibration that intervals of low growth were also intervals of low precipitation and high temperature, emphasizing the months in order of importance listed above. Fritts *et al.* (1965c) noted the interval A.D. 1273-1285 was characterized by low growth and could be inferred to be dry. However, they also noted that the departures in growth from a mean value of 1 for that particular time appeared to be surpassed between A.D. 512 and 1673 by 10 other intervals characterized by low growth. Therefore, it appeared to these workers that the so-called "great drought" was not as severe as droughts at other times and was probably only one of several factors in a chain of events that led to the disappearance of the prehistoric people from Mesa Verde at that particular time. The only verifications of these reconstructions are similar variations in ring-width chronologies of other sites and other species throughout Mesa Verde and in neighboring areas.

It was also noted that no period of low growth appears to have occurred after 1673 that was as low as the growth between 1276 and 1289. The growth of 1895 to 1906 was low, but the interval was shorter and the indices were larger than the corresponding values during the "great drought" of 1276 1289. Therefore, drought was inferred to be less severe after 1673, which is consistent with other notions about the onset of the cool moist period (sometimes called the Little Ice Age) that began in the 1300's and brought cool moist conditions in southwestern United States early in the 17th century (Fritts, 1965). Ring-width indices for the early 1900's at Mesa Verde suggest the climate early in the 20th century was unusually wet and cool, although in the last few decades the ring-width indices indicate that more average conditions have prevailed.

VII. Inferences from Chronologies with Different Growth Responses

Information obtained from a regression analysis or from a response function applied to a single chronology provides only a generalized estimate of variations in past climate since the response is integrated over one or more years. It is difficult to determine the season of occurrence of a particular climatic anomaly associated with variations in growth and whether the anomaly resulted from precipitation deficits, excessively high temperatures, or both. However, it was suggested in Section IV that the response and transfer function analyses can provide a solution to this

problem, if ring-width chronologies are available from two or more sites or species which respond in different ways to the same conditions of climate. The following study of LaMarche (1974a) applies this principle by using two ring-width chronologies in the same species and area which respond differently to anomalies in temperature and precipitation in the respective tree sites.

The two ring-width chronologies were developed from *Pinus longaeva* in eastern California. One was an arid-site chronology from the forest border derived by Edmund Schulman and utilized by Fritts (1965). The other was a 5405-year ring-width chronology which was developed at the upper elevational limits of the species by LaMarche and Harlan (1973). Response functions of ring-width variation indicate that these trees were responding in a direct manner to variations in temperature for the spring, summer, and autumn seasons. Moisture was less often limiting, though narrow rings were sometimes associated with extremely dry years. LaMarche (1974a) also found that the ring-width record in the high-elevation chronology was consistent with trends in temperature during the spring, summer, and autumn at both neighboring and distant localities where weather records were available.

However, response function analysis indicated ring-width variations in drought-sensitive *Pinus longaeva* in the same area but at lower elevation were directly related to precipitation and inversely related to temperature (Fritts, 1969, 1974) (Fig. 8.1). Not only do the chronologies at the upper and lower elevational limits differ in their response to particular climatic factors, but the record from the high-elevation chronology was inferred by LaMarche (1974a) to average the temperatures over a period of 15 or more years. As a result, the ring-width chronology for the high-elevation trees expressed more low-frequency variance than the chronology from the more arid-site trees at lower elevations. The first-order autocorrelation in the former ranged between 0·6 and 0·8, but in the latter it ranged between 0·0 and 0·3. The large differences in the amounts of variance at different frequencies in the two time series, along with the difference in lag of from 1 to 15 years between the climatic effect and the tree-growth results, prohibited a straightforward calibration using transfer function analysis (see Chapter 6). Therefore, LaMarche elected to simply plot 20-year means of ring widths from the high- and low-elevation trees and to infer the appropriate climatic anomaly from the observed departures in growth.

The mean ring-width departures for the two sites and the inferred climatic anomalies are shown in Fig. 8.9. Specific departures in past growth which sometimes persisted for more than 300 years were inferred to be long periods of anomalous temperature and precipitation, which
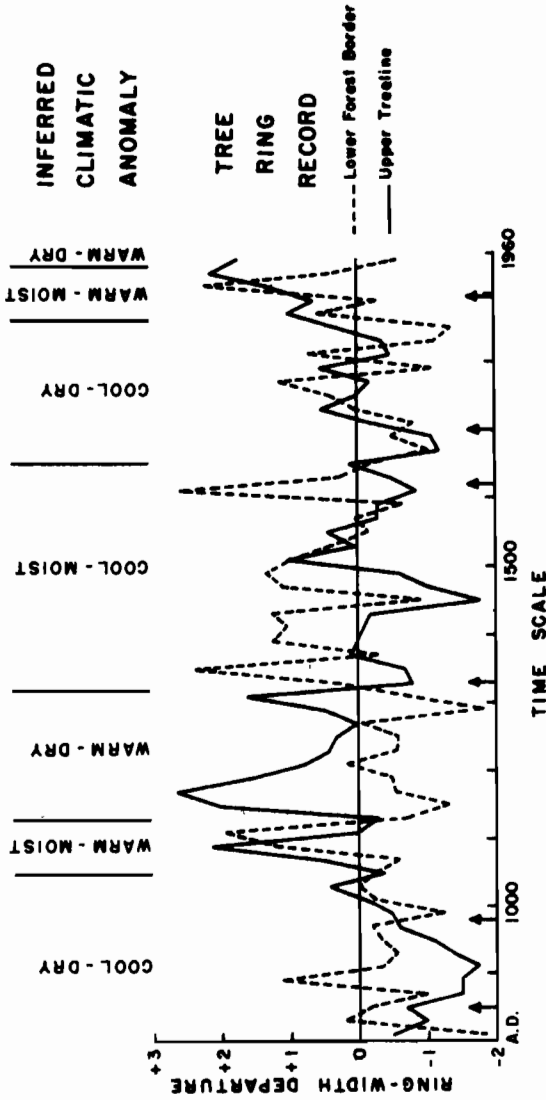
FIG. 8.9. The 20-year average growth, expressed in standard normal values, in *Pinus longaeva* on lower forest border and upper tree line sites of the White Mountains of California, and the precipitation and temperature anomalies inferred from the departures in ring width. Arrows show dates of glacial moraines in the nearby mountains. (From LaMarche, V. C., Jr. (1974). *Science* **183**(4129), 1043–1048. © 1974 by the American Association for the Advancement of Science)

were punctuated by shorter episodes showing climatic variations of a different kind.

LaMarche further linked the inferred temperature–precipitation anomalies to features of the general circulation. This was accomplished by examining the existing meteorological records for the area, identifying the months and years when the anomalies in moisture or temperature had been especially marked, and examining maps of the corresponding heights of the 700 mb pressure surface (about the same as the atmospheric pressure at 3 km) over western North America (Fig. 8.10).

It was noted that the most common anomalies, especially during spring and autumn in recent decades, have been warm–dry and cool–moist situations (Maps C and A, Fig. 8.10). The warm–dry conditions were associated with a low pressure *trough* over the North Pacific Ocean and a high pressure *ridge* over the Rocky Mountains which brought warm dry continental air into California. Cool–moist and cool–dry anomalies (the latter were less frequent in the modern period) were associated with an upper-level trough which caused cold moist air to flow from the ocean or cold dry air to flow southward off the North American continent (see Maps A and B, Fig. 8.10). The warm–moist conditions occurred in summer and involved anomalous extension of what is referred to by meteorologists as the upper level Bermuda High, bringing moisture and warmth from the east into California during July.

LaMarche inferred from the past ring-width record that not only were temperatures often lower in the past at the tree sites but that they were the result of a more frequent occurrence of an upper level trough over western North America than occurred during the modern period. Such an inference assumes the principle of uniformitarianism in that the climatic anomalies in the past are assumed to have been similar to those of the present, except in frequencies of occurrence.

The inferences of LaMarche seemed to be verified by their consistency with the past circulation over western North America suggested by Lamb (1969a), who used different kinds of evidence for his reconstructions. It was noted by LaMarche, however, that while the general circulation over western Europe and elsewhere in western North America was similar to that over California, there were periods of time when the records of climatic variations over the two continents differed.

The 100-year mean growth at the upper tree line plotted for each century since 3000 B.C. is shown in Fig. 1.15 in Chapter 1 (Gates and Mintz, 1975), along with data on expansion and contraction of glaciers primarily in western North America and northern Europe as described by Denton and Karlén (1973). Expansion of glaciers which occur in the same general regions of the trees are clearly associated with periods of low
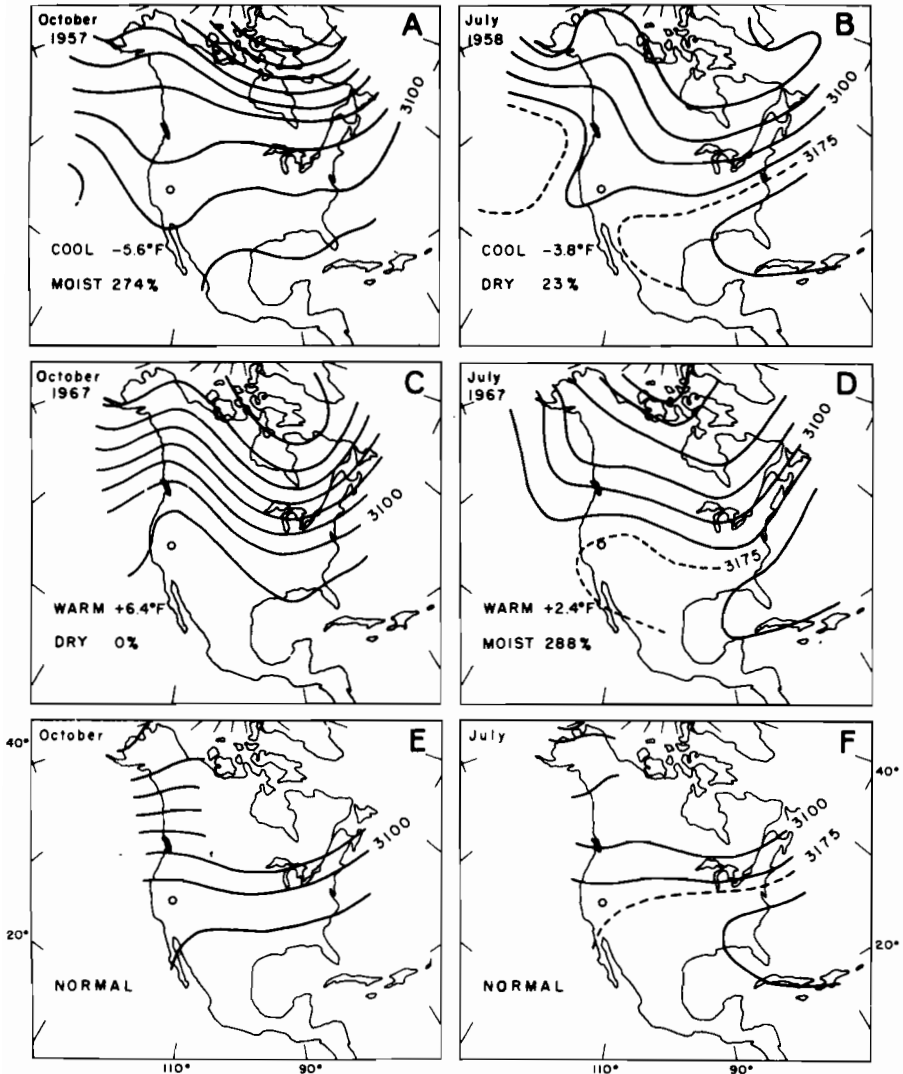
FIG. 8.10. Examples of 700 mb pressure height (about the same as the atmospheric pressure at 3 km) maps for selected months associated with large precipitation and temperature anomalies in the White Mountains of California. Different frequencies of these or similar circulation patterns in the past were offered as explanation of the climatic anomalies inferred from intersite comparisons of ring widths (Fig. 8.9). (From LaMarche, V. C., Jr., 1974, *Science* **183**(4129):1043–1048. © 1974 by the American Association for the Advancement of Science)

growth, which are inferred to be cool. The glacier data, though not dated on as fine a time scale, serve as a kind of independent verification of the climatic anomalies reconstructed from the tree-rings.

VIII. Reconstruction Using Multivariate Transfer Functions

A. Climatic Variations in Arid Regions affecting Streamflow

Stockton (1971a 1975) and Stockton and Fritts (1971a) applied the techniques of dendroclimatology to the reconstruction of past streamflow from river basins in semiarid western North America. A model is used which assumes that the amounts of annual streamflow for the water year, the twelve months from October through the following September, is a function of precipitation, temperature, and evapotranspiration as they vary throughout the river basin and from season to season. Since ring widths of trees in the watershed vary in response to the same climatic parameters, direct calibration of ring widths with variations in streamflow is obtained, using modern hydrological measurements to establish the correlation between the two. The calibration is then used to estimate the streamflow for the years in the past when no hydrologic records existed, using long tree-ring chronologies from the river basin.

Methods were first tested on two watersheds of different size, one in northcentral Arizona and one in westcentral New Mexico. Several tree-ring samples were obtained from *Pseudotsuga menziesii* on different sites within each watershed. For such studies, careful statistical analyses were made, and response functions for temperature and precipitation data were obtained for streamflow as well as for ring width.

For example, in one watershed both streamflow and tree growth were found to be directly correlated with precipitation during all months of the water year. However, the response functions for tree growth often emphasized the moisture of late autumn and winter, while the response functions for streamflow emphasized precipitation in April and July. Also, high temperature extremes during the months of December, April, and May apparently promoted high streamflow but were limiting to tree growth in the studied site. This is explained by the effect of higher than normal temperatures during the three months mentioned above which favor snow melt and streamflow but adversely affect the physiological conditions in the trees that in turn cause lower growth. Differences were also noted among the response functions for the trees in different sites, and it was thought that a multivariate transfer function was appropriate to reconstruct streamflow.

A power spectrum analysis (see Chapter 6) of differences in data in regard to frequency revealed that there was more low-frequency variance in the tree-ring data than in the records of streamflow. This discrepancy, which was attributed to differences in the statistical generating processes of the two types of data, suggests that the best reconstruction of streamflow may require tree growth lagged for a number of years.

Statistical models listed in Table 8.II describe the ways tree rings were matched with streamflow for seven calibration attempts and includes the percentage of streamflow variance accounted for in each case. The establishment of the coefficients associated with the predictors of each equation involved the following procedure: (1) extraction of the eigenvectors of tree growth (Equation 7.18), (2) regression analysis using the eigenvector amplitudes of growth and sometimes actual values of prior streamflow to statistically estimate streamflow, and (3) conversion of the coefficients for the amplitudes to the transfer function (Equation 7.21), the elements of which become weights identified with the coordinates of the original tree growth (Stockton, 1975).

For hydrological reasons Models 1, 2, and 3 (Table 8.II) were constructed to utilize values of both prior streamflow and tree growth to predict streamflow. One difficulty with such a model is that only estimates of the prior streamflow values, not the actual data, are available for years before the calibration period. This introduces an additional error factor into the prediction equation. However, the reconstructions using Models 4 through 7, which did not possess the additional error,

TABLE 8.II Various models using different sets of lags for reconstructing annual runoff of the upper San Francisco River from ring-width chronologies in the watershed and the percent variance reduced[a]

Predictand	Variables of model Ring-width predictors	Prior runoff predictors	% Variance reduced
1. Runoff (f_t)[b]	$x_{t-3}, x_{t-2}, x_{t-1}, x_t$[c]	with $f_{t-3} + f_{t-2} + f_{t-1}$[d]	71·5
2. Runoff (f_t)	$x_{t-2}, x_{t-1}, x_t, x_{t+1}$	with $f_{t-2} + f_{t-1}$	64·0
3. Runoff (f_t)	$x_{t-1}, x_t, x_{t+1}, x_{t+2}$	with f_{t-1}	72·2
4. Runoff (f_t)	$x_{t-3}, x_{t-2}, x_{t-1}, x_t$		60·5
5. Runoff (f_t)	$x_{t-2}, x_{t-1}, x_t, x_{t+1}$		55·1
6. Runoff (f_t)	$x_{t-1}, x_t, x_{t+1}, x_{t+2}$		72·2
7. Runoff (f_t)	$x_t, x_{t+1}, x_{t+2}, x_{t+3}$		66·0

[a]From Stockton (1971) and Stockton (1975). [b]Runoff for water year t. [c]Ring-width indices for 3 years prior to year t through year t. [d]Runoff for water year 3 years prior to year t through the year prior to t.

were shown by power spectrum analysis to exhibit a different time-series structure than the actual streamflow records. Thus it was concluded by Stockton (1975) that Model 1 is superior to Models 3 and 6, even though the reconstructions using the latter two models have an additional source of error. In each case of reconstruction, the streamflow record from a nearby gauging station was used to verify the reconstructions.

Stockton (1975) applied this same modeling and calibration procedure to reconstructing streamflow from the Colorado River Basin, which covers 283,605 km². Seventeen tree sites within or near the watershed were used, and the streamflow record for Lee Ferry, Arizona, adjusted for diversion of water from 1896 to 1961, is calibrated with the growth record of the 17 tree sites. The same models shown in Table 8.11 were used, and Model 5 was shown to yield the best reconstruction, with a calibrated streamflow variance of 82% for the dependent data set (see Fig. 7.2). The transfer function from the calibration was applied using the 17 ring-width chronologies to reconstruct streamflow as far back in time as all ring-width records are complete. These reconstructions have already been presented in the first chapter (Fig. 1.16).

The inclusion of the growth indices of the two prior years (x_{t-1} and x_{t-2}) (See Model 5, Table 8.11) appears to adjust for differences between the generating processes of the trees and the generating processes of streamflow that produce the respective time series (see Chapter 6). The indices for one year following (x_{t+1}) account for a lag of one year between the climatic input and the resulting streamflow, as well as for lags of tree growth behind the occurrence of climate.

Stockton (1975) compares the power spectra of (1) the actual streamflow record, 1896–1961, (2) the reconstructed streamflow record 1896–1961, and (3) the entire reconstructed streamflow record 1564–1961. He concludes that the frequency distribution of the reconstructions resemble those of the actual streamflow sufficiently to accept model 5 as the best.

The reconstructed long-term mean for the flow of the Colorado River for 1569–1961 was 13·0 million acre feet, which was over 2 million acre feet less than the mean of the gauged record for 1896–1961 of 15·03 million acre feet. The estimated variance for the longer reconstructed record, which was corrected for variance lost in regression, was 17·01. This was less than the corresponding figure of 18·42 for the variance of the actual streamflow during period 1896–1961.

Later work of Stockton and Jacoby (in press) and Stockton (1976) examined differences in ways the hydrological data were adjusted and attempted calibrations using different time periods. Since they obtained estimated long-term means as high as 14·0 million acre feet, they argued

that a reasonable long-term estimate of the mean annual flow for the Colorado River is 13·5 million acre feet which is an estimate with a ±0·5 million acre feet error.

Stockton points out that these statistics, representing the longer reconstructed period, will improve estimates of expected water yield because they are derived from a larger sample. Furthermore, he notes that the reconstructions (Fig. 1.16) indicate that droughts were more common in the past than during the period of record after 1896. Also, since 1569, the wetness of the period 1905–1930 was matched in extent only by one other period, 1601–1621. Stockton recommends that the corrected statistics using the longer record from tree-rings should be used to manage Lake Powell, a newly created reservoir on the Colorado River, because they represent a record six times as long as the actual gauged record and they have a higher probability of being closer to the actual flow of future years.

Stockton and Jacoby (in press) verified their reconstructions by means of independent streamflow data estimated from an upstream station for the interval 1896–1914. The trends in the two data sets were generally in agreement except for a few years of high flow. They conclude that the overall reconstructions from tree rings appear unbiased in that the number of times they exceed the values estimated from the upstream flow are the same as the number of times they are less.

B. Climatic Variations and Hydrologic Conditions in Subpolar Regions

Tree-ring analyses of hydrologic situations are possible in subpolar as well as arid regions. Stockton and Fritts (1973) used the rings from *Picea glauca* growing on the natural levees of the Peace–Athabasca Delta system along the western border of Alberta, Canada, to reconstruct past variations in the levels of Lake Athabasca.

A dam obstructing river flow in the headwaters of the Peace River appeared to cause a permanent drop in the water levels of the lake and the nearby delta system, both of which are downstream from the dam site. High water levels in the past had resulted in flooding and mineral enrichment of soils within the delta region. With the apparent drop in maximum water levels and a decrease in flooding, scientists feared that the ecology of the delta might be permanently altered. While measurements back to 1935 recorded relatively high lake levels and associated flooding, fragmentary evidence existed suggesting that these records may not have been representative of the water levels and flooding history occurring over a longer period of time. Reconstruction of a longer

record was thought necessary to make the best decisions on future management of the delta system.

Although the trees on the levees in the area were near neither their arid nor cold limits, where climatic factors would limit growth, it was thought that local conditions of soil moisture and flooding associated with the levels in the waterways may have been recorded by the growing trees. Replicated cores were extracted from each of 10 or more trees from six sites distributed within the delta system (Fig. 8.11).

At first only one site was sampled (site 1), and the rings were examined for variability in width and for crossdating to ascertain whether a
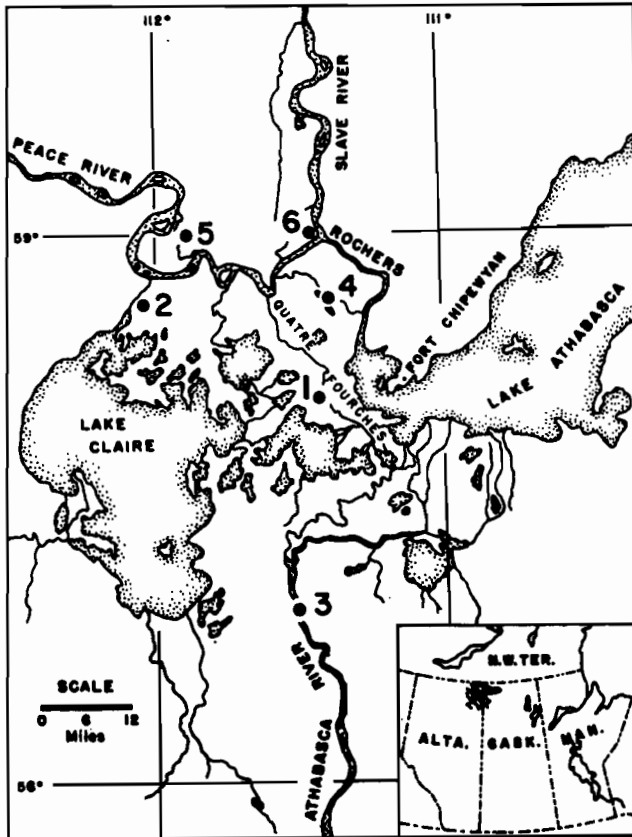
FIG. 8.11. Location of six sites of *Picea glauca* sampled throughout the Peace–Athabasca Delta system to reconstruct past levels of Lake Athabasca. (From Stockton and Fritts, 1973, courtesy of the American Water Resources Association)

regional factor such as flooding was affecting growth. Both variability and crossdating were evident, and 54% of the ring-width variance was common to all sampled trees of the site. The percentage of variance remaining in the group chronology was higher than had been found for many trees on mesic sites to the south, but it was somewhat lower than that for trees in arid forests. Also, it appeared that the ring-width chronology was correlated to some extent with the available lake level records.

With these promising results, Stockton returned to the delta region and sampled five additional sites (Fig. 8.11). Some sites were chosen to represent different drainage classes and others were chosen because of their strategic location as potential monitors of the water levels in the inlets and outlets to the delta system.

It was noted that *Picea glauca* grew most vigorously on the well-drained sites at the top of levees. When a stream meander is cut off, water levels become higher, soil aeration apparently declines, there appears to be a deterioration of *Picea glauca* growth, and species typical of wetter habitats begin to invade the forest. A model was created in which it was assumed that growth at each site during the year of flooding, t, and during the following year, $t+1$, may be correlated with the water level in the lake. The further assumption was made that growth at each site may be either directly or inversely related to the water levels, depending upon the drainage characteristics at the soil, the proximity to a waterway, and the timing of the water level fluctuations within each year.

The ring widths in each of the sites were crossdated and standardized as in Equations 6.7 and 6.8, and the principal components (eigenvectors) were extracted from the six ring-width chronologies. The most important eigenvector reduced 61·2% of the variance (Fig. 8.12), and all of its elements corresponding to the six sites have large negative weights. The second eigenvector reduced 13·6% of the variance, exhibiting positive weights for sites 2, 5, and 6, which are the three sites most closely associated with the Peace River, and negative weights for the other sites, which are more closely related to the Athabasca River (Figs 8.11 and 8.12). The third eigenvector reduced 10% of the variance and included a positive weight for site 3 and a negative weight for site 4, with weights near zero for the other four sites. This analysis indicates a 61% similarity in variance of all six tree sites (eigenvector 1), but suggests that two important differences exist among the tree sites associated with 13·6% and 10·0% of the tree growth variance, respectively.

The dependent variables chosen for this analysis were the mean water levels in Lake Athabasca for three 10-day intervals which provide an index to the amount and timing of flooding in the delta system. The first is
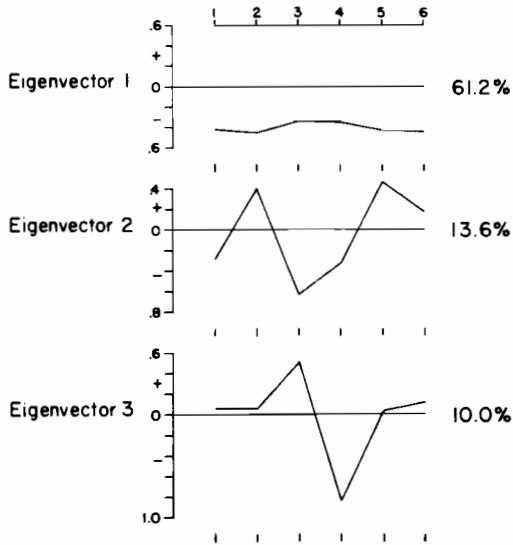
FIG. 8.12. The first three eigenvectors of the six ring-width chronologies from the Peace–Athabasca Delta area sites located in Fig. 8.11. (From Stockton and Fritts, 1973, courtesy of the American Water Resources Association)

the measured height of water during May 21–30 at about the time growth begins, the last, September 21–30, represents conditions after growth had ceased, and the middle period is July 11–20. The statistical model used is:

$$\hat{Y}_t = b_0 + b_1 X_{1,t} + b_2 X_{1,t+1} + b_3 X_{2,t} + b_4 X_{2,\cdot+1} + \cdots$$
$$b_{11} X_{6,t} + b_{12} X_{6,t+1} \qquad (8.1)$$

where $\hat{Y}$ is the predicted lake level during one of the three 10-day periods at year t; $X_{t,t}$ and $X_{t,t+1}$ are the mean ring-width indices for site 1 for years t and $t+1$; and b_0 is a constant adjusting for differences in variable means. Actually, canonical regression was used (Glahn, 1968), but all canonical weights were retained. The results are the same as if three multiple regressions had been run for each of the three 10-day periods, with 12 predictor variables representing ring width.

The transfer function weights are plotted in Fig. 8.13. Site 1 is poorly drained and the weights indicate that the most pronounced effect of higher than average water level is a reduction in growth during year $t+1$. Sites 2 and 3 include trees on better-drained soils, so the weights are more often positive as high rather than low water levels are associated with high growth. At site 2, higher than average water levels in May have a

pronounced and immediate effect on growth, but if the high water occurs later in the season, the effect appears in the next year's growth $t + 1$. Site 4 is poorly drained and the largest response to high water is inverse, apparently due to poor aeration, and the response occurs in the first-year growth.
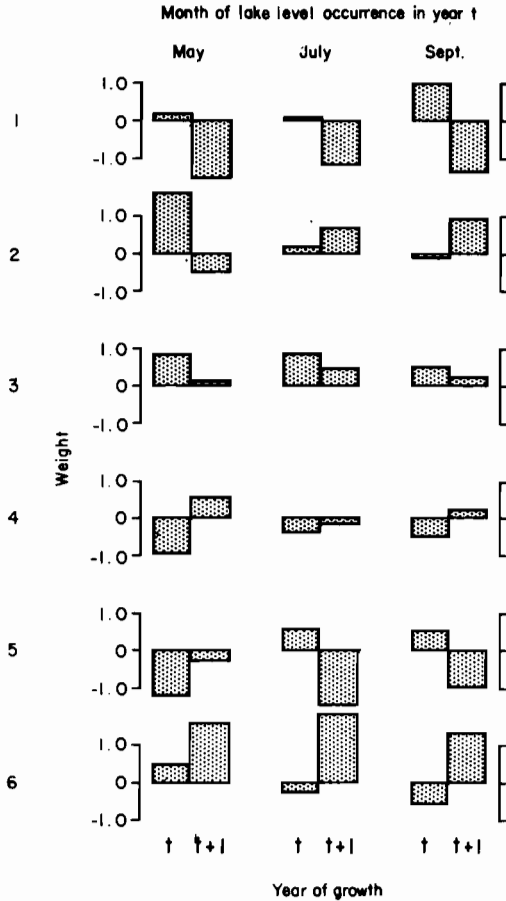
FIG. 8.13. Plots of all the regression coefficients of the transfer function used to reconstruct levels of Lake Athabasca for three different 10-day intervals using the variations in ring widths from six different tree sites. Positive values designate direct relationships between the growth and lake level and negative values designate inverse relationships. (Redrawn from Stockton and Fritts, 1973)

The elements of the transfer functions for sites 5 and 6 have opposite signs, apparently for hydrologic reasons. The sites are located along the Peace River (Fig. 8.11), where the former site is approximately 25 miles (40 km) above a major outlet (Rochers) from Lake Athabasca, while the latter is at the confluence of the Peace River and the outlet. High growth at the two sites is associated with high water levels in the nearby river. However, when the trees at the confluence (site 6) exhibit higher growth than site 5 upstream, a proportionately higher than average flow is indicated from the outlet than from the Peace River, reconstructing high water levels in the lake. When growth is higher for trees at site 5 than at site 6, the relative flow in the Peace River is greater than that of the outlet, reconstructing levels which were probably lower in the lake.

The lake levels that are reconstructed from tree rings for years 1810 through 1967 have been included in Chapter 1 (Fig. 1.17). Stockton and Fritts infer from the extended lake-level record that the variance of the May 21–30 lake levels for the 1935–67 interval is only one-third the variance for the longer record; the variance of lake levels for July 11–20 during the 1935–67 interval is one-half that of the longer record; and the variance for September 21–30 is similar to that of the longer record. The mean levels for the longest available record 1810–1967 do not appear to be different from the 1935–1967 measurements. The tree rings indicate that the long-term natural variability of early season levels of Lake Athabasca is greater than one would expect from the 1935–1967 measurements. Extremely wet and extremely dry years occurred more frequently during the 1810–1934 interval than during the more recent period.

Management of the Peace–Athabasca Delta system now incorporates the construction of a temporary earthen dam across one of the outlets every few years, artificially creating a high lake level and an associated flooding of the neighboring terrain until the impounded high water washes out the dam. This management procedure has resulted because it is believed that the occasional high water shown by analysis of tree rings is all that is necessary to maintain the delta system in its present ecological state.

Quantitative verification was not possible because of the shortness of the calibration record. However, the reconstructions were verified to a limited extent by historical references, direct observations, and botanical evidence. A dendrochronological method of verification using the methods of Alestalo (1971) might have been to return to the area after the reconstructions were made and to date leaning trees on the wave-cut terraces to see if the dates correspond to the high-water years indicated by the above dendrohydrological analysis (Alestalo, 1971).

C. Climatic Variations and Studies of Sea Surface Temperatures

Surface water temperatures in the North Pacific Ocean influence the storms that enter various regions over the west coast of North America, making possible the calibration of tree growth (as representative of climate) with sea surface temperatures. Mild conditions occur in the extreme west of North America and cold dry conditions occur in the East when the central North Pacific is anomalously warm and the eastern North Pacific and northern Gulf of Alaska are anomalously cool. Wet winters develop when the portion of the North Pacific between Hawaii and California is anomalously warm (Namias, 1969, 1971, 1973).

Since anomalous variations in ring widths of trees along the Pacific Coast are a result of anomalous variations in precipitation and temperature at those sites and since these factors result from anomalies in the movement of storms over the North Pacific, variations in ring widths from both coastal and inland sites can be modeled as sources of information on past anomalous variations in temperatures of the ocean surface. Douglas (1973) tested the possibility by analyzing five standardized ring-width chronologies from sites in southern California along with features of sea surface temperatures at three coastal stations in California (Port Hueneme, Balboa, and La Jolla). He found that the monthly data in sea surface temperatures could be divided into three natural seasons, where winter is November through February, spring is March through June, and summer is July through October. Autumn was not defined, because it was thought to represent only a short period bridging the warm temperatures of summer and the cold temperatures of winter.

Douglas examined several statistical models relating tree growth and climate and concluded that the best reconstructions were obtained for sea surface temperatures by using the following equation.

$$\hat{Y}_t \doteq b_0 + b_1 X_{1,t-1} + b_2 X_{1,t} + b_3 X_{1,t+1} + b_4 X_{1,t+2} + \cdots$$
$$b_{17} X_{5,t-1} + b_{18} X_{5,t} + b_{19} X_{5,t+1} + b_{20} X_{5,t+2} \qquad (8.2)$$

where $\hat{Y}_t$ is the estimated sea surface temperature for a station and season in year t; the b's are regression coefficients associated with tree-ring indices from sites 1 through 5 for years $t-1$, t, $t+1$, and $t+2$; and b_0 is a constant. A stepwise multiple regression was used, and only those coefficients with an F ratio greater than 2 were entered into the regression equation.

The results of the calibration using these 20 possible predictors from five sites are shown as model 1 in Table 8.III, and they include the

TABLE 8. III Several statistics for equations using 3 kinds of models for reconstructing sea surface temperatures at 3 coastal locations in California for 3 seasons[a]

Model number	1			2			3		
Number of predictors	20			12			10		
Kind of predictor	Indices for 5 sites[b]			3 Eigenvector amplitudes lagged[c]			10 Eigenvector amplitudes of indices lagged[d]		
Station and season	$\%\ s_x^2$	F ratio	No. of variables	$\%\ s_x^2$	F ratio	No. of variables	$\%\ s_x^2$	F ratio	No. of variables
Port Hueneme									
Winter	45	6·3	4	27	6·1	2	42	5·6	4
Spring	61	7·7	6	26	3·8	3	52	6·4	4
Summer	53	5·4	6	33	5·3	3	14	4·4	1
Balboa									
Winter	24	9·2	1	23	4·0	2	47	6·0	3
Spring	52	9·9	3	67	6·5	7	70	7·3	7
Summer	63	7·5	5	56	7·9	4	34	4·3	3
La Jolla									
Winter	23	4·1	3	11	2·6	2	37	3·5	4
Spring	41	5·4	5	15	3·6	2	67	7·3	6
Summer	46	6·7	5	46	6·7	5	40	4·1	4

[a]From work of Douglas (1973), and unpublished results. [b]Indices from 5 sites were lagged for 4 years from $t-1$ to $t+2$, making a total of 20 possible predictor variables (Equation 8.2). [c]The 3 most important eigenvector amplitudes calculated for the 5 chronologies for year t and the amplitudes lagged as in Equation 8.2. [d]The 10 most important eigenvector amplitudes of data used in model 1. [e]Percent calibrated variance.

percent variance calibrated, the F ratio for the total regression, and the number of tree-growth variables selected in the stepwise process. The reconstructions for this model which calibrated the largest percentage of the variance are for sea surface temperature of the spring and summer seasons. In four out of six cases the percent calibrated variance exceeds 50%.

The ring-width indices were substituted into the appropriate regression equation and estimates of sea surface temperatures were obtained for A.D. 1611–1964 (Fig. 8.14). Douglas attempted two additional reconstructions of sea surface temperatures using eigenvector amplitudes of tree growth. In one analysis (Model 2, Table 8.III) eigenvectors were extracted for the five chronologies of tree growth. The first three eigenvectors which reduce 87% of the variance in tree growth were selected, the amplitudes of the eigenvectors computed, and the amplitudes for year $t-1$, t, $t+1$, and $t+2$ used as predictors of sea surface temperatures (3 eigenvectors and 4 lags making a total of 12 predictors). In the second analysis (Model 3, Table 8.III) the data for the five tree sites and for years $t-1$, t, $t+1$, and $t+2$ were subjected to eigenvector analysis (5 trees at 4 lags making a total of 20 variables). The first 10 amplitudes of eigenvectors were selected to statistically estimate sea surface temperatures since they reduced 89% of the tree growth variance. No marked improvement in reconstruction was observed, and in most cases the calibrated variance was less and the F ratios lower than when the actual ring-width values were used as predictors.

Douglas attempted several verifications of the multiple regression reconstructions (Table 8.III, Model 1), including a comparison of some early records at San Diego for 1854–1872 with reconstructed temperatures at nearby La Jolla. He found that the winter reconstructions are significantly correlated with these early records, but unfortunately no significant agreement between spring and summer temperatures and those of the early records was observed.

Other independent records suggest that positive anomalies in sea surface temperatures occurred within the California current in 1869, 1871, 1877, 1885, and 1889, while negative anomalies occurred in 1864, 1882, and 1886. The sign of the anomalies is correctly reconstructed by tree rings in seven of the eight years (not in 1871).

Unusual occurrences of numerous warm water organisms off the California coast were reported in the middle of the 19th century, a period that Douglas reconstructs to be particularly warm. Douglas has also compared his reconstructed sea surface temperatures with deposits of Pacific hake fish scales taken from cores of the Santa Barbara Basin. He notes that decades with large year-to-year variability in sea surface
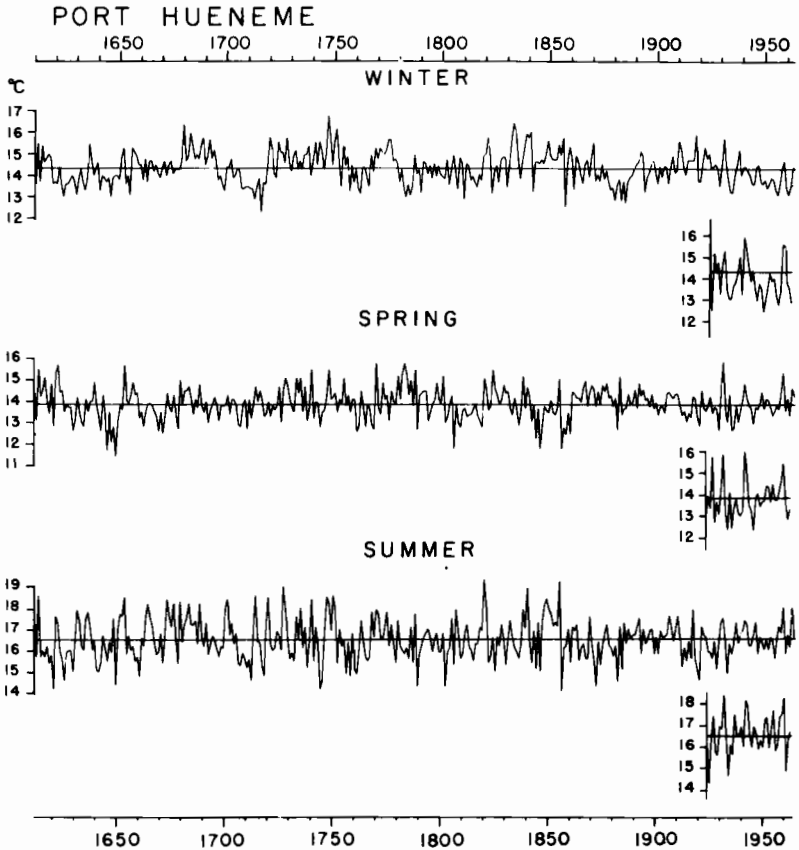
FIG. 8.14. The reconstructed sea surface temperatures for Port Hueneme as estimated from five ring-width chronologies in Southern California. The transfer function consisted of the significant multiple regression coefficients selected from 20 possible ring-width predictors. Predictor variables were the indices for years $t-1, t, t+1$, and $t+2$, where t is the year in which the sea surface temperatures were estimated (see Table 8.III). The actual sea surface temperatures used for calibration are plotted below and to the right of the estimates. (From Douglas, 1973)

temperatures are also decades with large counts of hake scales. The correlation between number of fish scales and the standard deviation of the reconstructed sea surface temperatures for each decade proved to be significant ($r = 0.35$). These results suggest that large fluctuations in sea surface temperatures may have resulted in the death of large numbers of fish whose scales were deposited in the ocean sediments.

Douglas (1973) summarizes the paleoclimatic significance of his results by pointing out that decades of warm sea surface temperatures occurred in the 1610's, 1680's, 1770's, 1830's and 1850's. This condition is hypothesized to be the result of weak atmospheric pressure gradients along the California coast. He suggests that a contrasting temperature distribution prevailed in the decades of the 1620's, 1640's, 1670's, 1760's. and 1880's, during which cold conditions may have resulted from a strong pressure gradient parallel to the California coast.

Douglas attributes these conditions to possible variations in the strength and positioning of the North Pacific high pressure system in summer and in the location of an upper-level low pressure trough off the coast of North America, particularly in late autumn.

Comparing the results using eigenvector amplitudes as predictors with those using actual growth indices (Table 8.III), it can be seen that regression on amplitudes in this case is inferior to the use of the ring-width indices themselves. This appears to be true for cases in which the numbers of variables are not excessive and where correlation among the predictors is not extremely high. However, when there are many highly correlated variables and the numbers of variables approach the numbers of observations, principal component analysis is more appropriate. The number of variables can be reduced to a reasonable size, and the smaller-scale variances representing noise can be eliminated by excluding those principal components which reduce little variance.

D. Climatic Variations Affecting Biological Systems

Since it was shown that ring-width variations can be linked with variations in sea surface temperatures and thereby with hake fish population, it was thought that other sea organisms might be affected by sea surface temperatures and also subject to population estimation and reconstruction backward in time. Clark et al., (1975), investigated this possibility by using tree rings and yearly catch statistics of *Thunnus alalunga* (albacore tuna), a fish which is known to be affected by sea surface temperatures. The percentage of annual catch north of San Francisco, California, during the years 1938–1961, were the only available quantitative measurement of the *Thunnus alalunga* population.

The predictors used were the eigenvector amplitudes of ring width for 49 sites in western North America which are similar to those shown in Fig. 7.15 and described in detail in Chapter 9. A stepwise multiple regression analysis was used to obtain the following equation:

$$\hat{Y} = 35 \cdot 12 + 5 \cdot 76 A_2 + 5 \cdot 13 A_8 + 8 \cdot 56 A_4' - 6 \cdot 17 A_9' + 11 \cdot 54 A_{10}' \qquad (8.3)$$

where $\hat{Y}$ is the estimated percentage of albacore tuna and A and A' are eigenvector amplitudes of tree growth corresponding to the catch year and the following year, respectively. The subscripts refer to the eigenvector number. The five variables of the ring-width amplitudes for the dependent period from 1930 to 1961 accounted for 83% of the fish-catch variance, a statistically significant result.

Figure 8.15 shows the annual estimated percentage of albacore catch reconstructed by tree rings, assuming a constant level of fishing technology where the shaded area in the figure represents the dependent data set. The elements of the transfer function associated with the tree growth during the year of the catch (a) and during the year following the catch (b) are calculated and plotted (Fig. 8.16) to check the reasonableness of the calibration relationship. Each map represents the departure in growth associated with higher catch percentages and anomalously high sea surface temperatures north of San Francisco.

Since the tree-ring data were from arid-site trees, high growth could be assumed to indicate anomalously cool, cloudy weather with above normal precipitation, and low growth could be assumed to reflect warm, sunny, and dry conditions. During the fishing season (Fig. 8.16a) tree growth associated with high catch was low in northwestern United States, indicating that fewer than normal storms were entering this area. This would indicate the weather over the ocean also was unusually sunny and mild—warm conditions with high solar radiation which would warm the waters and favor the movement of fish into the region. These warm conditions would then be expected to result in increased evaporation during the following autumn and winter which would lead to increased
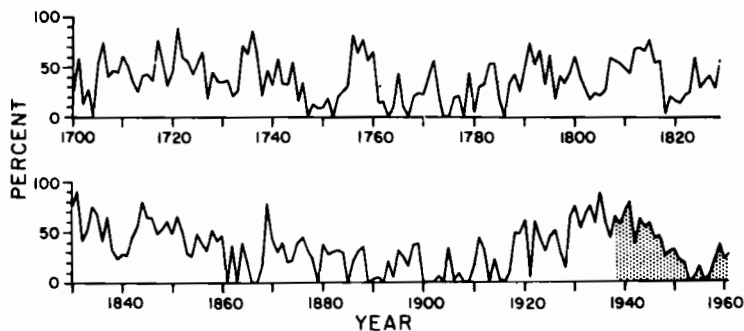
FIG. 8.15. Percent of the total catch of *Thunnus alalunga* (albacore tuna) taken north of San Francisco estimated from the calibration equation applied to ring-width variations for A.D. 1700 to 1961 from western North America. Shading indicates the dependent calibration period. (From Clark *et al.*, 1975, courtesy of *Nature*)

'cyclonic activity, increased precipitation along the coast north of San Francisco, and, ultimately, above-average growth in the Northwest during the following spring (Fig. 8.16b). With deflection of storms into the Northwest, fewer storms would be expected to pass through the Great Basin where tree growth was below average. Other growth anomalies were also consistent with the weather systems that might be expected preceding and following a summer of warmer than normal sea surface temperatures and high fish catch north of San Francisco.
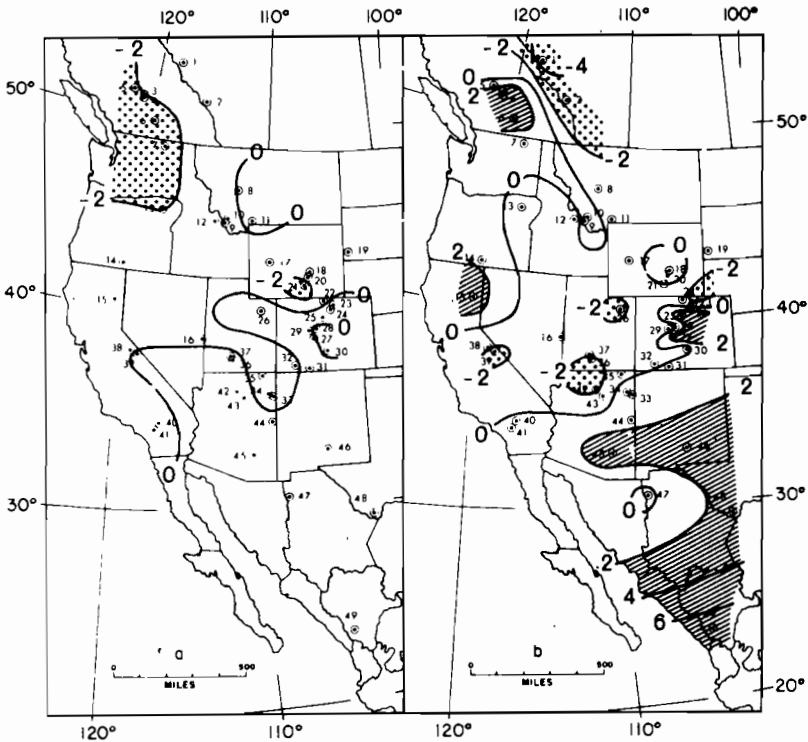
FIG. 8.16. Tree-growth anomaly patterns associated with above normal catch percentages of *Thunnus alalunga* (albacore tuna) by the fishing fleet north of San Francisco. Map *a* shows the growth anomalies during the year of the catch and Map *b* shows the growth anomalies for the year following the catch. Both are obtained as linear combinations of the eigenvectors and then weighted as indicated in Equation 8.3. (From Clark *et al.*, 1975, courtesy of *Nature*)

Qualitative data on fish catch for the independent period prior to 1938 were found to be consistent with the percentages reconstructed from tree rings. These results substantiated that there was a meaningful relationship linking the albacore tuna and ring-width variations. The authors suggested that this catch reconstruction indicates the presence of long-term changes in the ocean system (Fig. 8.15) which are not evident in the shorter record of catch statistics available since 1938.

Clark *et al.* (1975) conclude that the success of this study suggests that tree-ring variations can be used to objectively reconstruct other past climatically caused biotic variations. They believe the study provides useful information about the climatic controls of *Thunnus alalunga* (albacore tuna) distribution and that similar studies can help in anticipating variations in other biotic populations that could result from future climatic variations.

E. Variations in Temperature and Precipitation

An experiment is described in this section which tests the applicability of eigenvector patterns of tree growth over western North America to the reconstruction of monthly temperature and total monthly precipitation at selected climatic stations back in time prior to record-keeping. Monthly mean temperature and monthly precipitation were obtained for Boise, Idaho; Sacramento, California; and Phoenix, Arizona. Data from all climatic stations with long and homogeneous records were calibrated with the eigenvector amplitudes of tree-growth patterns over western North America. The regression equations obtained were used to reconstruct past climate at the three stations from the amplitudes of spatial variations in tree rings. A portion of the climatic record was withheld from calibration and used as independent data to test the reconstructions.

Calibration was accomplished in the following manner: (1) Amplitudes of the first 15 eigenvectors of tree growth for 49 sites throughout western North America at lags of t and $t + 1$ were selected as possible predictors of climatic variables for the years 1911–1960. (The amplitude data are for eigenvectors similar to those in Figs 7.15 and 7.16 and are described in more detail in Chapter 9). The climatic predictands included monthly temperature and precipitation data for June through December of the year $t - 1$ and January through July of year t so as to correspond to the 14-month year used for the response function analysis (Fritts, 1974). However, in this particular test they were the predictands, not the predictors. (2) Stepwise multiple regression analysis was used to obtain the appropriate and significant regression weights for statistically

estimating each monthly climatic variable using the 15 amplitudes for year t and for year $t + 1$. (3) The resulting regression equations were then applied to independent tree-ring amplitude data to reconstruct the monthly climatic data for the independent period, extending from the beginning of the record through the year 1910. The actual data from the independent period were then compared to the reconstructed data using the reduction of error statistic (Equation 7.4).

In general, the multiple regression equations for reconstructing the individual monthly data did not hold up when applied to data for the independent period, even though the regression equations for the dependent period 1911–1960 were highly significant. Out of a total of 84 possible regression equations (14 months of precipitation and 14 months of temperature at three stations), the reductions of error using independent monthly data were zero or negative 72 out of 84 cases. The tree-ring chronologies which are integrated records of climate over an entire year simply did not have sufficient information in their differences to reconstruct the monthly climatic data.

Therefore it was hypothesized that the tree rings might reconstruct averages for the 14-month year even though they cannot reconstruct data for the individual months. To test this hypothesis the monthly reconstructions for temperature and precipitation obtained in the above test were averaged (totaled) and compared to the independent climatic data which were also averaged (totaled) for the 14 months. Data for both June and July were used twice to allow computation of the 14-month interval. The reduction of error statistic was recomputed and a sign count made of the independent data set (see Chapter 7) to test whether the predicted departure (from the dependent mean) was correctly reconstructed (Table 8.IV).

TABLE 8.IV Verification statistics of climate reconstructions using tree-ring data to estimate mean temperature and precipitation for a 14-month period[a]

Station	Variable	Reduction of error	Sign test — number of Agreements	Disagreements
Boise	Temperature	0·000	21	19
Boise	Precipitation	+0·120[b]	28	14[b]
Sacramento	Temperature	+0·292[c]	43	14[c]
Sacramento	Precipitation	0·000	25	35
Phoenix	Temperature	+0·336[c]	24	9[b]
Phoenix	Precipitation	+0·332[c]	17	4[c]

[a]Estimates for individual months were summed for 14 months and compared with the sums of actual measurements of climate prior to 1911. [b]Significant at the 0·95 level. [c]Significant at the 0·99 level.

It is seen from the table that the relationships are significant for both temperature and precipitation at Phoenix, for temperatures at Sacramento, and for precipitation at Boise. The lack of predictability of temperature at Boise may be explained as either the result of localized climatic data, which can be poorly correlated with the climate of the larger region which affected the spatial patterns of tree growth, or the result of a paucity of highly sensitive tree-ring chronologies in the area. The same may have been the case for precipitation at Sacramento, where a large number of zero values for summer months limit the variance usable for calibration and where there are no chronologies near the climatic station. However, four of the six analyses did pass the 0.95 probability level of significance for independent data, and it is concluded that even single station data at certain localities can be reconstructed from tree rings if the data are averaged over several months.

It was hypothesized that reconstruction of climatic data for single stations, or for several stations representing a small region, is more likely to be accomplished using tree-ring chronologies located near the climatic station. The following is a preliminary report on a test of this hypothesis made by Shatz (personal communication), utilizing 21 long and homogeneous precipitation records that were paired with at least one yearly ring-width chronology at distances from the climatic station ranging from 2 to 60 miles (3 to 97 km), with an average distance of 17 miles (27 km).

Monthly precipitation for each year was totaled for the March–June interval. Data for the years 1909–1960 were available from all 21 climatic stations, so 32 out of these 52 years were selected at random to be used for calibration with the 21 paired ring-width chronologies. The same 32 years of information were used from all data sets and the remaining 20 years of data serve as independent checks. In addition, a number of the climatic records include valid information prior to 1909 and these were also utilized as additional independent data. All climatic and tree-ring data were normalized using the means and standard deviations for the 32-year calibration set.

Stepwise multiple regression analysis was employed using the 32 randomly selected years, as shown in the following model:

$$\hat{y}_t = b_1 x_{t-1} + b_2 x_t + b_3 x_{t+1} + b_4 x_{t+2} + b_5 x_{t+3} \qquad (8.4)$$

where $\hat{y}_t$ is the normalized estimate of the total precipitation for the four-month period for year t, and b_1 to b_5 are significant regression coefficients associated with normalized ring-width indices for one year prior to year t

TABLE 8. V Statistics for 10 tree-ring chronologies which calibrated significantly with spring precipitaion at nearby climatic stations[a]

Pair number	1	2	3	4	5	6	7	8	9	10
Species	P.e.[d]	P.e.	Ps.m.[e]	Ps.m.	P.e.	Ps.m.	P.p.[f]	P.f.[g]	Ps.m.	Ps.m.
Distance in km between pairs	97	11	43	32	40	11	24	3	13	40
Rank of tree-ring statistics	5	11	2	7	3	6	15	12	4	1
Subscripts of significant coefficients	2,5	3	2	3	2	2	2,4	2	2,3	3
Percent variance calibrated	34	13	36	17	18	42	22	23	51	27
Independent test 1909–1960										
signs +	13	8	12	11	15	15	13	9	13	11
signs –	7	12	8	9	5[b]	5[b]	7	11	7	9
positive product mean	0·65	0·31	2·66	1·44	0·73	2·94[b]	1·21[b]	1·26	2·11[b]	1·36
negative product mean	0·80	0·31	1·70	1·05	0·78	0·81	0·15	1·26	0·79	0·62
reduction of error	−0·29	−0·12	−0·09	0·02	0·14	0·40[c]	0·37[c]	−0·17	0·25[b]	0·04
Independent test pre-1909										
signs +	9	3	11	—	18	3	5	—	22	2
signs –	0[c]	1	3	—	6	0	4	—	6[c]	1
positive product mean	1·24	—	4·60[c]	—	0·97	—	0·92[c]	—	3·72	—
negative product mean	0·00	—	0·39	—	0·45	—	0·25	—	1·75	—
reduction of error	0·70[c]	—	0·34[b]	—	0·34[c]	—	0·26	—	0·15[b]	—
Verified by independent data	✓		✓		✓	✓	✓		✓	

[a] Preliminary analysis by Shatz (unpublished). [b] Significant 0·95 level. [c] Significant 0·99 level. [d] Pinus edulis. [e] Pinus edulis. [f] Pseudotsuga menziesii. [g] Pinus ponderosa. [g] Pinus flexilis.

through three years following year t. The values for all insignificant regression coefficients in Equation 8.4 are set at zero.

A total of 10 out of the 21 pairs exhibited significant calibration statistics with the total precipitation for these four months (Table 8.V), with percentages of calibrated variance ranging from 13% to 51%. Additional information provided in the table includes the particular variables entered into the regression with significant partial regression coefficients, and the rank of the tree-ring chronology based upon first-order autocorrelation and mean sensitivity statistics. The first in the rank had the highest mean sensitivity value and the lowest autocorrelation coefficient.

A comparison of the data from the 11 chronologies that did not calibrate showed no consistent relationship between the degree of calibration and either the distance between tree and climatic stations or their elevations. However, 8 of 10 of the chronologies which did calibrate were ranked 10 or higher, confirming that the statistical quality of tree-ring chronologies, rather than their closeness to climatic stations, is important to establishing significant climatic relationships. For some indeterminable reason, perhaps due to the site itself, the calibration for the highest ranking chronology (Table 8.V, no. 10) did not hold up in the verification.

A total of 6 out of the 10 chronologies which exhibited significant calibration were verifiable with independent data (Table 8.V). In all six cases of verification, the regression coefficient for growth of year t was significant, while in three of the four cases that did not verify growth of year $t+1$ was the variable selected for calibration by the use of the stepwise regression procedure. Apparently there was insufficient linkage at a lag of one year to hold up when tested against the independent data set.

Since six of the significant calibration relationships were also shown to have significant verification statistics, it can be concluded that precipitation for a four-month interval in the spring can be reconstructed to some extent from variations in tree rings from nearby sites. However, these reconstructions using a chronology from only one site exhibit considerable statistical noise, since the highest percent variance reduced for the dependent set was only 51%.

There are several possible explanations for the low calibration percentage:

(1) Some of the climatic records may have been faulty and included information irrelevant to the climate at the tree sites.

(2) The tree-ring chronology may not have included enough variance related to the climatic parameter with which it was calibrated, a situation

which arises when (a) the nonclimatic noise in the chronology is too large, or (b) the trees simply do not respond to the particular climatic information with which they were calibrated.

(3) A large part of the tree-ring chronology variance may have been related to climatic factors not included in the calibration, and this uncalibrated variance acted as noise.

(4) The trees may have responded to precipitation directly during certain months in the calibrated season and inversely during other months in the calibrated season, so that there was no net correlation of growth with the average precipitation for the four month interval.

It is apparent from the results described in this chapter that while it is often possible to successfully reconstruct seasonably averaged data such as streamflow, lake levels, and climatically linked population data, attempts to reconstruct precipitation on a station-by-station basis involves a large amount of noise and the climatic reconstructions are likely to include considerable error in the statistical estimates. One method of minimizing this noise is to average a large number of chronologies and climatic data stations and relate the spatial patterns in one to the spatial patterns of the other. Such an approach is now feasible by using the averaging capabilities of principal components. The following chapter describes these rather recent developments.

Chapter 9

Reconstructing Spatial Variations in Climate

I. Introduction

The atmosphere of the earth is a fluid system being continually mixed on scales of motion ranging from large planetary whirls to minute molecular motions. Day-to-day changes in the weather are generally caused by the movement of intermediate-scale low pressure and high pressure systems (cyclones and anticyclones) which migrate over a few thousand kilometers of the earth's surface. These intermediate-scale systems can produce weather conditions lasting from a fraction of a day to a number of days over large geographic regions, and when changes in weather occur they are often associated with the approach and passage of one or more of these pressure systems.

Air masses which are separated from one another by boundaries called *fronts* are intermixed by these systems. The temperatures and moisture of different air masses vary so that the passage of a front is often marked by abrupt changes in air temperature and moisture as well as wind direction. These intermediate-scale cyclones and anticyclones may be modified locally by associated smaller-scale systems such as hurricanes, tornadoes, and thunderstorms. Such localized phenomena, at times connected with frontal passage, can create apparent discontinuity and variability in the circulation system when viewed from a point on the earth's surface.

The *cyclones* and *anticyclones* are themselves part of still larger planetary circulations, which are most obvious at altitudes of several kilometers above the earth's surface. Such large-scale systems may move very slowly or persist for months and even for years over a region, steering the cyclones and anticyclones into certain areas and away from other areas over the surface of the earth.

These large-scale systems can affect the weather over the entire globe, causing anomalies of one kind to occur in particular sectors of the systems which are correlated with anomalies (often of different kinds) in other sectors. For example, the sub-Saharan drought of 1968 through 1973 is apparently associated with higher-than-normal pressure in the planetary systems over western Europe, and lower-than-normal pressure south of the Azores and in east central Africa (Winstanley, 1973; Namias, 1974). It may also be associated with anomalous weather occurring elsewhere around the globe.

Both the intermediate- and large-scale circulation systems produce a certain amount of spatial coherence in climate. If weather records for a given set of years are taken from neighboring stations, they usually resemble one another and are directly correlated. Stations separated by greater distances, such as those on opposite sides of continents and mountain systems are usually less well correlated, although some correlation may still exist. Depending upon their relationship to the planetary systems that steer the cyclones and anticyclones over the specific regions, the correlations may be either direct or inverse. For example, winters may be dry in Pacific southwestern North America during years in which many winter storms are passing along the Pacific Northwest, and similarly, years of cold winters in eastern United States may be years of warm winters in the West. As a result of such long-distance correlations, there is a certain amount of information on climatic variability that is not random over the globe.

The storage and exchange of energy among various components of the earth–atmosphere system can dampen the variability of the circulation systems and create a certain amount of nonrandomness in climatic

records. For example, the rates of cooling in autumn and of warming in spring are governed by the rates of energy released and stored at the land and water surfaces. An anomalously warm or cold ocean may be responsible for a persisting climate over nearby continents (Namias, 1974; Gates and Mintz, 1975). The presence of a widespread early snowfall can affect the albedo of the earth and hasten the onset of winter or a late snowfall can delay the beginning of the warmer spring climate (Kukla and Kukla, 1974). Large ice masses, such as those that occurred 17,000 years ago, can be associated with extremely long-term climatic changes even in regions where the ice was not present (Gates and Mintz, 1975).

Persistence in the various parameters of weather and climate can lead to substantial autocorrelation in the climatic record (Jones, 1975) and to intercorrelations among climatic variables in different regions (Walker and Bliss, 1932; Bjerknes, 1962, 1966; Namias, 1953, 1969; Mitchell *et al.*, 1966; Lamb and Johnson, 1959). Kutzbach (1970) describes several major centers of action in the Northern Hemisphere and characterizes their spatial and temporal variations. Blasing (1975) describes several large-scale modes of pressure variation over the North Pacific and North American continent and discusses some innovative procedures for analyzing them.

The term *synoptic climatology* (Barry and Perry, 1973) is applied to studies of large-scale variations in climate in which the general circulation of the atmosphere must be considered over both time and space, while the term *climatography* is applied to the mapping of climate. Such studies often include analysis of averages, variances, or anomalies of various kinds, expressed as departures from long-term means. They may include differences in means from one period to the next, frequencies of occurrences of various climatic types or events, correlations among variables distributed over space, and other representations of climate as it varies through both time and space. The term *dendroclimatography* which has been introduced in Chapter 1, is the name of the relatively new field in which the spatial variations in tree rings are employed to reconstruct and map the spatial variations in past climate. Figures 1.13 and 1.14 include examples of early studies in which tree-growth maps for western North America are used to infer regional variations in climate. The following pages summarize some of the most important developments in this type of research, some of which utilize techniques described in earlier chapters, and others which employ new techniques designed specifically for mapping analysis.

This chapter will include a general discussion of dendroclimatographic data and examples of statistical models that are useful. A particular

feasibility study is then described which documents the potential of the field, raises some climatological problems, and suggests certain improvements which are incorporated in subsequent reanalysis work. The most pertinent results from climatological analyses and reconstructions growing out of the feasibility study are summarized. In particular, a new procedure for identifying and describing variations in climate is discussed and used to interpret the climate reconstructed from the spatial variations in tree growth. Subsequent sections describe the details of the reconstructions, their verification, and other applications to analysis of spatial variations in climate. The chapter concludes with a discussion of present and future prospects for dendroclimatic reconstruction and related tree-ring work.

II. The General Nature of Dendroclimatographic Analysis

It has been established that ring widths are especially suitable for analysis of past climate because the growth layers can be dated accurately. The methods described below require absolute dating so that all observations in the spatial arrays of both climate and tree rings can be placed in their proper time sequence.

Inferences of year-to-year climate from growth rings are complicated, however, by the fact that a portion of the tree-growth response can lag behind the occurrence of a climatic event (see Figs. 1.10 and 5.9), and the climate of various seasons can affect growth differently. An understanding of the growth response for specific species and sites is therefore necessary for constructing appropriate models for calibration. Results from different models are tested in order to select the best statistical relationship. This is then applied to yearly tree-ring data to obtain yearly climatic estimates.

A climatographic model was suggested by the work of LaMarche and Fritts (1971a) in which eigenvectors of spatial variations in tree growth were found to resemble the eigenvectors of spatial variations in precipitation over the same area and period of time (Fig. 7.16). This suggested that a spatial pattern of climatic anomaly may produce a spatial pattern of tree-growth anomaly, and that the eigenvector amplitudes of climate might be calibrated with the eigenvector amplitudes of tree growth (Equation 7.20).

The climate-growth models used to test this possibility are similar to those in Table 8.II, the only difference being that the data vary through space as well as time. The models assume that modes of variation in precipitation, temperature, or other climatic parameters, measured over

a grid of weather stations, are linearly related to corresponding modes of tree growth. Maps of tree growth are then transformed to corresponding maps of climate.

III. The Statistical Model

The objective is to obtain a transfer function $_pT_m$ which can be applied to m tree-ring chronologies associated with n years ($_mF_n$) to obtain estimates at p climate stations for n years of record ($_pp_n$). This can be accomplished by solving Equation 7.21 for each of p predictand data points

$$_p\hat{P}_n = {}_pT_mF_n \tag{9.1}$$

but such solutions involve considerable computations, and excessive numbers of degrees of freedom are used up.

A technique referred to as *canonical analysis* is applied to obtain an optimal solution as it combines redundant data from neighboring stations into orthogonal covarying components (Glahn, 1968; Blasing, unpublished). Two orthogonal matrices, $_pA_g$ and $_kB_g$, are derived which can be multiplied by matrices $_nX_p$ and $_nY_k$ respectively to obtain two orthogonal sets of amplitude variables, $_nW_g$ and $_nQ_g$.

$$_nW_g = {}_nX_pA_g \tag{9.2}$$

$$_nQ_g = {}_nY_kB_g \tag{9.3}$$

where g is equal to the smaller number of p or k. Each W variable is orthogonal to all other variables in the $_nW_g$ set, and each Q variable is orthogonal to all other variables in the $_nQ_g$ set. Furthermore, each variable in $_nW_g$ is correlated with only one variable in Q, and is orthogonal to all other Q variables in the $_nQ_g$ set. This is expressed mathematically as

$$\left(\frac{1}{n}\right)_g W_n'Q_g = {}_g\Lambda_g \tag{9.4}$$

where $_gW_n'$ is the transpose of $_nW_g$ and $_g\Lambda_g$ is the diagonal matrix of *canonical correlations* (with zeros in the off-diagonal elements) between each W variable and the corresponding Q variable with which it is matched. The g (diagonal) elements of $_g\Lambda_g$ are arranged in order from the highest to lowest canonical correlation coefficient.

According to Blasing (unpublished), if $g = k$ (that is $k \le p$), then the equation to estimate Q from W is

$$_n\hat{Q}_g = {_nW_g}\Lambda_g \tag{9.5}$$

Applying Equations 9.2 and 9.3, Equation 9.5 can be expanded:

$$_n\widehat{Y_gB}_g = {_nX_p}A_g\Lambda_g \tag{9.6}$$

or, multiplying both sides by ${_gB_g}^{-1}$

$$_n\hat{Y}_g = {_nX_p}A_g\Lambda_gB_g^{-1} = {_nX_p}T_g \tag{9.7}$$

where the transfer function $_gT_g$ is composed of a set of *canonical regression coefficients* that transform values of $_nX_p$ into estimates of $_gY_g$.

As in the case with eigenvectors, small-scale variance may be eliminated by selecting only the first h canonical variates, so that only the large-scale features of growth are used to reconstruct the large-scale features of climate. If all g canonical sets are used, the elements of $_gT_g$ are the same as the usual multiple regression coefficients with p elements of X statistically predicting k elements of Y. Such multiple regression provides the best fitting relationships for the calibration period, but more degrees of freedom are consumed and they may not hold up on independent data as well as the reduced set of canonical variates.

Thus, canonical analysis is used: (1) to obtain covarying modes of behavior between the two variable sets, (2) to eliminate the small-scale modes which have the lowest covariance between sets, (3) to maximize the number of degrees of freedom in the final analysis, and (4) to gain efficiency and stability by solving for a reduced number of variables.

IV. A Feasibility Study

The tree-ring data used for the first dendroclimatographic reconstruction test described in the chapter consisted of 49 chronologies from western North America (Stokes *et al.*, 1973). LaMarche selected this tree-ring set from a collection of several hundred sites for analysis of possible sunspot and tree-growth relationships (LaMarche and Fritts, 1972). It includes a variety of topographical situations and species, ranging from central British Columbia, Canada, to Durango, Mexico, and from California to South Dakota.

The climatic data used in this study are monthly values of surface pressure for the Northern Hemisphere adjusted to mean sea level and tabulated for 1900 through 1962, excluding the years for 1939-1944 (these missing data were later obtained or estimated). Preliminary examination had shown substantial correlation of tree growth with pressure data at sizable distances from the tree sites. Thus, a grid was

chosen to include data for 100 points located at every 10 degrees from 25 to 65 N latitude and 165 E to 5 W longitude.

Since the ring-width index represents the integrated effect of climate for several seasons in the growth year, the seasonally averaged climatic data were used for all four seasons. This introduces a change from the more conventional meteorological approach which uses January data to represent winter and July data to represent summer. Each season is defined as follows:

Summer	July, August, September
Autumn	October, November, December
Winter	January, February, March
Spring	April, May, June

The growth for a particular year was matched with pressure data for the prior summer, autumn, and winter seasons, as well as with that of the spring in which growth began. Thus the variables of pressure include 100 grid points for four seasons which were to be estimated from 49 ring-width chronologies.

The size of the problem actually exceeded the capacity of the computer and would have consumed all available degrees of freedom, so the following simplifications were made. All data for each of the 400 pressure variables and the 49 tree-ring variables were normalized (Equation 7.5). The pressure data for each season were subjected to principal component analysis, and the first eight and most important eigenvectors, reducing approximately 80% of the variance, were selected for further study. The amplitudes of the eigenvectors (Equation 7.19) were obtained for each season, providing a total of 32 variables of pressure (eight for each of four seasons). We shall refer to these as $_nY_i$.

Similarly, the first seven eigenvectors of tree growth and their amplitudes (LaMarche and Fritts, 1971a) were used and they reduced 57% of the variance. A more recent analysis of the same data is shown in Figs 9.1 and 9.2, which utilizes the amplitudes of the first 10 eigenvectors to reduce 63% of the tree-growth variance. We shall refer to these as $_nX_p$.

The eigenvector variables for pressure were orthogonal only for the eight variables within each season, and therefore further analysis was required to reduce them to completely orthogonal components. The first part of canonical analysis was run as in Equations 9.2, 9.3, and 9.4. Matrices $_nW_g$ and $_nQ_g$ were obtained, where the first are the seven canonical amplitudes of the 49 ring-width chronologies (Equation 9.2) and the second are the seven canonical amplitudes of pressure for the four seasons (Equation 9.3). Matrix $_pA_g$ (Equation 9.2) was multiplied by the eigenvectors of tree growth, $_mE_p$, to obtain matrix $_mZ_g$ as follows:
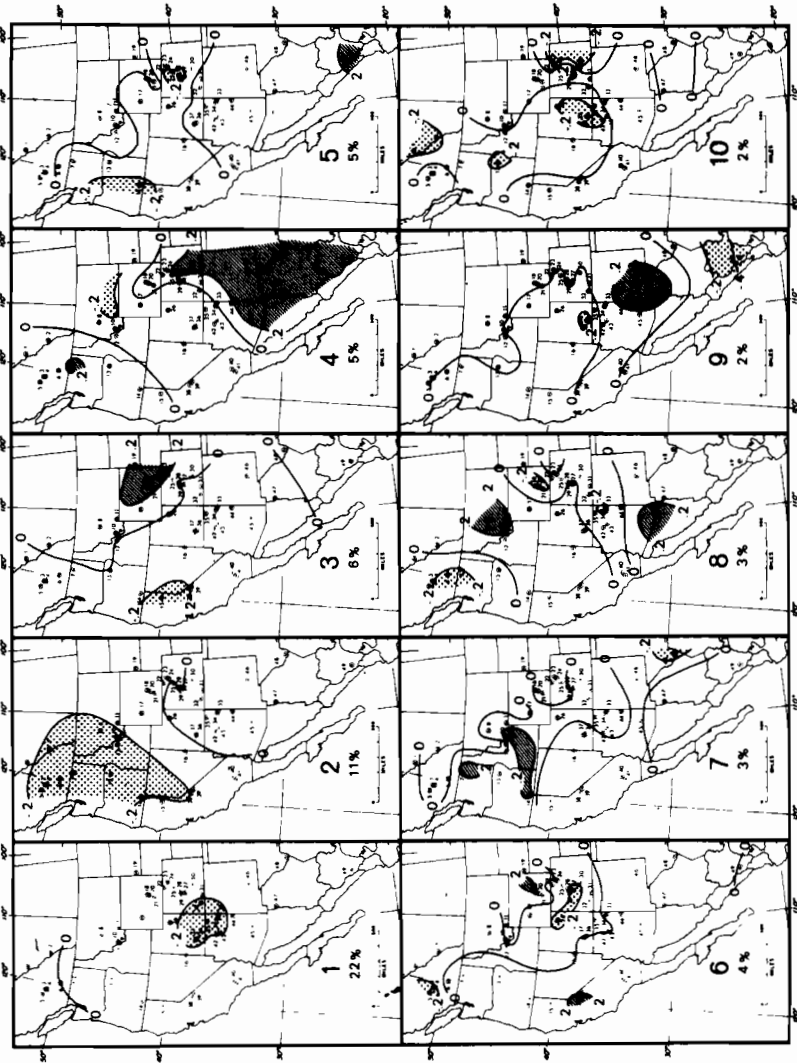
FIG. 9.1. The first 10 eigenvectors representing the spatial variations in tree-ring indices from 49 ring-width stations for 1700–1962. The eigenvectors are ranked in the order of their importance, that is, in order of the variance they reduce which is indicated by the percentage figure in lower left of each map. (Drawing by M. Huggins)
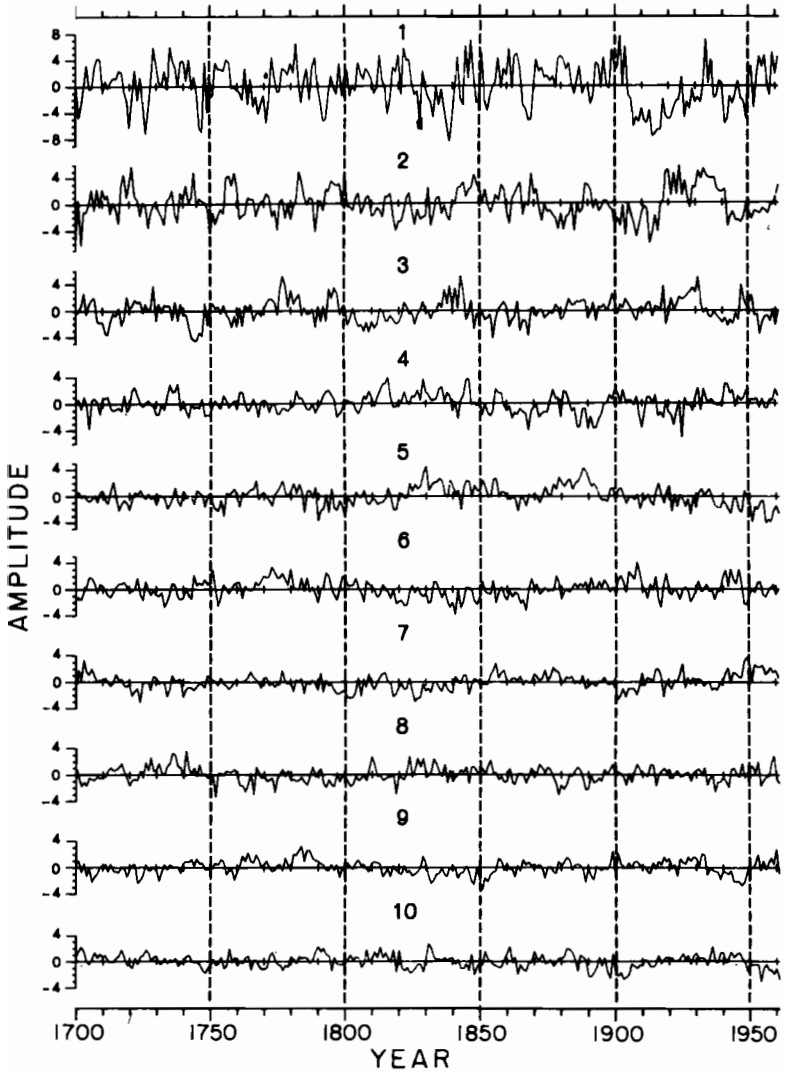
FIG. 9/2. The amplitudes of the first 10 eigenvectors shown in Fig. 9.1 plotted in standard deviations (normalized units) to show their variations through time. Note the decrease in the variance associated with the increasing rank.

$$_mZ_g = {_m}E_p A_g \tag{9.8}$$

This matrix includes the eigenvectors of tree growth canonically weighted to give maximum relationship with variations in pressure. The values for the elements are ordered according to the canonical correlation coefficients and mapped in Fig. 9.3, while the values for amplitudes $_nW_g$ are plotted in Fig. 9.4.

The transfer function that was obtained in this particular study differed from Equation 9.7, since the appropriate computer program had not yet been developed. The amplitude series $_nW_g$ were used as predictors of the normalized pressure for 400 seven-variable multiple regression analyses. Hence,

$$_p\hat{P}_n = {_p}R_g W'_n \tag{9.9}$$

where $_pR_g$ is the complete set of 2800 regression coefficients relating the seven canonically weighted amplitudes of growth to the pressure at 100 grid points for four seasons. The regression coefficients were applied to transform $_gW'_n$ for the years 1700-1899 into the estimates of $_p P_n$ the latter representing past anomalies in pressure for 1700-1899. The estimates of $_p P_n$ were converted to millibar pressure anomalies by multiplying each item of $_p\hat{P}_n$ by the appropriate standard deviation for the season and grid point.

Figure 9.5 includes examples of the mean pressure reconstructions and the corresponding mean growth anomalies for two selected decades. Although the differences between the two growth anomalies are not large, there are substantial differences in the pressure estimates. Analyses of these pressures, which are described later in the chapter, indicate that the mid-North American climate during the summers of 1731-1740 was dry and warm, but during winter there were unusually frequent outbreaks of cold Arctic air. During 1771-1780 the summers were anomalously cool and moist but the winters were milder than normal.

The anomalies of pressure for each season were averaged by pentads and mapped. The maps showing the most marked pressure anomalies for winter are included in Fig. 9.6a, b, and c. These maps clearly show periods of anomalous pressure centered over the Gulf of Alaska which are associated with anomalies of opposite sign over Hudson's Bay or the North Atlantic. During most of the 19th century (Figs 9.6b and c), higher than normal pressures persisted in the Gulf of Alaska, indicating a weak Aleutian Low and cold air in the Arctic. However, in the 18th century, surface pressures were lower for the North Pacific, indicating a stronger

Aleutian Low and somewhat warmer temperatures in North America, a pattern that was common during the 20th century.

The percent pressure variance reconstructed at all grid points for each season during the calibration period averaged $23 \cdot 7\%$ for summer, $20 \cdot 6\%$ for autumn, $24 \cdot 0\%$ for winter, and $18 \cdot 5\%$ for spring. The best reconstructions were for the pressure over the subtropics of both oceans, over the north Pacific Ocean, and over the North American continent
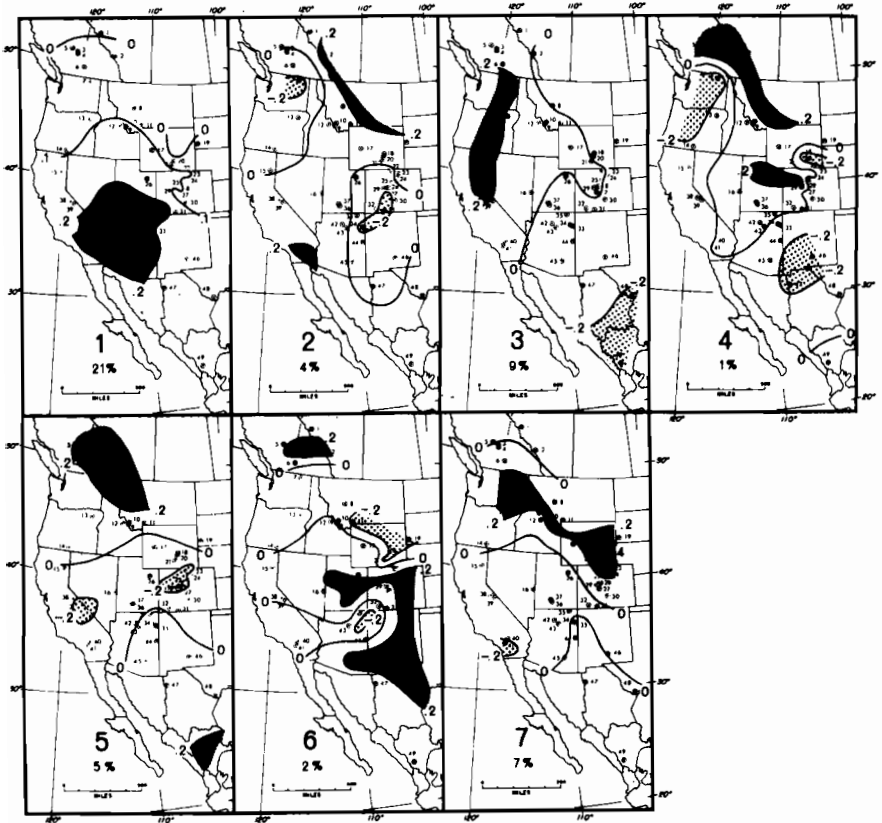
FIG. 9.3. Plots of the eigenvector patterns of growth canonically weighted to give maximum correlation with anomalies in surface pressure $(_mE_pA_g$, Equation 9.8). The maps are ranked from high to low correlation with the pressure anomalies, and the percentage in the lower left of each map is the variance in the growth that was reduced by each weighted set. Note that the weights which are ranked in the figure according to the correlation with the pressure anomalies are no longer in the order of the variance in growth that was reduced. (Fritts *et al.*, 1971)

where the percentages of variance reconstructed ranged from 30% to 50%. The percent variance reconstructed for the North Atlantic was so small that the reconstructions in that area were judged to be insignificant (see Fritts *et al.*, 1971).

It was concluded from this feasibility study that the multivariate technique was very promising but that the task of reconstruction might be improved by 1 changing the pressure grid to eliminate the area of poor reconstruction in the Atlantic Ocean and to include more area in the Western Pacific and the Asian mainland, (2) defining the seasons differently, 3 including tree growth in the model for at least one year before and for two years after the occurrence of climate, and (4)
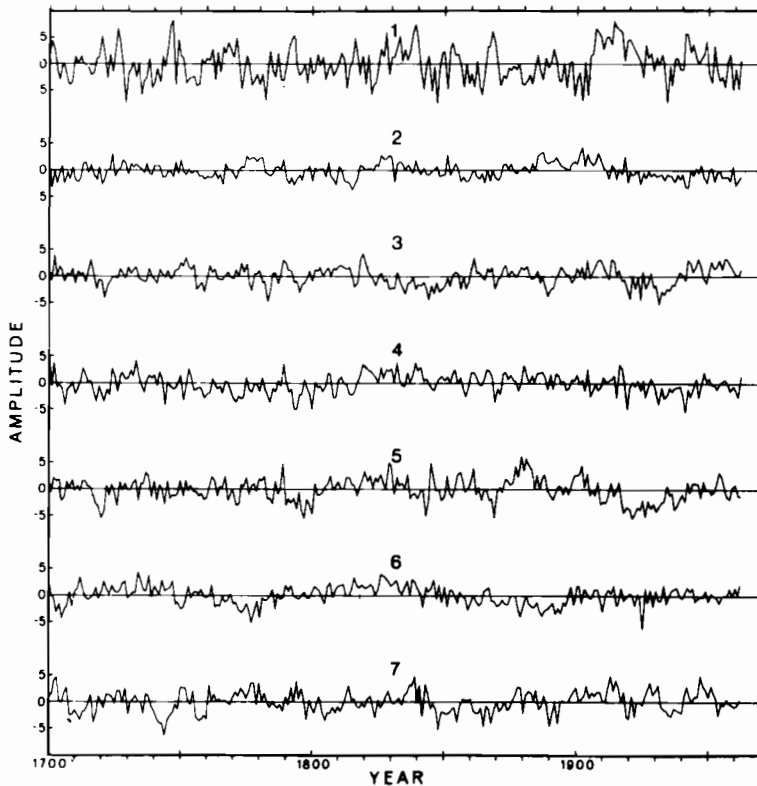
FIG. 9.4 Plots of the amplitudes of the seven eigenvectors of tree growth $_nW_g$ canonically weighted to give maximum correlation with surface pressure. Plots are ordered from high to low correlations with pressure. Fritts *et al.*, 1971
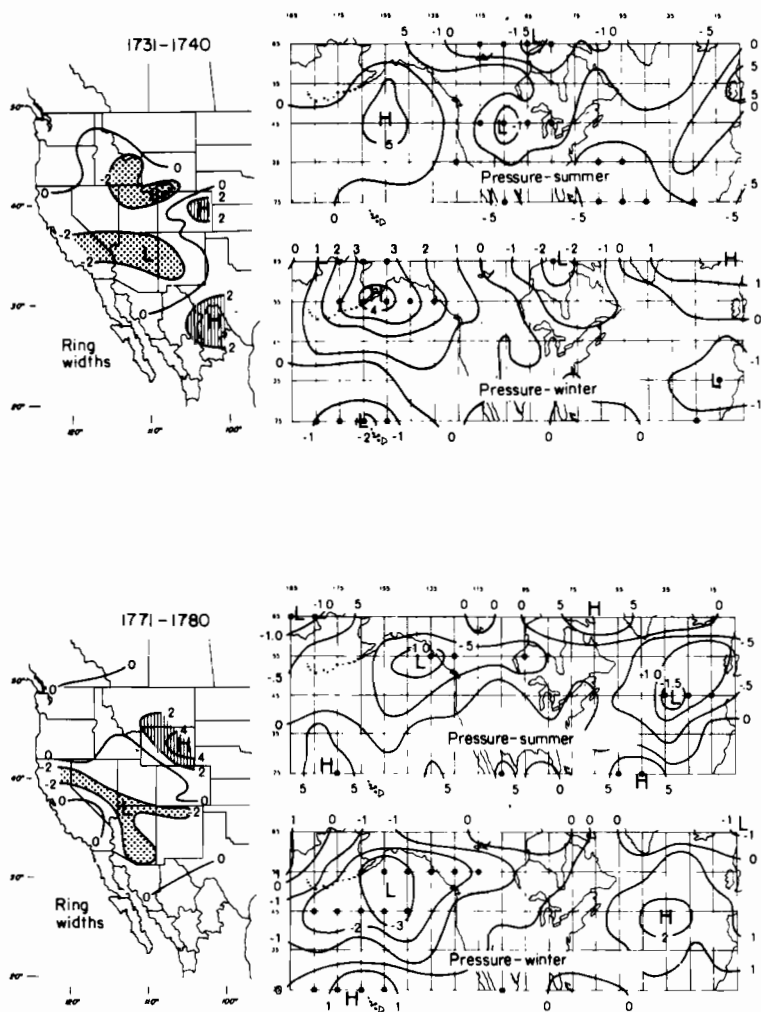
FIG. 9.5. The mean anomalies in growth (left) for two decades of the past are substituted into the transfer function to obtain reconstructed anomalies in surface pressure (right) for summer and winter seasons. Square dots indicate those reconstructed data points that exceed two standard errors of estimate and may be inferred to be significant. (Drawing by M. Huggins)
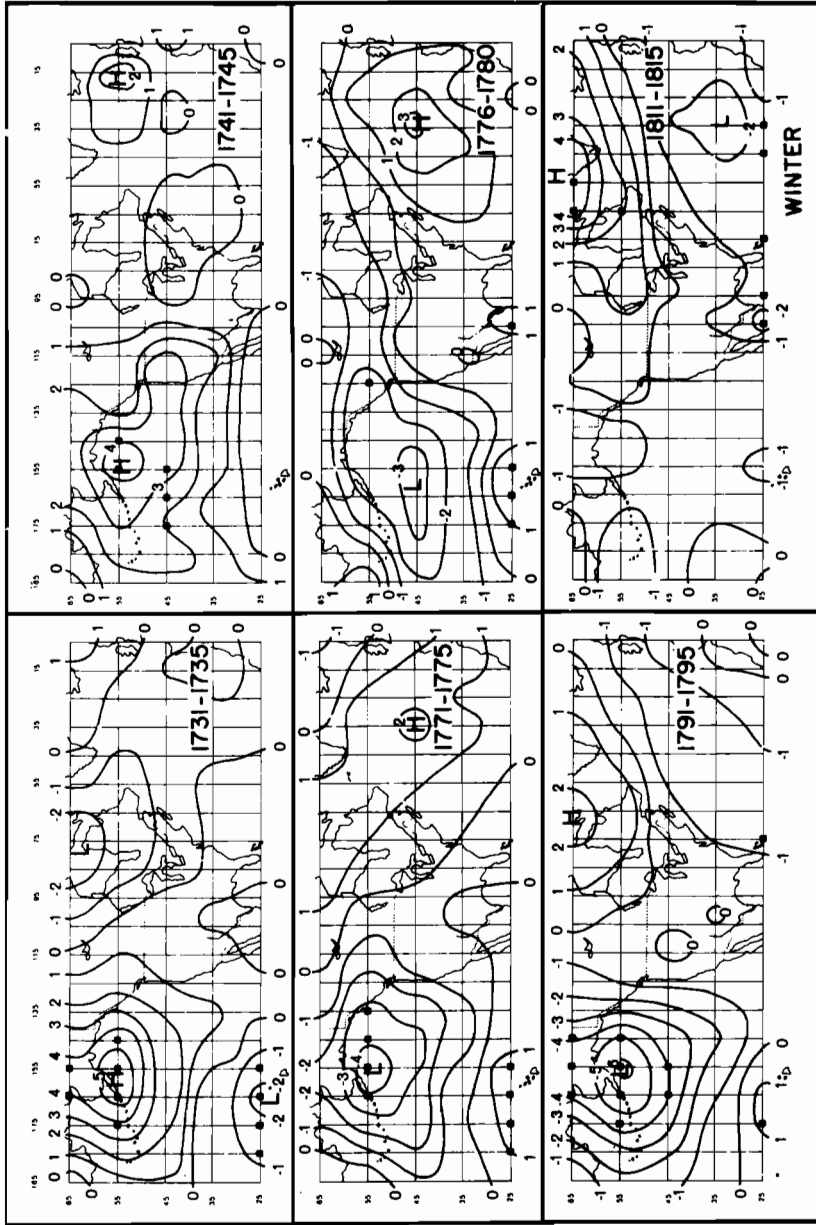
FIG. 9.6. Reconstructed pressure anomalies for January-March expressed in millibars for selected pentads during the interval (a) 1731-1815, (b) 1816-1845, and (c) 1846-1945 as derived from anomalous ring-width indices. Square dots indicate the five-year mean anomaly at the grid point was greater than twice the standard error. Only pentads with five or more pressure estimates exceeding two standard errors are shown. (Fritts *et al.*, 1971)

(b)
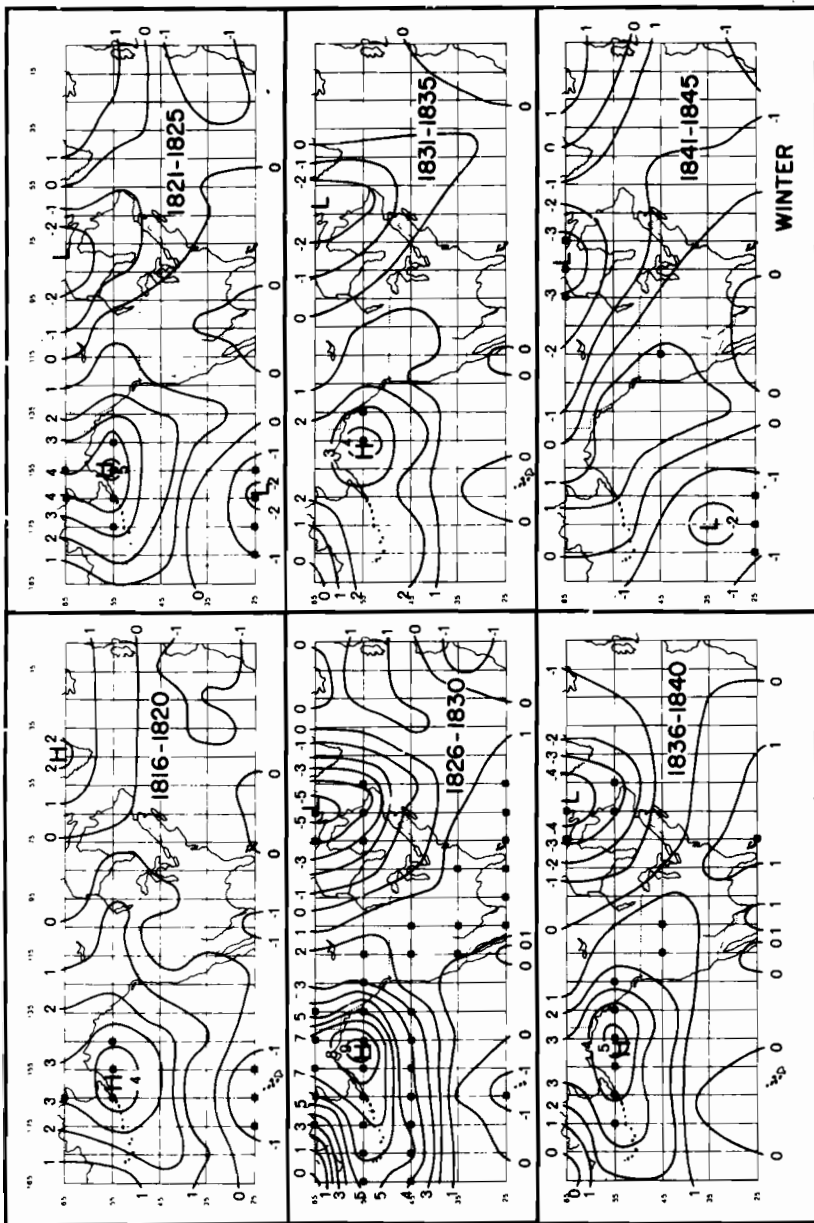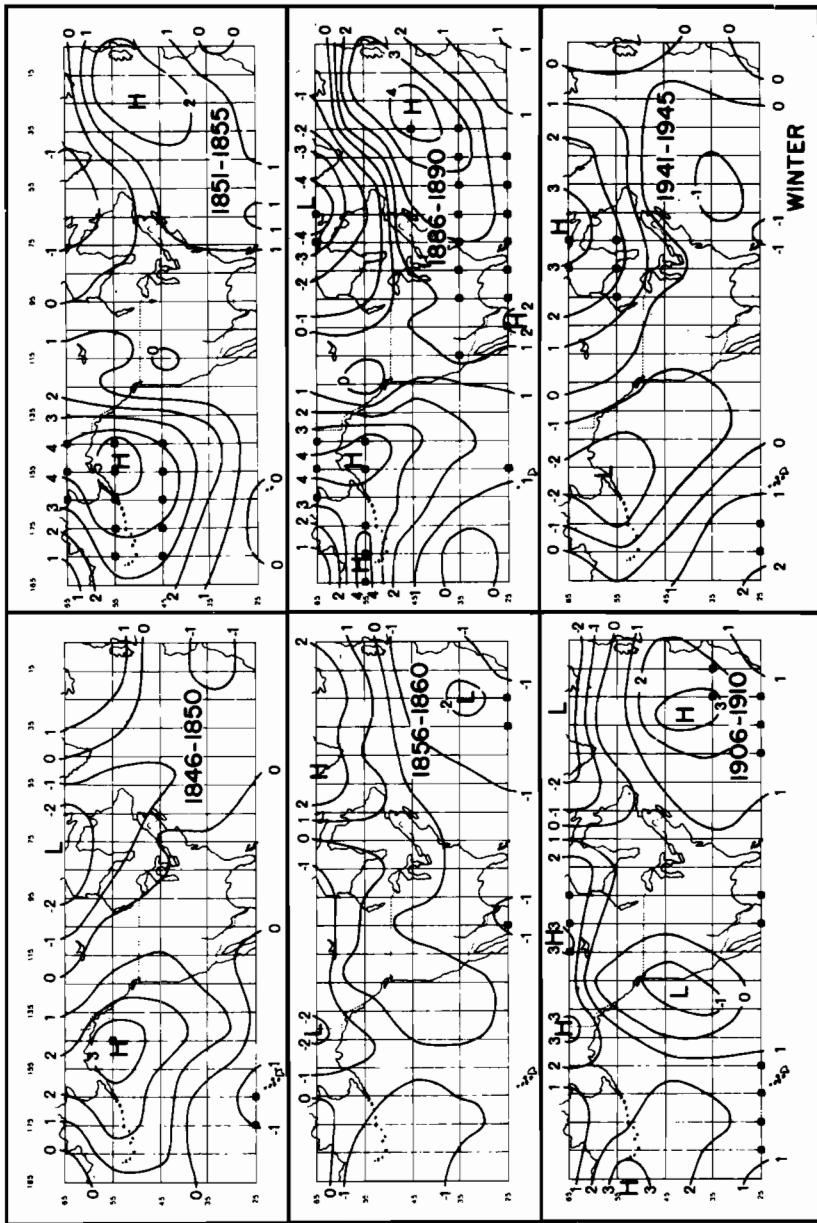
analyzing each season independently. The following sections describe several reanalyses.

V. Recalibration

The data and models utilized in the feasibility study were altered in an attempt to improve the climatic reconstructions. The same sources of pressure data were used, but the pressure grid was changed to include 96 grid points from 20°N latitude to 70°N latitude and from 80°W longitude across the Pacific Ocean to 100°E longitude. The grid included data at every 20° longitude for 60° and 70°N and every 10° longitude at latitudes 20°, 30°, 40°, and 50°N. The east Asian coast was included partly to allow use of its long climatic record as independent checks, and partly to include a larger area upwind of the tree rings.

The pressure data for the revised grid were examined using principal component analysis and other techniques to ascertain the natural climatological seasons for the particular grid that was selected (Blasing, 1975). December, January, and February were found to be the most similar winter months and were chosen to represent that season. June was found to differ significantly from July and August, so the latter two months were used as summer.

The recalibrations were obtained using the eigenvector amplitudes from the correlation matrix of the same 49 ring-width chronologies used in the feasibility analysis (Equations 7.18 and 7.19, Figs 9.1 and 9.2). The eigenvectors differed only in that the entire 1700-1962 period was analyzed rather than the 1700-1930 interval, and additions and corrections had been made on a few of the chronologies.

Not only was the statistical model changed but the pressure and tree-ring data were treated differently: (1) The mean for each pressure data point from 1899-1966 was subtracted from each seasonal value, but no division by the standard deviation was made. Thus the actual pressure variance was preserved. (2) The eigenvectors of pressure were extracted by season for the entire calibration period 1899-1966 using the covariance rather than the correlation matrix. This allowed a greater weight to be placed on areas where the pressure variations were greatest. (3) Different numbers of eigenvectors were used to represent the pressure and tree-growth variance, depending upon the model to be tested. (4) The tree-ring climatic models involved various lags by utilizing the amplitudes of the tree-ring data for year t and lagging them by one or more years to determine which combination of lags best fit the relationship. As a result, the amplitudes between lags were often nonorthogonal. (5) Canonical regression was used, as in Equation 9.7, to obtain the coefficients for reconstructing amplitudes of pressure from amplitudes of tree growth.

Only the canonical sets which calibrated more than 1% of the variance in the pressure amplitudes were selected. The canonical regressions for reconstructing the amplitudes of pressure were multiplied by the appropriate eigenvectors of pressure (Equation 7.21) to obtain the pressure transfer functions. The amplitudes of tree growth for each year were then multiplied by this transfer function to reconstruct the yearly anomalies in pressure.

The data used to assess lagging relationships including amplitudes for the ring widths in year $t - 1$, t, and $t + 1$ up to year $t + k$ $(_nX_p$, Equation 9.7) may be written as follows:

$$(_nX_p)_{t-1}, (_nX_p)_t, (_nX_p)_{t+1}, (_nX_p)_{t+k} \tag{9.10}$$

However, all the amplitudes could not be used because they would have exceeded the available degrees of freedom. Several calibrations were attempted which involved varying numbers of pressure amplitudes, varying numbers of tree growth amplitudes, varying lagged relationships, and varying the season (Table 9.1). The square of the multiple correlation, which was used to measure the calibrated amplitude variance, is also partially affected by the degrees of freedom that are used up in the calibration. The percent variance due to the loss of degrees of freedom can be estimated from the square of the correlation expected for random numbers (R^2 random) as follow:

$$R^2 \text{ random} = \frac{k}{n-1} \tag{9.11}$$

where k is the number of predictor variables and n is the effective sample size, which in this case is assumed to be equal to the number of years used for calibration. The percent amplitude variance calibrated is subtracted from the R^2 random (Table 9.1) and the square root taken to estimate d, a measure of the statistical fit above that expected for random numbers. This value is analogous to, and may be tested as, the correlation coefficient.

The following inferences were drawn from the various calibration statistics (Table 9.1):

(1) More significant variance was calibrated (that is the values of d were generally larger) for those models using 10 or fewer eigenvector amplitudes of pressure. It appears that high-order amplitudes of pressure are too small scale or have too little variance to be useful in these climatic reconstructions.

(2) Little significant variance was reduced by models incorporating greater lags than those for years t and $t + 1$ as shown in Rows 4, 5, and 6 in the table.

TABLE 9.1 Selected statistics from calibrations using amplitudes of tree rings (X) to reconstruct amplitudes of pressure (Y)

					Season Reconstructed									
		Variables[a]			Winter Dec–Feb		Early Spring Mar–Apr		Late Spring May–June		Summer July–Aug		Autumn Sept–Nov	
Line	Y	X	R^2 Random[c]	df[b]	R^2 Amp[d]	d[e]	R^2 Amp[d]	d[e]	R^2 Amp[d]	d[e]	R^2 Amp[d]	d[e]	R^2 Amp[d]	d[e]
1	20	20_t	0·318	43	0·360	0·205					0·354	0·190		
2	20	20_{t+1}	0·323	42	0·347	0·155					0·350	0·164		
3	20	$15_t, 15_{t+1}$	0·484	32	0·532	0·219					0·526	0·205		
4	20	$10_{t-1}, 10_t, 10_{t+1}$	0·484	32	0·507	0·152					0·546	0·249		
5	20	$10_t, 10_{t+1}, 10_{t+2}$	0·492	31	0·519	0·164					0·527	0·158		
6	20	$8_{t-1}, 8_t, 8_{t+1}, 8_{t+2}$	0·525	29	0·565	0·200					0·555	0·173		
7	10	20_t	0·318[f]	43[f]			0·393	0·274	0·380	0·249	0·388	0·265	0·457	**0·390**[h]
8	10	$10_t, 10_{t+1}$	0·323[f]	42[f]			0·392	0·263	0·449	**0·355**[g]	0·424	**0·318**[g]	0·464	**0·369**[g]
9	10	10_t	0·159[f]	53[f]			0·214	0·235	0·248	**0·298**[g]	0·217	0·241	0·274	**0·336**[g]
10	10	10_{t+1}	0·161	52							0·280	**0·345**[g]		
11	6	10_t	0·159	53	0·292	**0·365**[h]								

[a]Subscript t represents the calendar year of the predictand, except for autumn when it represents the following year. [b]Degrees of freedom. [c]R squared for random numbers. [d]R squared for reconstruction of pressure amplitudes. [e]Square root of the difference between R squared amplitudes and R squared random numbers. The highest and most significant value for a particular season is printed in bold type. [f]One less degree of freedom and higher R squared for random numbers used for autumn. [g]Significant $p \geq 0.95$. [h]Significant $p \geq 0.99$.

(3) In the case of autumn, winter, and early spring, the best models were those including no lag and associated with growth commencing in the concurrent spring season. This result is reasonable in that there is ample time for climate during these three seasons to modify conditions which in turn influence important plant processes. Since no value of d for early spring was significant, the spring seasons were classified differently in subsequent analysis.

(4) The best model for late spring (May–June) includes growth in years t as well as $t + 1$. Since the growing season usually starts in May, it is reasonable that a portion of the climatic influence is transferred to the next year's growing season.

(5) The best model for summer includes only the amplitudes for year $t + 1$, but the model using years t and $t + 1$ (Table 9.I, Line 8) is also significant. Apparently growth slows down sufficiently during this season so that climate for year t has less influence on the width for year t than it does for year $t + 1$.

The percent variance calibrated at each pressure grid point was calculated by subtracting the residual variance from the total variance at each point, dividing the result by the latter and multiplying by 100 to obtain a percentage figure. The results for all grid points are mapped in Fig. 9.7 for three different winter and summer models. The areas of significant calibrated variance for winter and summer are different, but many similarities among the models for a given season are apparent.

For example, the areas of significant calibrated variance for winter include Alaska and the Canadian Arctic, the extreme North Pacific (including an area south of Korea), Mexico and the United States Southwest, the central North Pacific along latitude 20° west of Hawaii, and for some models, in mainland China.

The areas of significant calibrated variance for summer include the Canadian and east Siberian Arctic, western United States, a large area in the central North Pacific, and the Asian mainland along 100°E longitude (the western boundary of the pressure grid).

It was concluded that pressure can be reconstructed for a substantial portion of the grid, although the area of significant reconstruction is less than half the area used for calibration. It is hoped that pressure reconstructions may be improved in the areas of poor calibration by utilizing tree rings from additional sites, especially those from Canada, Alaska, and the Asian continent.

An inability to reconstruct pressure in a given region does not imply that other climatic variables cannot be reconstructed. For example, precipitation anomalies in certain regions may be associated with increased frequencies of cyclones and anticyclones and increased

numbers of frontal passages but not with anomalies in the mean seasonal pressure in that particular region. In such cases, temperature or precipitation may be reconstructed even though there is little possibility of reconstructing the pressure variance.
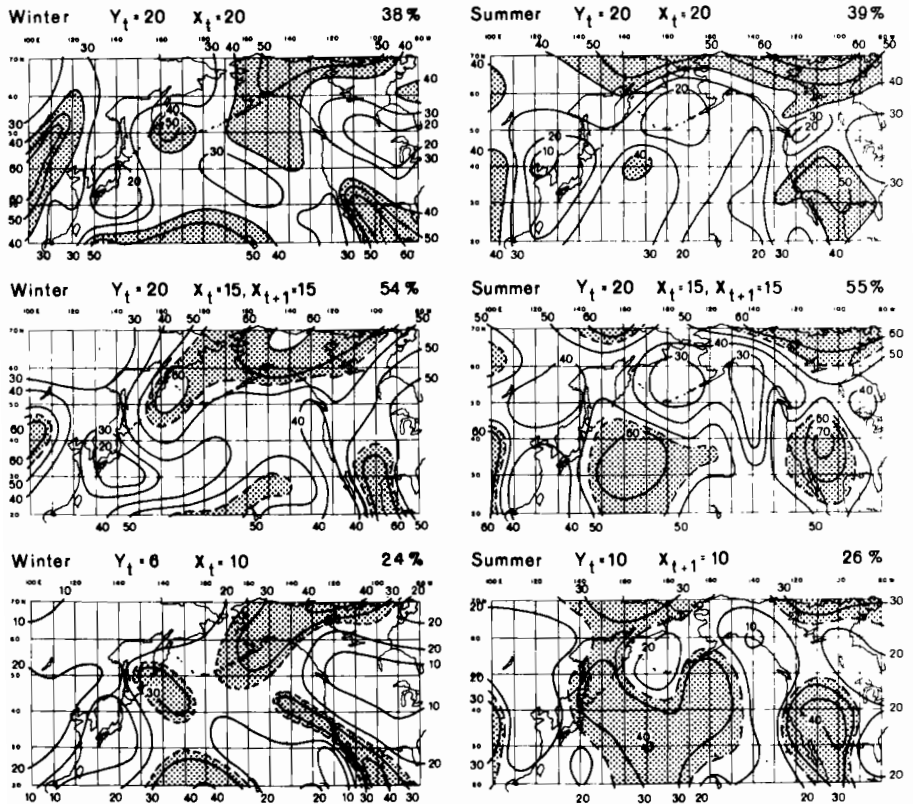
FIG. 9.7 The percent variance calibrated over the spatial grid of pressure using six different models included in Table 9.1. Shading designates the areas where the percent variance exceeds the approximate 0·95 confidence limits and can be considered to be significant. The variable numbers and the total percent of pressure variance reduced are shown above each map. (Drawing by M. Huggins)

With the exception of early spring, the models with the highest values of d (values in bold type in Table 9.1) are significant. Those for winter and summer were selected for the following analyses.

VI. Climatological Studies

When the feasibility study was undertaken to reconstruct spatial variations in pressure from tree growth, it was thought that the anomalies in pressure would be readily interpretable in terms of anomalies in storm tracks, air flow, temperature, and precipitation. However, it soon became apparent that heretofore no summary had been made of the seasonal climate over the selected grid of pressure, and there was little reliable basis for interpreting the new reconstructions. Some climatologists had looked in depth at only the months of January and July, while others dealt only with average conditions over a particular region. Still other investigations were limited to analyses of particular years and seasons or to consideration of only the last few decades, during which measurements were available from the upper atmosphere as well as the surface.

Therefore, Blasing (1975) undertook the task of studying the 20th century climate in terms of the surface pressure variance over the newly selected grid. He developed a technique which was used to classify and identify anomalous patterns in the seasonal pressures. Each of these anomaly patterns, which were called *pressure types* (Fig. 9.8) were in turn associated with anomaly patterns of cyclone occurrences, temperature, and precipitation in the United States, and tree-ring widths in western North America. The most pertinent results to dendroclimatographic analysis are described and summarized in the following sections.

A. Identification of Pressure Types

Eigenvector techniques have mathematical properties which limit their usefulness in describing climate. The eigenvector patterns, unlike the natural pressure patterns, are constrained to be mutually orthogonal. Also the eigenvectors are constrained to express both positive and negative modes of behavior like mirror images of the same pattern, yet the actual modes of climate rarely behave in exactly opposite fashions. Years with anomalously high pressures in certain regions are not always balanced by years with anomalously low pressures in the same regions. As a result, features observable in climatic data require linear combinations of two or more eigenvectors for adequate characterization (see Julian, 1970, and Blasing, 1975).
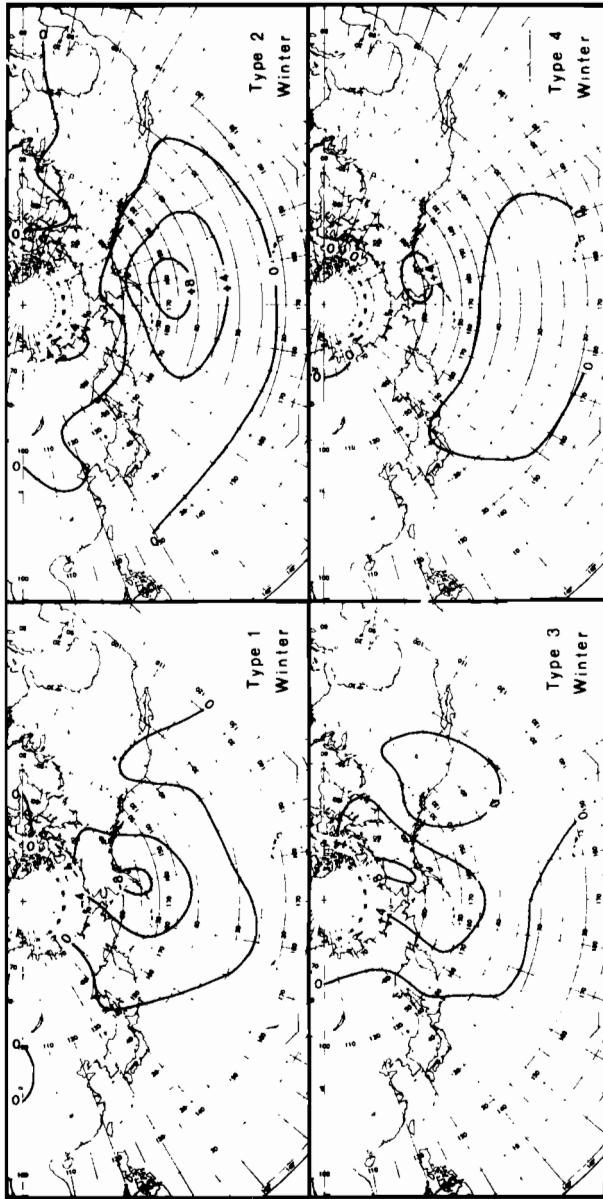
FIG. 9.8. The spatial correlations anomaly types of pressure for winters from 1899 through 1966. The number of the type is assigned in order of its importance during the 20th century. (Blasing, 1975)

The typing procedure developed and programmed by Blasing (1975) circumvents the above constraints of eigenvector analysis. It finds modes of seasonal climatic behavior (or growth or any other selected variable) that are recognizable in the data for certain years included in that analysis, but are not necessarily associated with an anomaly of opposite sign. Therefore the types, unlike eigenvectors, are characterized only in their positive representation.

The statistical procedure, which was first described by Lund (1963), computes the correlations among patterns in a field of variables at a given time with patterns at other times. In this particular analysis, the pressure departure patterns of each year from 1899-1966 are correlated with all other pressure departure patterns for the 68 years used in the analysis. The resulting correlation coefficients are then searched to identify that pattern in pressure which is highly correlated with the greatest number of other pressure patterns.

The procedure Blasing developed differs from that described by Lund in that it averages data for the selected year with the five other best correlated departure patterns (Blasing, 1975). The averaging process filters out some of the noise due to individual yearly variations, and it preserves the essential features that give rise to the correlations.

The mean pressure anomaly of the six best correlated years becomes the first spatial correlation anomaly type, which is then correlated with the remaining yearly departures. All anomaly patterns that are correlated with the six-year mean (that is, which are equal to or greater than a prespecified correlation value) are classified as that type and are removed from the data set. The procedure is repeated on the remaining data until the correlation coefficients among yearly anomaly patterns fall below a minimum acceptable value, at which time the analysis stops and the remaining years not associated with any type are left unclassified. Four spatial correlation anomaly types of pressure were identified for winter (Fig. 9.8) and five were identified for summer (Blasing, 1975).

B. Characterization of Types

The data on cyclones, temperature, precipitation, and tree growth were each averaged for the five years which were best correlated with each summer and winter pressure type, the averaged normalized ring-width departures were mapped (Blasing, 1975). The resultant plots (see Fig. 9.9) represent the anomaly patterns in each variable corresponding to each pressure type. Since these data are used later in the chapter to describe past climate, the most important results are summarized in the following sections.

1. *Winter*

The four pressure anomaly types for winter were numbered in the order of their importance, plotted on maps, and isobars drawn as in Fig. 9.8. Type 1 exhibits a negative anomaly in pressure centered over the Alaskan Peninsula. Type 2 consists of a positive pressure anomaly south of the Alaska Peninsula and a negative pressure anomaly over nothern Siberia. Type 3 exhibits a positive pressure anomaly centered over Alaska, with a region of slight negative anomaly along the west coast of North America. Type 4 includes an area of positive pressure anomaly along the south coast of Alaska and a large area of weak negative anomaly over the North Pacific Ocean.

Characteristics of Type 1 winters are shown in Fig. 9.9. The most characteristic winters of this type were those ending in 1931, 1953, 1945, 1912, and 1927 listed in order of decreasing correlation with the mean type. An above-normal number of cyclone-days occurs in the area of negative pressure anomaly over the Alaska Peninsula. High cyclone frequencies also occur in certain areas of Asia, in northwest Canada, in areas north of 30°N from 140°E through southern California to Texas, and in the western portion of the Mississippi Valley.

Climatologically, the latter two areas represent cyclone tracks along which the storms intensify when warm moist air from the Gulf of Mexico is drawn into them, increasing precipitation in the central Plains and along the east slope of the Rocky Mountains (Fig. 9.9). Counterclockwise circulation around the area of negative pressure anomaly results in anomalous northward or northeasterly flow of relatively warm air from the Pacific Ocean into western Canada and northwestern United States, causing temperatures there to be above normal. With fewer storms, precipitation along the west coast of the United States is below average.

Blasing (1975) states that "the upper air pattern for Type 1 winters involves a strong Aleutian Low and a tendency for a broad ridge [high pressure] over the western United States." When such winters prevail, there is also a smaller than normal number of polar outbreaks of cold air in the United States and above normal precipitation along the south coast of Alaska because of the greater number of storms there.

The tree-growth pattern associated with Type 1 winter indicates that low growth occurs in Canada and the Great Basin, while in the extreme Southwest and southern Rocky Mountains growth is high, probably due to the abundant winter moisture brought into the area by the northerly flow. The high growth over Wyoming, southern Idaho, and southern Montana probably reflects mild winters and the upslope flow of moist air from the south that may occur there.

Type 2 winter is best exemplified by the years 1937, 1949; 1932, 1911,
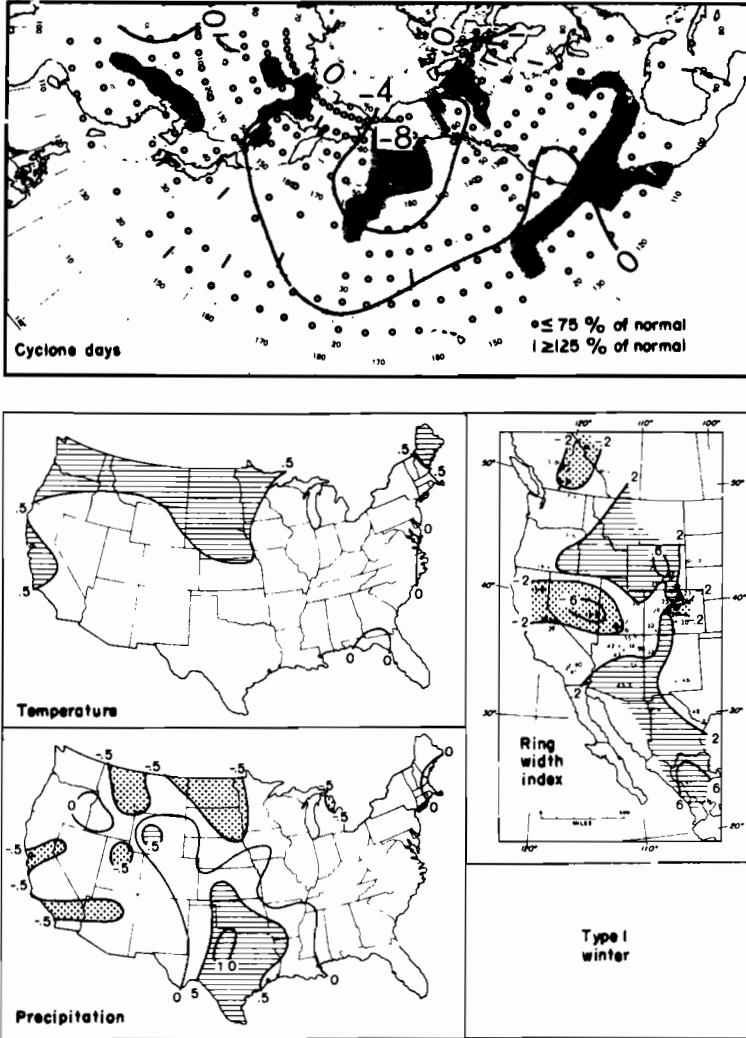
FIG. 9.9. Anomalies of climate and ring-width index occurring in the five years characterizing Type 1 winters. Cyclone days are expressed as percentage of normal for each five-degree gridsquare. Shading indicates large areas of anomalously high cyclone frequencies. Isobars of pressure are superimposed on the cyclone-day anomaly map. Temperature, precipitation, and ring-width index anomaly values are in standard deviation units for each parameter at each station or site. (Blasing, 1975)

and 1952, and it exhibits anomalously high pressures in the central North Pacific, where frequencies of cyclones are low (Fig. 9.8). A higher than normal number of cyclones enter the United States along the Oregon and northern California coast and move east–northeast bringing colder than normal temperatures to the entire western United States and warmer
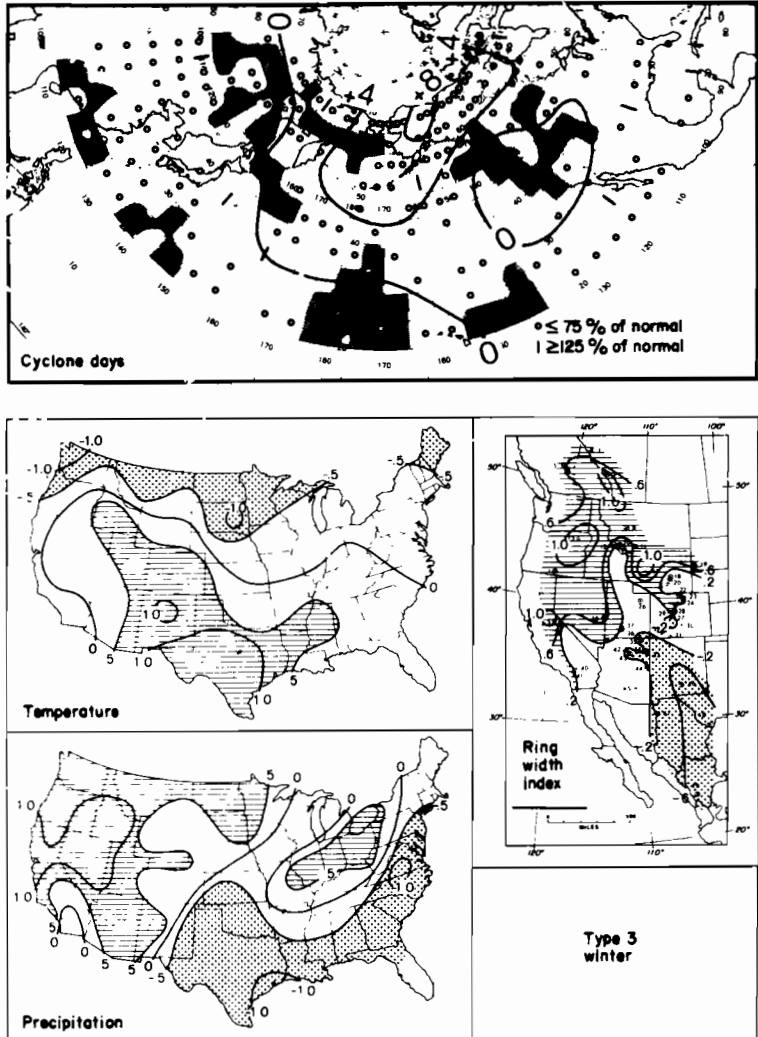
FIG. 9.10. Same as Fig. 9.9, but for Type 3 winters. (Blasing, 1975)

than normal temperatures to the eastern United States. Precipitation is much above normal in the Ohio and lower Mississippi valleys, somewhat above normal in the northern Great Plains and Great Basin, and below normal in the extreme Pacific northwest. The tree rings are wider than normal over the Colorado plateau of the Southwest and lower than normal over northern California, Oregon, Idaho, and Washington. Illustrations and more details on this and other winter types are presented by Blasing (1975) and Blasing and Fritts (in press).

The anomalies associated with Type 3 winters are shown in Fig. 9.10. The years best correlated with the type are 1907, 1916, 1956, 1904, and 1909. The area of positive pressure anomaly over the extreme North Pacific, Alaska, and northwestern Canada is associated with a smaller than normal percentage of cyclone days there. A larger than normal number of cyclones enters the continent farther south along the Canadian and United States west coast. Blasing (1975) suggests that there is an upper air ridge over the North Pacific Ocean, a well-defined trough (an area of lower pressure) off the west coast of the United States, and a weak ridge over west central United States. Lows entering the west coast of the United States often head northeastward in the direction of the upper air flow, although it is not uncommon for them to enter British Columbia and follow a southeastward course. The number of storms are near normal for central and eastern North America. Anticyclones following the cyclones across North America often remain farther north than normal, leaving the central and southern United States with warm air. Cyclones are also common in Asia for latitudes between 50°N and 65°N.

During Type 3 winters the northern United States is anomalously cool because of the southward flow of air from the Arctic, but temperatures elsewhere in the United States are above normal. Precipitation in western United States is high due to the frequent passage of storms. The warm, moist air from the Gulf of Mexico meets the cold air farther north than normal causing abnormally high precipitation in the Ohio River Basin and western Appalachian Mountain areas. Lower than normal precipitation in the southern United States is due to the low percentage of cyclones there.

In all respects except the growth pattern, Type 3 winters are opposite those of Type 1. While tree growth for Type 3 years is high in northwestern North America where precipitation is also high, it is low in New Mexico and extreme western Texas where temperatures are higher than normal and precipitation is low.

Type 4 winter is best exemplified by the years 1962, 1963, 1957, 1965, and 1930, with anomalously high pressure centered over the southern coast of Alaska and slightly below-normal pressures over the central
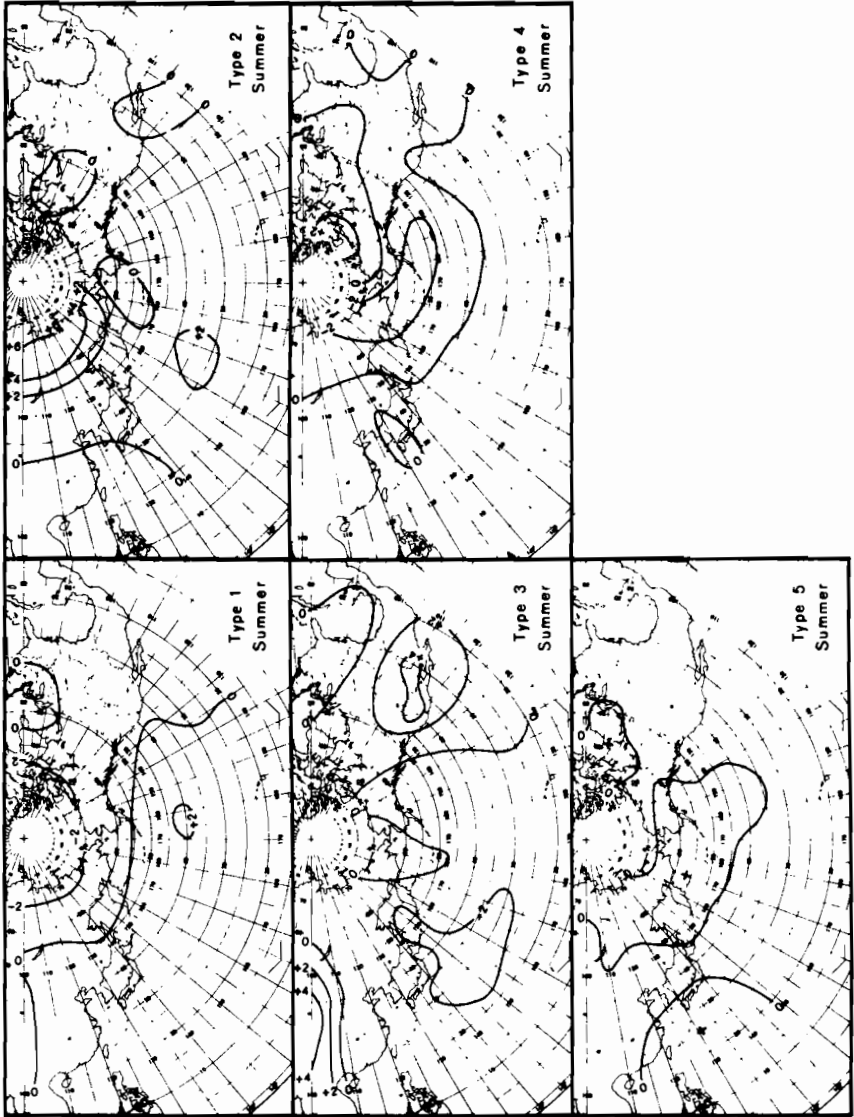
FIG. 9.11. The spatial correlation anomaly types of pressure for summers from 1899 through 1966. (Same as Fig. 9.8. Blasing, 1975. Blasing and Fritts, 1975.)

North Pacific (Fig. 9.8). Cyclones are more frequent than normal along the 45° parallel in the central North Pacific. They are also more frequent over the Baja California and Hudson's Bay areas. Temperatures are much below normal in the entire Northwest and the northern Plains— especially over the upper Mississippi Valley—and precipitation is below normal in the central and southern Plains, the northeast, and west coast regions of the United States. High growth occurs in northern British Columbia, in the northern Sierra Nevada, the Great Basin and central Rocky Mountains, and in southern Arizona; and low growth occurs in the Cascades and northern Rocky Mountains, southern California, northern Arizona, and New Mexico.

2. Summer

The five pressure anomaly types for summer as described by Blasing (1975) are included in Fig. 9.11. Type 1 exhibits higher than normal pressures in the central North Pacific and lower than normal pressures in the Arctic. Type 2 exhibits a higher than normal presure anomaly in northeastern Siberia and in the western North Pacific. Type 3 is characterized by anomalously high pressure along the western borders of the grid in central Asia, over the Pacific Coast and the Great Basin of the United States, and over the Bering Sea. Lower than normal pressures occur over the western North Pacific Ocean and over eastern North America. Type 4 has many features in common with a typical winter anomaly pattern showing anomalously low pressure over the Bering Sea and the Gulf of Alaska, and higher than normal pressure anomalies over the Arctic Ocean, northern Alaska, and northwestern Canada. Type 5 exhibits a weak positive pressure anomaly over northeastern Asia, southern Alaska, and the northern parts of the North Pacific. Positive anomalies are found in central Canada and in the China Sea.

Figure 9.12 includes the climatic data associated with Type 1 summers for 1955, 1937, 1949, 1935, and 1933. Anomalously high pressure over the Pacific Ocean indicates a northwesterly displacement of the north Pacific High. As a result, storms are displaced northward and mean summer pressures are low along the Arctic Ocean. Cyclones are more common in the Caribbean Sea, across Mexico, in areas of western United States, and along the Washington and Oregon coast. More cyclones than normal also occur in the central North Pacific to the southwest of the high pressure area.

The West Coast and Great Basin area, where Type 1 summer cyclones occur more frequently than average, is a region where such activity is actually quite rare. The cyclone days, though above normal in number, represent weak, short-lived systems associated with a northerly

displacement of a quasi-stationary low that develops over the Southwest during the summer. Warm, dry air is advected into western United States bringing drought and higher than normal temperatures except for areas along the Mexican border of California and Arizona where rainfall is above average.
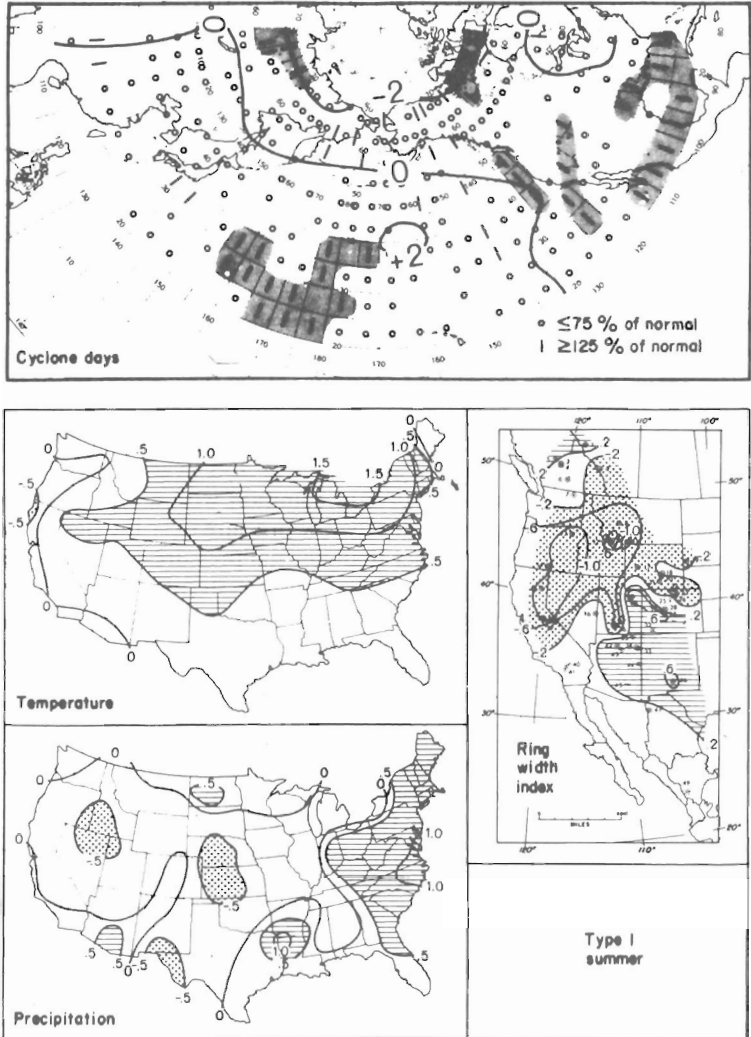
FIG. 9.12. Same as Fig. 9.9 except for Type 1 summers. (Blasing, 1975)

Blasing (1975) suggests that the Atlantic Subtropical High is displaced northward bringing above-normal temperatures to the eastern United States, especially in the Great Lakes. The association of this condition with hurricanes in Type 1 summers accounts for the higher than normal precipitation in the east and Gulf states, as well as the large number of cyclone days in the Caribbean and central Mexico.

The circulation patterns associated with Type 1 summers resemble those described by Namias (1960) which occur in conjunction with drought in the Great Plains of the United States. During such summers there is a tendency for a drought-producing anticyclone to appear over the United States. However, if it is small in size, the eastern coast is typically under the influence of a moist tongue of air from the Bermuda High to the east over the Atlantic. Some good examples of Type 1 circulation occurred during the dust bowl years of the 1930's, while the best example of this pattern occurred in the summer of 1955 bringing extreme drought to the Plains and moisture-laden hurricanes Connie and Diane to the East.

The higher than normal precipitation anomaly along the boundary of the north central United States is associated with excessively severe storm activity, often accompanied by hail and heavy local precipitation. Blasing (1975) suggests that these features are triggered by the southern end of cold fronts which are located in Canada. Above-normal precipitation also occurs in the portion of the southern Alaskan coast called the panhandle. Tree growth occurring in Type 1 summers is much below normal in northwestern United States but above normal in northern British Columbia and southwestern United States.

Type 2 summer is best exemplified by the years 1922, 1921, 1920, 1917, and 1919, with higher than normal pressures over northern Siberia and the western North Pacific, and lower than normal pressures and greater frequency of cyclones southwest of the Alaskan mainland, over central Canada, and west of Baja California. Temperatures are above average over the northern Rocky Mountains and the Great Basin, and lower than normal over southern Arizona, New Mexico, and coastal areas of the United States Pacific Northwest. Precipitation is generally below normal along the western Canadian–United States border, and above normal over Arizona. The growth anomalies are lower than normal in Canada, the Pacific Northwest, Idaho, and central Wyoming, and high throughout the entire Southwest. Illustrations and more details on this and other summer types are presented by Blasing (1975).

Type 3 summer is best exemplified by 1927, 1928, 1930, 1929, and 1926, and it represents an extreme north–south (meridinal) circulation with marked high pressures along the western boundary of the pressure

grid (100°E longitude) and over the southwestern United States (Fig. 9.11). Pressure is anomalously low over the western North Pacific. Temperatures are above normal throughout the Pacific Northwest of the United States and southern Arizona and generally below normal throughout the southern Rocky Mountains, much of the central Plains and Midwest, and especially over the Great Lakes. Precipitation is much above normal throughout the central Rocky Mountains and high plains from southern New Mexico to southern Montana.

The tree-growth anomalies for Type 3 summers exhibit low growth in the Canadian Rocky Mountains and North Pacific states, southern Idaho, Nevada, northern California, and southern Arizona, but high growth throughout western Montana, Wyoming, Colorado, New Mexico, northern Arizona, and north central Mexico.

Type 4 summer is best exemplified by the years 1909, 1908, 1903, 1950, and 1964, and it is characterized by lower than normal pressures and an increased number of storms from northeastern Siberia to the Gulf of Alaska, including more than normal storms over the ocean west of the North American continent. Pressures over western North America are somewhat lower than normal but higher than normal over northwestern Canada. A higher than normal number of cyclones move inland in a southeasterly direction along the western Canadian coast, bringing cool temperatures to large portions of the United States. Precipitation is above normal over the western United States/Canadian boundary, Arizona, southern California, southern Nevada, and large areas in the Mississippi Valley and Great Lakes. Tree growth for this cool, relatively moist type is anomalously high except in Colorado, New Mexico, and the Colorado Plateau of Arizona and Utah.

Summer Type 5 resembles Type 1 in that it is associated with drought (Fig. 9.13). The five best examples of Type 5 are 1963, 1957, 1959, 1936, and 1954, characterized by higher than normal temperatures throughout the central United States and by a drought area extending from the Plains to the eastern seaboard and the Northeastern United States.

The Pacific Subtropical High is displaced north of its normal position, and areas of weakly positive pressure anomaly and below-normal cyclone days occur in the extreme North Pacific, southwestern Pacific, the south coast of Alaska, and central Canada. Upper air features include two anomalously deep troughs of low pressure which occur off both the east and west coasts of North America associated with high-pressure ridging over the central portions of the United States. The upper-level jet stream in the Central Pacific is displaced to the north and at times becomes split, the southern current plunging south bringing low pressure and cold air to the Pacific Northwest, and the northerly current flowing over the Arctic

and then returning southward in the trough along the east coast bringing a southward advection of cold, dry air (Fig. 9.13).

Type 5 summer differs from Type 1 in that the upper level troughs are more apparent, the Atlantic Subtropical High is not as likely to be
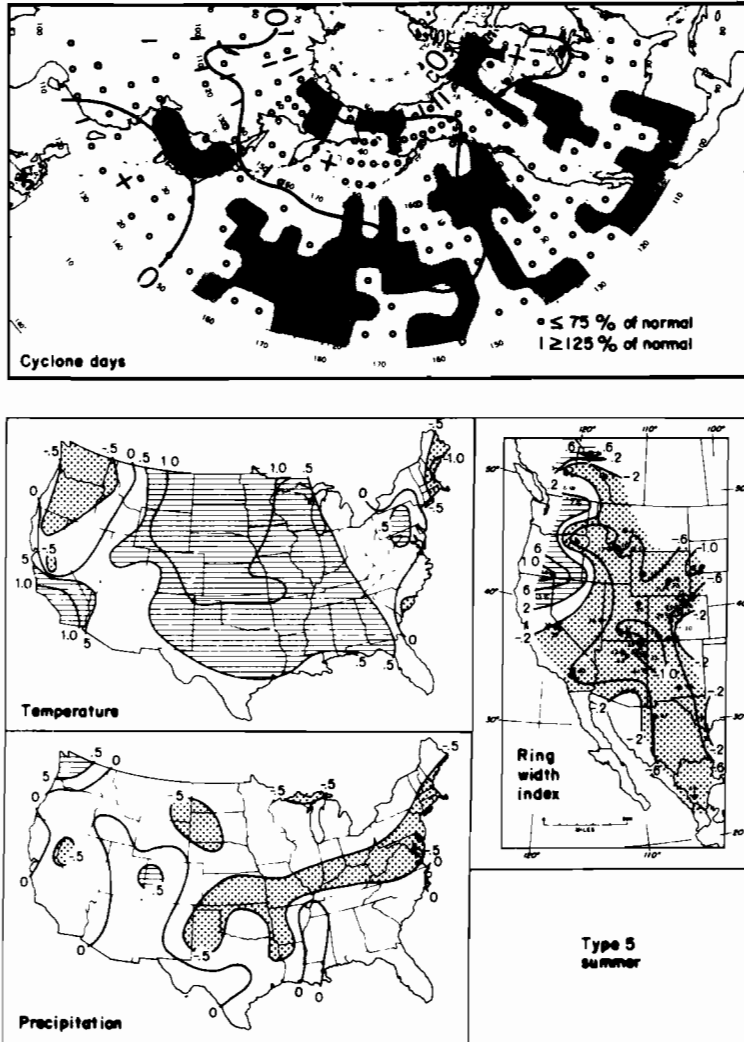
FIG. 9.13. Same as Fig. 9.9 except for Type 5 summers. (Blasing, 1975)

displaced northward, and drier air is advected into the eastern portions of the continent. Under a Type 5 regime, drought conditions occur over the eastern half and central portions of the United States associated with the descending air entering the eastern trough.

Tree growth for Type 5·is below normal for large areas of western North America, with the exception of northern California, Oregon, and Washington where growth is above normal.

It is apparent from the work of Blasing (1975) that each pressure type is associated with a characteristic set of climatic conditions, synoptic situations, upper air circulations and patterns of tree growth. If it is possible to associate one or more of these types that are present in the modern period with the reconstructed pressure anomalies for past years, it would then be possible to infer the climatic conditions that must be associated with them. In the next section attention will be directed to reconstructing and typing the anomalies in past atmospheric pressure. Subsequent sections include the climatic interpretation and verification.

C. Reconstruction of Pressure Types

It was noted in Section V that the best calibrations use models with 10 or fewer eigenvector amplitudes of both tree growth and pressure (Table 9.1). The question arose as to what is the minimum number of variables necessary to reconstruct a particular phenomenon such as the pressure types.

Blasing (1975) addressed himself to this problem by developing a minimum-sized model that would reconstruct only the large-scale patterns represented by the four winter pressure types. It was reasoned for the model development that the best reconstructions of the particular types could be obtained by using only those eigenvector amplitudes that occurred consistently in the five type years (see subsection B). Therefore the values for the eigenvector amplitudes of pressure were tabulated for each year that was best correlated with the type (Table 9.II). An examination was made of the absolute value of the eigenvector amplitude, the mean amplitude for the five years, and the consistency in amplitude sign.

For example, the amplitudes of eigenvector 1 are large and their signs consistent for all years within Types 1, 2, and 3 (Table 9.II). The amplitudes of eigenvector 2 for pressure are large and signs are consistent for those years in pressure Types 2, 3, and 4, although the signs of the amplitudes are less consistent. Blasing noted that the amplitudes for eigenvectors 1-6 were moderately consistent for at least one type but were generally inconsistent for all higher-order pressure eigenvectors. He

concluded that the pressure types were sufficiently well represented by the first six eigenvectors to justify their exclusive use in reconstructing them. Another set of statistics, V^2 (Sellers, 1968), which measures the percent variance reduced by each amplitude during each year, were examined and these data substantiated the decision to use only the first six.

TABLE 9.II Amplitude values of the first 10 pressure eigenvectors associated with years characterizing winter pressure types[a]

Type	Year	1	2	3	4	5	6	7	8	9	10
1	1931	33·12	15·73	3·14	−9·73	1·99	−0·16	2·53	−3·48	−7·50	−0·63
	1953	20·08	−7·20	7·82	−8·09	7·31	0·98	2·07	5·50	−1·80	1·75
	1945	18·90	1·47	8·41	−3·37	−1·52	−0·63	−0·87	0·08	−6·17	−0·05
	1912	10·60	−4·58	−1·37	−4·87	2·06	−3·29	1·44	−4·12	−3·72	0·49
	1927	13·66	−5·10	−0·96	−2·89	−1·71	−0·12	3·78	−0·64	−2·36	−3·90
2	1937	−29·16	−25·06	−5·34	12·17	−1·36	7·72	−2·44	−1·47	0·93	−3·18
	1949	−22·66	−18·88	−6·85	13·61	−8·49	−1·79	−2·75	1·72	−2·38	−0·06
	1932	−16·26	−19·76	0·66	4·84	10·68	4·07	4·21	1·48	1·62	−3·05
	1911	−21·80	−6·24	−1·26	−3·44	5·08	0·50	−3·26	−2·44	−3·68	−2·21
	1952	−9·84	−9·37	−3·28	0·97	1·64	5·78	0·43	4·36	2·99	0·01
3	1907	−32·02	28·84	−8·55	−11·06	−4·51	−9·44	−4·20	−0·06	−0·89	2·04
	1916	−28·80	10·36	−4·46	−6·69	−4·82	1·56	2·60	0·32	1·27	1·69
	1956	−19·99	12·71	−4·51	1·23	4·29	21·65	6·75	0·35	−2·89	−1·35
	1904	−26·07	10·67	−0·12	−2·64	3·17	−12·41	4·16	5·83	6·22	2·12
	1909	−15·76	7·95	−16·05	−13·89	−6·55	−3·16	−1·89	8·82	3·41	−6·95
4	1962	−9·82	11·39	3·34	16·94	−1·21	−1·94	0·59	3·64	−6·31	0·22
	1963	15·30	26·54	1·97	21·38	0·49	−3·04	0·82	0·54	−4·53	1·74
	1957	−15·80	11·02	23·69	4·82	7·86	0·38	−6·10	−0·22	−2·41	−0·54
	1965	−2·42	9·76	7·53	4·51	2·98	7·43	1·66	7·64	6·01	0·29
	1930	−3·84	4·87	4·68	8·04	7·03	−1·31	−2·86	−7·02	5·23	−4·99
Total % Variance Reduced by Eigenvector[b]		34·7	16·8	10·6	8·1	5·6	4·7	2·9	2·4	1·7	1·5

[a]Blasing, 1975 [b]For all years from 1900–1966.

The amplitudes of the tree-growth eigenvectors were examined in the same way. The first seven amplitudes of tree growth had both consistent signs and high mean values for all five years associated with at least one of the four types. There were several type years for eigenvectors 8 through 10 in which both the magnitudes of the amplitudes were 2·0 or greater (the average expected for random numbers) and the V^2 were sufficiently large. No amplitude for eigenvectors above 10 reduced enough variance or appeared systematically related to any type, so only ring-width

eigenvectors 1 through 10 were used in the calibration and reconstruction. A similar analysis for summer led to the selection of the first 10 eigenvectors of pressure and the first 10 eigenvectors of tree growth.

The square of the multiple correlation for predicting the amplitude variance for these two minimum-sized models for winter and summer (Row 11, Table 9.I) are 0·292 and 0·280, but when these data were converted to total pressure, variance percentages declined to 24% and 26% (Fig. 9.7). The areas of significant calibrated variance for the minimum-sized models were not substantially different from those for the larger models, except that there was less significant variance over the Asian continent. On the other hand, the area of statistically significant reconstruction was greater for the summer minimum-sized model than for the larger models even though the total percent variance calibrated was less. Therefore, the minimum-sized models were inferred to be superior to the larger ones, especially for reconstructing the pressure types. Except when stated otherwise, the results from these minimum-sized models are used in all subsequent analyses.

VII. Summarization of Reconstructions for Winter Using the Pressure Types

Once a transfer function is obtained (Equation 9.7) it can be applied to the tree-ring data for each year to obtain the reconstructions. For the following discussion the reconstructions are departures of pressure (expressed in millibars) for a particular year and season over 96 grid points. Isobars are drawn to obtain pressure anomaly maps for half of the Northern Hemisphere. The reconstructions are obtained for each model and season back to 1700, totalling 263 maps. Figures 9.14 and 9.15 include examples of four such seasonal maps.

The selected years were chosen because historical records for North America indicated interesting anomalies in climate, and the reconstructions could be examined for consistency with the available facts. The year 1815-16 was chosen because the volcano Tambora erupted late in 1815, ejecting clouds of dust into the upper atmosphere. No outstanding anomaly was recorded for the winter, but the following summer was exceptionally cold in New England and became known as "the year without a summer" (Ludlum, 1966). Temperatures were reported much below normal, snow fell in June in New York, Vermont, New Hampshire, and Maine, and frosts were reported for July and August as far south as Pennsylvania and New Jersey, with drought extending into early autumn. The disastrous year was culminated with a

killing frost in northern New England before the end of September (Ludlum, 1966).

The reconstruction for winter (Fig. 9.14) indicated a Type 1 pattern which is shown in Fig. 9.9 to bring generally warm, mild weather that would not be likely to evoke any recorded comment. However, the reconstruction for summer resembled Types 2 and 5, both of which are accompanied by anomalous cold and drought in the New England states. (See section VI for details on circulation of Type 5 summers.)

Figure 9.15 includes two winters known to have marked contrasts in climates. The winter (December, January, and February) of 1866 was

Winter 1816

Summer 1816
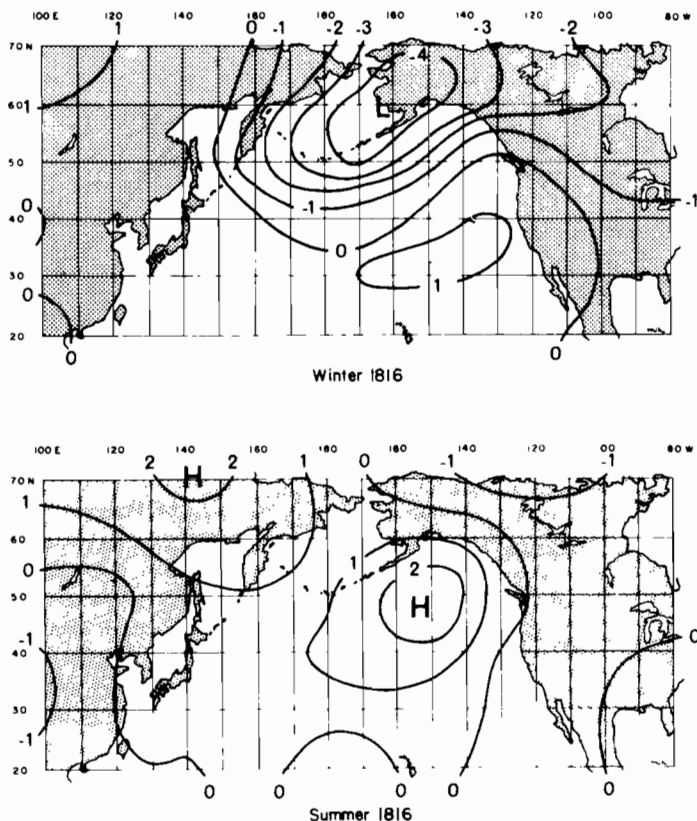
FIG. 9.14. Reconstructions of anomalies in pressure derived from tree rings for an interesting year in the 19th century. (Drawing by M. Huggins)

Winter 1866

Winter 1878
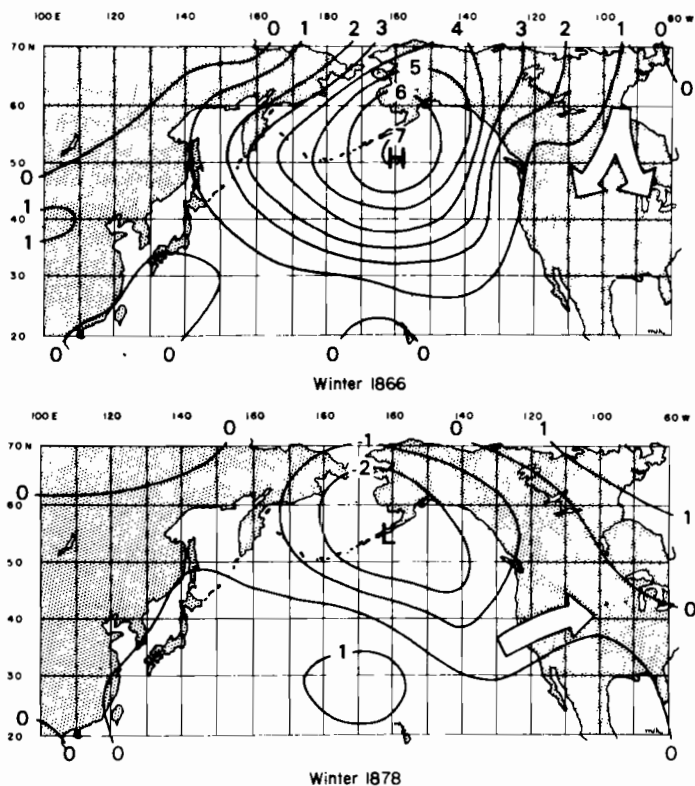
FIG. 9.15. Reconstructions of anomalies in pressure for winter derived from tree rings for two years known to be years of contrasting climate. The arrows show anomalies in atmospheric circulation inferred from the plots. (Drawing by M. Huggins)

reported by Stockman (1904) and Ludlum (1968) to be severely cold in the north central Great Plains, averaging 9·6°F above zero (−12·4 C) in central Minnesota. Temperatures were 3·3 F (1·8 C) below average for Fort Levenworth, Kansas, and 6·6 F (3·7 C) below average for Chicago, Illinois.

The reconstruction for the winter of 1866 (Fig. 9.15) exhibits an extremely strong Type 3 pressure pattern with anomalously high pressures over Alaska (Fig. 9.10) with an inferred anomalous flow of air from the Arctic as indicated by the arrows. This is consistent with the reported low temperatures in the north central states.

The winter of 1878, on the other hand, was unusually warm. Temperatures were as high as 14·0 F (7·8 C) above average at Fort Snelling, 10·0 F (5·6 C) above average at Fort Levenworth, and 11·4 F

(6·3°C) above average at Chicago. This winter as reported in the *Monthly Weather Review* for December, January, and February 1877-1878 was characterized by an abnormally strong Aleutian Low with numerous storms entering western Canada and northwestern United States. Heavy rains were reported in Texas and the Gulf Coast states, while there was a deficiency of moisture in the interior of the country. The reconstruction for winter of 1878 is a well-developed Type 1 pattern, which is consistent with the *Monthly Weather Review* report. The strengthened Aleutian Low apparently caused an anomalous influx of moist and warm air from the central North Pacific and the Gulf of Mexico (see arrow in Fig. 9.15) with anomalously high temperatures throughout the United States and high rainfall in Texas as reported.

Because of the immense amount of data and the difficulty in summarizing these reconstructions one year at a time, it was necessary to find a rapid way of characterizing the climatic patterns. One method used in the preliminary analysis (Fig. 9.6) involves averaging the data by decades or pentads and plotting mean maps. However, it was noted that the climatic variations did not confine themselves to arbitrarily assigned intervals of time. Contrasting anomalies within the interval can cancel one another so that the resulting mean does not represent the climate correctly.

An alternative method is to associate each reconstructed pressure anomaly with the best correlated 20th century type as described by Blasing (1975) and as summarized in the prior section. The frequency of occurrence of each type could then be studied through time, and associated anomalies in temperature and precipitation inferred from the types.

The occurrences of the types were identified in Fig. 9.16 by correlating the spatial patterns of the reconstructions with each of the pressure types (Figs 9.8 and 9.11). The correlation coefficients were examined, and each seasonal reconstruction classed as the type with which it was most highly correlated. When no coefficient was significant ($r \geq 0.3$), the type with the highest correlation was assigned, but the case was designated as insignificant. The full-sized bars plotted in Fig. 9.17 represent those cases in which the correlation was significant, while the shorter bars represent those cases in which the correlation was insignificant (Blasing and Fritts, in press).

In addition, the actual pressure data for the 20th century were correlated with each pressure type and tabulated in the same fashion as the reconstructions. The types were rearranged in the order of their importance during the period of reconstruction (18th and 19th centuries) and their occurrences plotted in Fig. 9.17. For ease in interpretation, the

predominant climatic anomaly within the United States that is
associated with each type is indicated to the right of the plotted data for
the 20th century.

It can be inferred from Fig. 9.17 that both the distribution through
time and the frequencies of occurrence of the types have varied
considerably in the past two centuries from those of our present century.
Type 1 winters, which exhibit a strengthened Aleutian Low, higher than
normal temperatures, and anomalously low precipitation in the far West
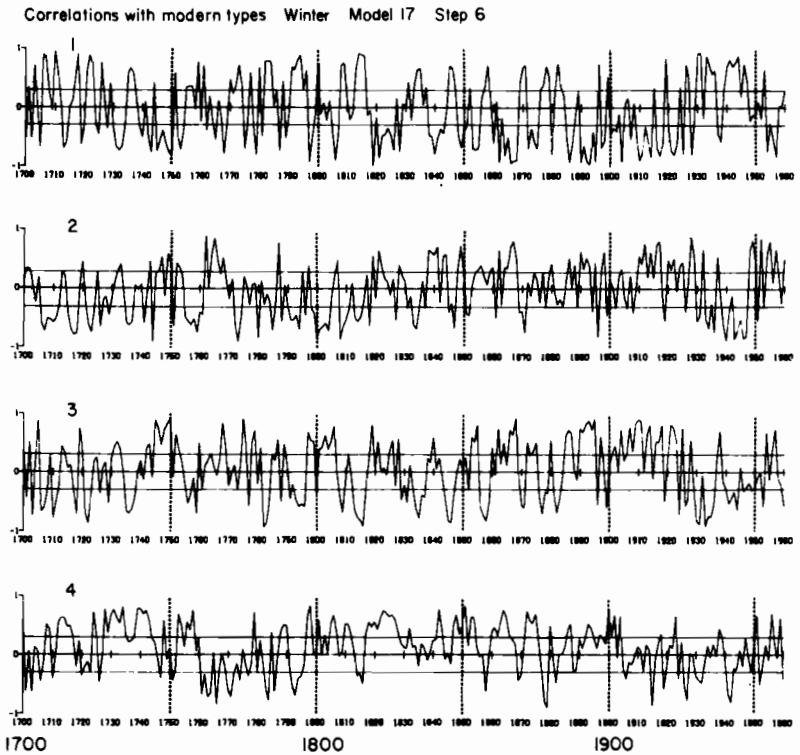
FIG. 9.16. Plots of the correlation coefficients between the pressure anomalies
reconstructed for each year from 1700 through 1960 and each winter type (see Fig. 9.8)
where the number of observations for each correlation coefficient are the values of the
anomalies at the 96 grid points. The line at a correlation of +0·3 marks the approximate
0·95 confidence level. All years with correlations above this line can be identified as
belonging at least in part to that particular type. The years with negative correlations
with a type, even though significant, have no concrete interpretation except that the
pressure anomaly reconstructions for the year were definitely not the particular type.

(Fig. 9.9) have occurred most frequently all three centuries. They occurred most often in the 18th century reconstructions (37%) and least often in the 19th century (28%), as compared to the present century (34%).

Type 3 winters (Fig. 9.10), which exhibit positive pressure anomalies centered over Alaska and are generally warm and wet in western United States but cold in the extreme north, appear only slightly more important
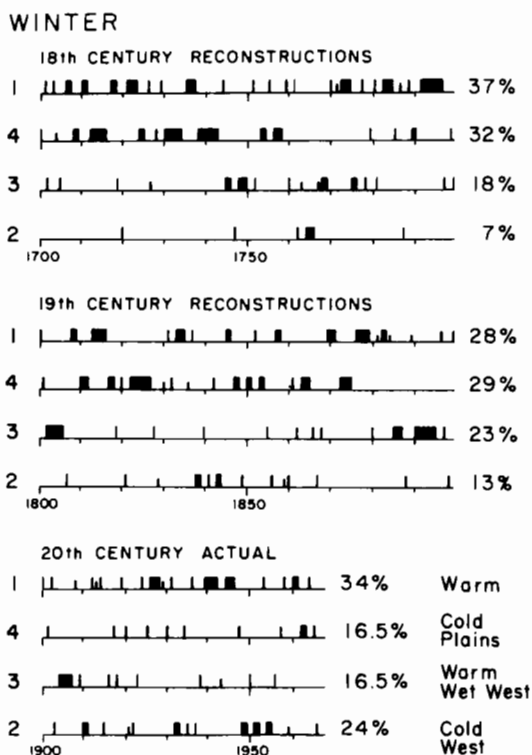
FIG. 9.17. The occurrences of the four winter pressure types as reconstructed from tree rings for A.D. 1700 through 1899 and as actually occurred in the pressure data from 1900 through 1966. Every year is identified as the type with which it is best correlated. The short bars designate those cases for which the correlation was less than 0·3 and therefore insignificant. The type numbers represent the order of their importance during the 20th century, but the order used in the figure represents their relative importance during the 18th and 19th centuries. The percentage occurrences of significant correlation are shown on the right, and the predominant climatic anomaly over the United States associated with each type is indicated as abbreviated descriptions next to the plots on the lower right. (Blasing and Fritts, in press)

in the two earlier centuries than in the current one. They occur 18% and 23% of the time compared to $16\cdot5\%$ for the 20th century.

Type 4 winters, with higher than normal pressure over the south coast of Alaska, lower than normal pressures over the central North Pacific, and anomalously cold outbreaks of arctic air into the northern Plains, occurred 32% of the time in the 18th century and 28% of the time in the 19th century, but only $16\cdot5\%$ of the time in the current century. This cold winter type was clearly more frequent in the past and there is a suggestion in recent records that it may be increasing in frequency at present (Blasing, 1975).

Type 2 winters, which exhibit a strong positive pressure anomaly in the north Central Pacific, a weak negative anomaly to the north and east (Fig. 9.8), and colder than normal winters in the far western United States, occurred 7% of the time in the 18th century, 13% of the time in the 19th century, and 24% of the time in the 20th century.

Figures 9.16 and 9.17 also show distinct climatic variations within the three centuries. For example, the first half of the 18th century can be characterized as varying between winters of general warmth and moderate dryness (Type 1) and winters of extreme cold in the high Plains (Type 4). Beginning in 1745, Type 3 winters were more common, with warmth and moisture in the West, cold in the extreme northern U.S. (Fig. 9.10), and the extremely cold winters in the Plains (Type 4) occurring less frequently. With the possible exception of the 1780's, these more mild conditions continued until 1810.

The cold Type 4 winters occurred with greater frequency between 1810 and 1875, interspersed with periods of warmth (Type 1). In the latter part of the 1840's and the 1850's, Type 2 (cold West) occurred somewhat more frequently. Starting with 1885, Type 3 dominated the circulation until near the end of the century. The persistent occurrence of Type 3 was broken by the occurrence of other types at the turn of the century, but beginning in 1905 Type 3 again occurred more frequently until near the end of the first decade. All four types occurred between 1910 and 1938, followed by a high frequency of occurrence of Types 1 and 2 until late in the 1950's. Since that time, Type 4 increased in frequency. For more details of these particular climatic reconstructions see Blasing (1975) and Blasing and Fritts (in press).

VIII. Verification of Reconstructions for Winter

The typing scheme not only provides a convenient means for characterizing the climatic reconstructions, but enables the comparison of the reconstructions with the climatic anomalies that actually occurred.

This section describes three ways in which the reconstructions were compared with actual climatic data to establish verification. (1) The reconstructed types for the winters of 1900-1961 (the dependent data set) were compared to the types derived from the actual pressure data. (2) The temperature and precipitation anomalies associated with the reconstructed pressure for years prior to 1899 were compared with the temperature and precipitation anomalies for the type years of the 20th century. (3) Calibrations were made for the relationships between tree-ring anomalies and temperature and the reconstructions of these data prior to the calibration period were compared not only to independent temperature data but also to the patterns of temperature expected during the years of the 18th and 19th centuries reconstructed to be of each pressure type (Fig. 9.17).

A. Verification of Types Using the Dependent Data Set

Although the percent variance calibrated is highly significant, an additional test was made by comparing the type patterns in the reconstructed pressure field with those in the actual pressure field. The correlation coefficients of both the actual and reconstructed data with each type were examined and all significant cases, that is those equal to or greater than 0·3, were identified and classified as belonging to that type. If the correlation coefficient for more than one type was significant, the case was identified as belonging to more than one type. After both the actual and the reconstructed pressure fields were so classified, a contingency analysis was made in the following manner: A reconstruction was considered correct if both the reconstruction and actual data were significantly correlated with the same type. It was also assumed that the tree response to climate can sometimes lag one year behind the occurrences of actual climate, so that situations with a significant correlation lagging one year behind climate were tallied as correct along with those that were significant at no lag.

The number of years actually typed using pressure data from 1899 to 1960 are shown in Table 9.III (line 1) along with the number of years reconstructed as each type (line 2). The first question tested was: Given a year in which the actual pressures resembled a type, how many of the reconstructions were of the same type? Line 3 in the table includes these cases, while line 4 includes additional correct reconstructions allowing for a lag in the tree-ring responses one year behind the actual occurrence of the type.

The second question tested was: Given a reconstruction of a type, how many cases in the actual data were of that type? The no-lag associations

TABLE 9.III The number of joint occurrences between the actually occurring pressure types and the types occurring in the reconstructions for winters 1899 1960[a]

Line	Case	Type[b]				Any Type[c]
		1	2	3	4[d]	
1.	Years actually typed	21	19	18	11	56
2	Years reconstructed as the type	21	24	22	11	57
3.	Correctly reconstructed with no lag	13	12	10	3	34
4.	Additional correctly reconstructed given the actual occurrence with a one-year lag in tree growth	2	4	4	2	10
5.	Additional correctly reconstructed given the reconstructed occurrence preceded by the actual occurrence	3	4	4	3	12
6.	Total lines 3 + 4	15	16	14	5	44
7.	Total lines 3 + 5	16	16	14	6	46
8.	Percentage correctly reconstructed given the actual occurrence (line 6/line 1)	71	84	78	45	79
9.	Percentage actual occurrence given the reconstruction (line 7/line 2)	76	67	64	55	81
10.	Percentage actual frequency during the 20th Century (line 1/no. yrs)	34	31	29	18	90
11.	Percentage reconstructed frequency during the 20th Century (line 2/no. yrs.)	34	39	35	18	92

[a]Reconstructions using minimum model for winter, Table 9.II, line 11. [b]Includes all cases where r ≥ 0·3. [c]Cases where more than one type was identified in a particular year are tabulated only once in this column. [d]The best correlated years representing Type 4 occurred in winters of 1962, 1963, and 1966, which is after the period with continuous tree-ring data. Thus reconstructions and verification of Type 4 for the three years of highest actual correlation were not tested.

for this occurrence are the same as those in line 3 (Table 9.III). However, the lagged associations differ from line 4 in that the cases of reconstructed types—not the actual occurrences—are examined, that is cases where a particular reconstruction is preceded one year by an actual pressure

pattern of the same type. Line 6 in Table 9.III is the total number of successes given the actual type, and line 7 is the total number of successes given the reconstructed type. These data are then expressed as percentages in lines 8 and 9. In lines 10 and 11 the numbers of types in the actual and reconstructed data shown in lines 1 and 2 are expressed as percentages of all years examined for the 20th century.

The frequency of occurrence of types during the calibration period was nearly the same for the reconstructions as for the actual data (57 out of a total of 61 years). The results in line 8 in the table indicate that a total of 77% of the years were reconstructed as the correct type, with the actual occurrences of Type 2 being correctly reconstructed 84% of the time and occurrences of Type 4 (the most poorly correlated type) correctly reconstructed only 45% of the time. The analysis period did not include the three characteristic years of Type 4, 1962, 1963, and 1965. It is clear that given a reconstruction of a particular type in the dependent data set, the probability that the climate was actually correlated with that type is 0·79. However, the reconstructions for Type 4 are more likely to be in error than those of the other three types.

B. Verification of Types using the Independent Data Set

A more rigorous test of verification can be achieved by using climatic data for years outside the dependent set. While little reliable data on pressure exists prior to 1899 for North America and the North Pacific, there is more reliable information on temperature and precipitation available for a number of weather stations. It was reasoned that if the pressure reconstructions for the 19th century were correct, then those years reconstructed to be of a given type should exhibit precipitation and temperature anomalies resembling those in the 20th century belonging to that type.

An examination of the correlation coefficients between the pressure reconstructions and the four winter pressure types (Fig. 9.16) revealed that 18 out of the 25 cases for winters for the interval 1874-1898 are highly correlated with a type (only those cases where r was equal to or greater than 0·5 are used). Four winters resemble Type 1; one resembles Type 2; 11 resemble Type 3; and two resemble Type 4 (Blasing, 1975 and Blasing and Fritts, in press). A test was made as follows. Temperature and precipitation data for the United States, available in the World Weather Records (Clayton, 1927), during the 1874-1898 period were averaged, normalized, and plotted on maps for all years of a given type. Figures 9.18 and 9.19 include the results for years of Types 1 and 3 respectively, which

were the types most often reconstructed. The anomalies were compared and tested against the anomalies associated with the 20th century occurrences (Figs 9.9 and 9.10).

The four winters of the 19th century identified as Type 1 were remarkably in agreement with those prevailing in the 20th century

1878,1879,1882,1896
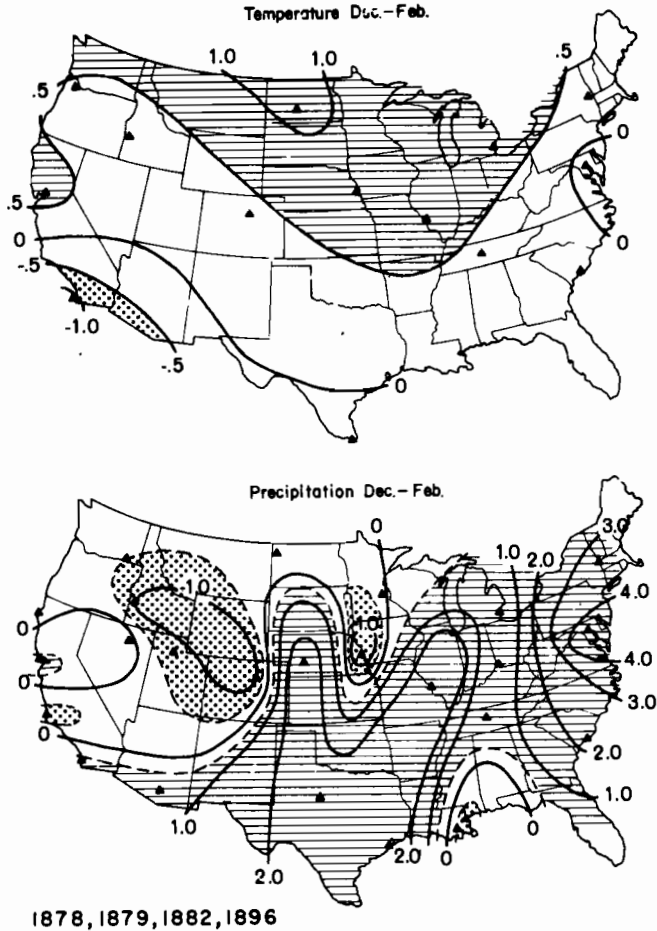
FIG. 9.18. The average anomaly of winter temperature and precipitation (expressed in standard deviation units) that occurred in the four years identified as being Type 1 in the independent period 1875-1898. The triangles indicate the location of the stations used as data points. The similarity of the climatic anomaly with those in Fig. 9.9 verify that the inferred climatic anomalies deduced from Fig. 9.9 are correct. (Blasing, 1975)

during Type 1 years. Both exhibited anomalies of high temperature throughout northern United States, low precipitation in the west, and a tongue of high precipitation associated with the northward flow of air from the Gulf of Mexico into the midcontinent. Only the heavy precipitation in the eastern third of the country is in disagreement. This
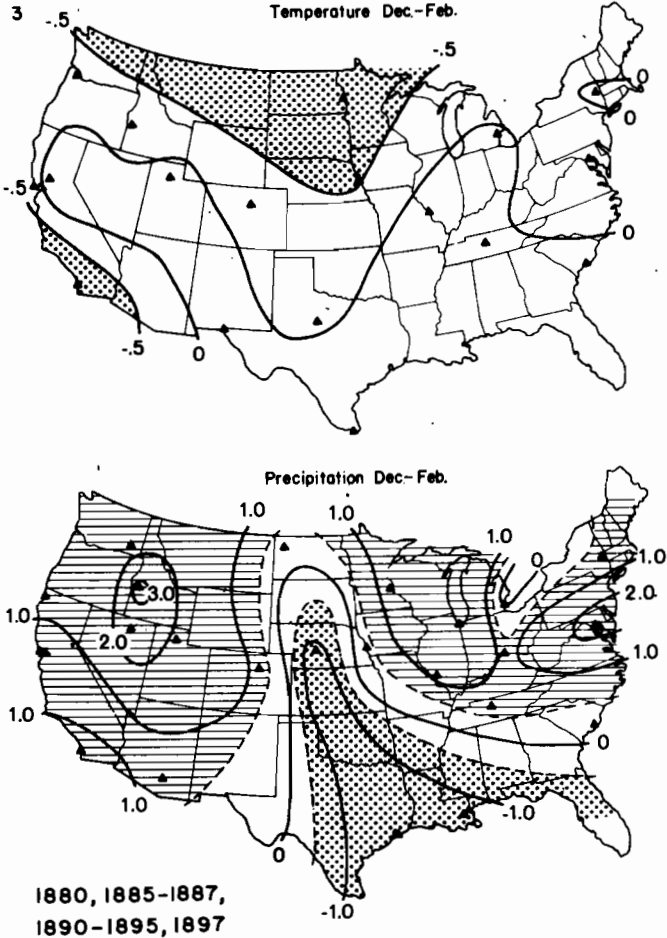
FIG. 9.19. The same as Fig. 9.18 except that it is for 11 years of Type 3 climate. The similarity of the climatic anomaly with those in Fig. 9.10 verify that the inferred climatic anomalies deduced from Fig. 9.10 are correct. (Blasing, 1975)

disagreement is not considered to be important because, (1) heavy precipitation can occur in the eastern United States during certain Type 1 winters, as in the winter of 1944-45, (2) the east coast of the United States is beyond the reconstructed pressure grid, and (3) predictability of pressure for the portion of eastern United States included in the calibrated grid, using the western tree-ring data set, is known to be low (Fritts *et al.*, 1971) (also see Fig. 9.7).

The temperature and precipitation anomalies associated with the 11 years reconstructed to be Type 3 winters (Fig. 9.19) are also in accord with the 20th century maps (Fig. 9.10). Temperatures in the northern states are lower than normal in both maps, while they are above normal from Nevada through southern Texas, the Mississippi Valley, and the Southeastern United States. Both maps show a tongue of anomalously cold air extending southward into the Plains. Similar high precipitation anomalies occur throughout the west and in the Ohio River Valley, and precipitation is low in the southern Plains and the Gulf Coast. The only important difference between the two maps is that low precipitation extends farther north for the 11 years in the 19th century. As was the case for Type 1 years, the differences in precipitation anomalies along the east coast are unimportant.

Though represented by few years, results for the other two winter types are just as encouraging (see Blasing, 1975, and Blasing and Fritts, in press). It is therefore concluded that the major anomalies in temperature and precipitation which were associated with each type in the modern record, at least for the middle and western portions of the continent, are verified for those years of the 19th century when the pressure types are reconstructed.

C. Consistency among Different Data Sets

The third approach to verification is to calibrate the amplitudes of tree growth with spatial variations of temperature at selected stations, to apply the tree-ring data to obtain the reconstructions, to test these reconstructions against data withheld for independent verification, and to check the reconstructions for their consistency with those obtained in the pressure analysis. Only the most successful analysis is included to illustrate the design of the experiment and some of the analysis limitations.

1. Calibration and Verification on Independent Temperature Data

An array of 18 North American climatic stations with long and apparently homogeneous records of temperature were selected. All

stations had complete data back to 1894, and the longest record extended back to 1870.

Eigenvectors were extracted from the spatial variations in winter temperature for 1910-1959 and the amplitudes of the first three eigenvectors, which together reduced 81·6% of the variance, were calibrated with the amplitudes of the first 10 eigenvectors of tree growth (Figs 9.1 and 9.2). The model resembles the one shown in line 11, Table 9.I.

Table 9.IV lists the 18 stations that were used, the reduction of error statistic (RE; Equation 7.4), the counts of signs, and the results of the product mean analysis (see Chapter 7). The overall calibrated temperature variance for the dependent period, 1910-1962, is listed in the

TABLE 9.IV Calibration and independent verification statistics for reconstructing December–February temperatures for 18 climatic stations[a]

Station Name	RE[b] Dependent	Independent	Sign +	Count −	Product +	Mean −
		Statistics[c]				
Abilene, Texas	0·086	0·026	13	10	1·6	1·0
Albuquerque, New Mexico	0·153[d]	−0·217	10	6	1·2	2·1
Boise, Idaho	0·287[e]	−0·002	21	19	6·1[e]	2·0
Brownsville, Texas	0·146[d]	0·214[e]	24	15	3·7[e]	1·1
Denver, Colorado	0·243[e]	0·020	25	11[d]	2·0	2·2
Dodge City, Kansas	0·190[e]	0·086	20	14	4·0	2·5
Edmonton, Alberta, Canada	0·218[e]	0·394[e]	17	4[e]	13·4[d]	4·1
El Paso, Texas	0·115[d]	−0·008	13	16	1·0[d]	0·4
Helena, Montana	0·241[e]	0·106	19	9	8·4[e]	2·5
Miles City, Montana	0·248[e]	−0·056	14	3[d]	8·0	9·7
Phoenix, Arizona	0·160[e]	−0·127	18	14	1·2	1·2
Red Bluff, California	0·186[e]	−0·300	20	11	1·1	1·1
Riverside, California	0·173[e]	−0·543	15	12	1·8	1·9
Salt Lake City, Utah	0·228[e]	−0·035	23	11	5·0[d]	2·4
Spokane, Washington	0·279[e]	0·039	19	8	6·0[e]	2·0
Winnemucca, Nevada	0·311[e]	−0·172	15	9	8·2[d]	4·6
North Platte, Nebraska	0·223[e]	0·109[d]	21	13	5·4	3·2
Roseburg, Oregon	0·273[e]	−0·463	20	11	1·1	1·2

[a]Amplitudes of 49 arid tree-ring chronologies used as predictors. [b]Reduction of error statistic is the same as the square of the multiple correlation for dependent period. [c]See text for explanation of statistics. [d]Significant P ≥ 0·95. [e]Significant p ≥ 0·99.

table as the RE statistic. It averages 0·209, but the individual values ranged from a low of 0·086 for Abilene, Texas, to a high of 0·311 for Winnemucca, Nevada. A total of 17 out of 18 of these calibrations were statistically significant.

The calibration equation was applied to the tree-ring data to estimate temperatures from 1700 to 1909 at each of the 18 climatic stations. Figure 9.20 includes one of the best and one of the poorest examples of verification. The reconstructed temperatures were then compared to the available independent temperature data for each of the stations prior to 1910 using the above mentioned verification statistics (Table 9.IV).
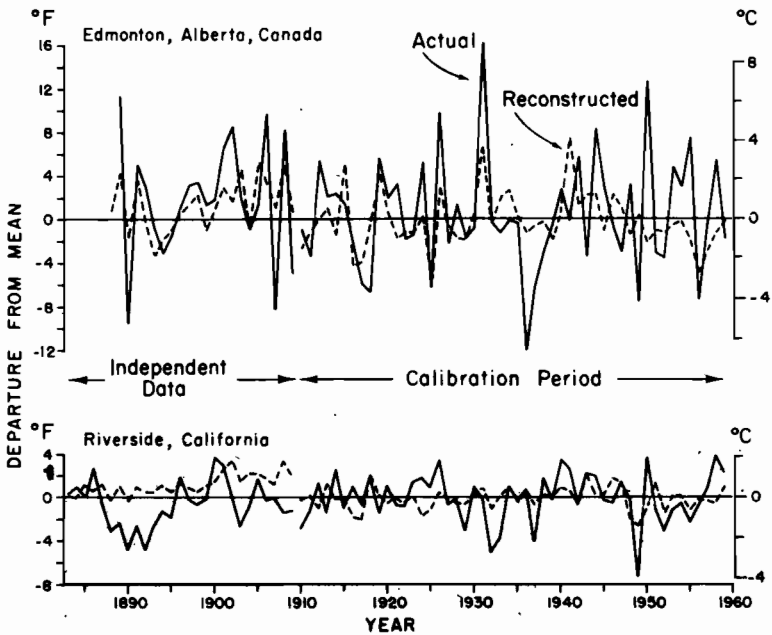
FIG. 9.20. The actual and reconstructed winter temperature for two calibrated stations included in Table 9.IV. The reduction of error statistic (RE) for the calibration period indicates relatively good agreement (0·218 for Edmonton and 0·173 for Riverside). The same statistic for the independent data indicates significant verification for Edmonton (RE = 0·394) and absence of verification for Riverside (RE = −0·543). The reconstructions for the latter station are rejected. (Drawing by M. Huggins)

The reduction of error for the independent data is positive at eight stations and exceeds the 95% confidence level for three of them. The sign of the winter temperature departures for the 18 stations is correctly reconstructed 327 times and incorrectly reconstructed 196 times, which is highly significant. The sign is correctly reconstructed more often than not for all but one station, but the sign counts for only three of these stations are significant. The positive and negative product means pooled for all stations are 4·4 and 2·1 respectively, and the positive product means are significantly greater than the negative product means for eight stations. The locations of the eight stations which exhibited the best reconstruction statistics are indicated as solid triangles in Fig. 9.21.

To test for the possibility that large-scale reconstructions were more accurate in certain years than others, the signs were examined year by year for all cases when six or more stations reported data (Table 9.V). During 11 of the 34 years examined, there were more positive than negative signs than could have occurred by chance. For 22 out of 34 years the values of the positive product means were two or more times those of the negative products. A total of 15 out of those cases with 10 or more observations were significant.

It is concluded from these data that verification statistics indicate significant agreement among the general patterns in climate for approximately one-half of the years available for testing and for 11 out of the 18 stations. However, the reconstructions for all 18 stations were utilized in the subsequent comparisons to allow analysis of spatial variations in climate.

2. Comparisons of the Mean Values of Temperature Reconstructions Stratified by Pressure Types

Since the same tree-ring data are used in the reconstruction of pressure and temperature and these two climatic data sets are physically related to one another, it is hypothesized that the reconstructions for the independent data periods should be mutually consistent only if the statistical relationships of both climatic variables with tree rings are real and significant. A test for the presence of a real linkage is made by stratifying the temperature reconstructions for winters from 1700 through 1899 according to the pressure types in the reconstructions (Fig. 9.17). The mean anomalies for reconstructed temperature in the years of each type for the 18th and 19th centuries (Fig. 9.21) could then be checked for consistency with the temperature anomalies in the 20th century that were known to be associated with the type years (Figs. 9.9 and 9.10). Years with Type 1 winters are reconstructed to be anomalously warm, especially in the north (Fig. 9.21), a pattern which is consistent with the

TABLE 9.V Independent verification statistics for reconstructing December–February temperatures tabulated by year for all cases with 6 or more reporting stations[a]

Year	Sign Count +	Sign Count −	Product[d] Mean +	−
1876	1	5	0·5	1·7
1877	5	1	3·0	5·5
1878	6	1	3·5	0·7
1879	8	1[b]	1·4	0·7
1880	6	3	1·9	0·9
1881	7	3	5·7[b]	0·1
1882	6	5	1·5	3·7
1883	13	0[c]	4·2[c]	0·0
1884	10	3	1·0[b]	0·0
1885	8	5	5·7[b]	1·4
1886	11	3	2·0	0·7
1887	10	5	3·9[c]	0·3
1888	13	2[c]	2·5[c]	0·3
1889	6	10	8·8	1·2
1890	14	2[c]	3·4[c]	0·1
1891	5	11	5·9	1·9
1892	3	13	0·8	1·3
1893	6	11	3·3	2·0
1894	2	16	4·0	2·0
1895	3	15	0·9	1·6
1896	15	3[c]	4·0[c]	0·7
1897	14	4[b]	3·0[b]	0·4
1898	12	6	2·2[b]	0·5
1899	10	8	3·6[b]	1·6
1900	15	3[c]	3·1[c]	0·1
1901	15	3[c]	8·2[c]	0·7
1902	16	2[c]	7·4[c]	0·5
1903	7	11	3·8	5·3
1904	13	5	2·9	1·5
1905	13	5	4·9	10·2
1906	15	3[c]	7·0	5·1
1907	10	8	3·8	4·1
1908	14	4[b]	.3·9[c]	2·3
1909	11	7	4·7	2·7

[a] See Table 9.IV and text for explanation. [b] Significant positive agreement (P ≥ 0·95). [c] Significant positive agreement (P ≥ 0·99). [d] Not tested for cases with less than 10 observations.

modern period (Fig. 9.9). The same pattern was again verified by actual temperature data in the late 19th century (Fig. 9.18). The general departure pattern reconstructed for temperature in Type 3 years (Fig. 9.21) also resembles the patterns for the 20th century (Fig. 9.10) and for the 19th century verifications (Fig. 9.19), though some differences in the placement of the zero lines are apparent.

The mean temperature anomalies reconstructed for Type 2 and Type 4 years in the 18th and 19th centuries (Fig. 9.21) are also in accord with the associated temperature anomalies in the 20th century (Blasing, 1975, Blasing and Fritts, in press). Therefore, it is concluded that the results from both the temperature and pressure calibrations are consistent with each other, although the pressure reconstructions appear more reliable than those for temperatures, as the individual reconstructions of temperature exhibit sizable errors with unreliable estimates for particular stations and years.
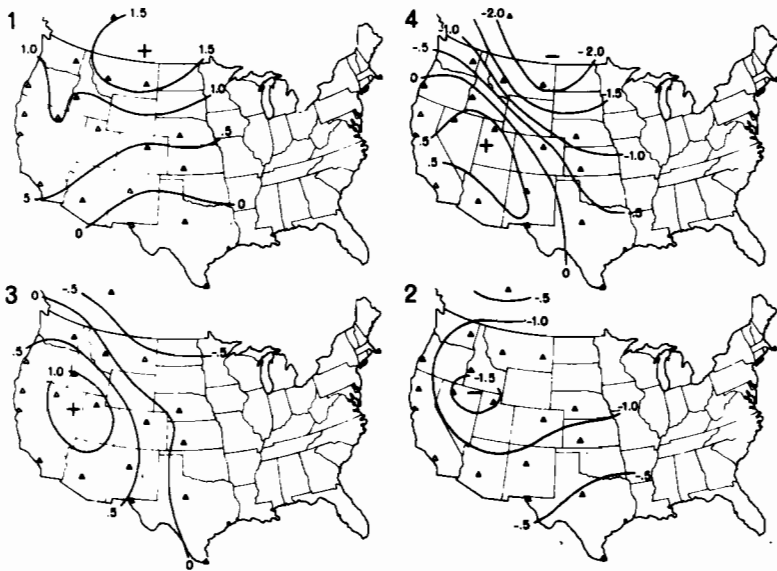
FIG. 9.21. The mean temperatures reconstructed for the winters 1700-1909 and stratified according to the types for 1700-1899, as in Fig. 9.17. The mean values are expressed in standard deviation units and the triangles show the locations of the 18 climate stations. The filled triangles are those stations with the best statistics and hence the most reliable reconstructions. (Drawing by M. Huggins)

Verification analyses using independent climatic data not used in calibration can provide objective and conclusive evidence that past climatic variations are accurately reconstructed. The best verification results are obtained when spatial variations in climate for a season are reconstructed from spatial variations in ring width. This occurs because the trees are natural integrators of climatic variations occurring over a number of months throughout the year. When principal component analysis is applied to many different tree-ring chronologies, the large-scale variations in the eigenvectors of growth are shown to be closely related to the large-scale variations in macroclimate.

These results may be formulated into the following working hypotheses: Climatic reconstructions for tree-ring data can be improved by (1) using data already integrated over space or over intervals of time representing at least several months, (2) averaging data sets via principal component or canonical analyses, or (3) averaging the reconstructions themselves by climatic type, by region, or for meaningful intervals of time as determined by typing analysis.

IX. Summarization of Reconstructions for Summer using the Pressure Types

Climatographic reconstructions of pressure, temperature, and precipitation have now been described for winter months, and the same techniques have been applied to climatic data for other seasons of the year. This section describes the reconstruction of pressure for summer and applies the summer pressure types to characterize the variations that have occurred during the last three centuries.

The reconstruction model for summer utilized growth at a one-year lag, so that the estimates from a particular set of tree rings are actually for the climate occurring in the preceding year. The reconstructions for each year are in turn correlated with five summer types to obtain a plot similar to the one shown in Figure 9.16 (Blasing, 1975; also see Figs 9.11, 9.12, and 9.13). The summer type best correlated with each reconstruction in the 18th and 19th centuries was assigned to that year and plotted in Fig. 9.22. The actual data for the 20th century are treated in the same way and are plotted in the figure along with a word description of the predominant anomaly in climate over the United States.

As for winter, the types were rearranged in the order of their relative importance for the 18th and 19th centuries. When the type occurrences in the reconstructions during the 20th century were compared to those for the actual pressure, it was noted that 60 out of 61 of the years were typed
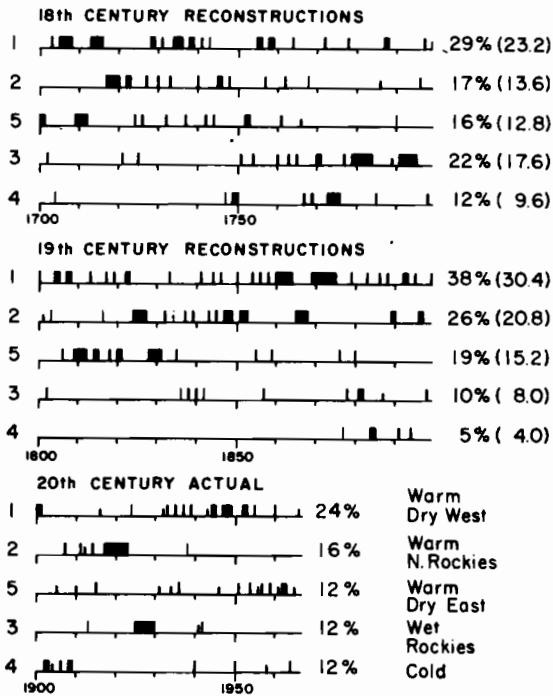
FIG. 9.22. The occurrences of the five summer pressure types as reconstructed from tree rings for 1700 through 1899 and as occurred in the pressure data from 1900 through 1966. The reconstruction percentages exceed the actual by 20%, the parentheses enclose the appropriate adjustment (see also text). See legend to Fig. 9.17. (Drawing by M. Huggins)

$(r \geq 0 \cdot 3)$, while only 48 actual occurrences were typed for the same period of time. It was concluded that the reconstructions were overestimating the types and that the frequencies of types should be adjusted by multiplying the percentage by $0 \cdot 8$ $(48/60 = 0 \cdot 8)$. The brackets in Fig. 9.22 indicate this adjustment.

It is apparent from the figure that the adjusted frequencies for the reconstructed summer climates of the 18th and 19th century varied from those in the 20th century. Summer Type 1, which was associated with dry and warm conditions in the central and western United States (Fig. 9.12), was reconstructed 23·2% of the time in the 18th century and 30·4% of the time in the 19th century, as compared to 24% of the time during the 20th century. Type 2, which was associated with anomalous warmth in

the Rocky Mountains, was estimated to have occurred 13·6% and 20·8% of the time in the 18th and 19th centuries, but occurred 16% of the time in the present century.

Summer Type 5, which is like Type 1 in that it is dry and warm in the central United States but differs from it in that drought is present in the eastern U.S., was estimated to have occurred 12·8% of the time in the 18th century and 15·2% in the 19th century, as compared to 12% during the 20th century.

Type 3, which is characterized by wet conditions in the Rocky Mountains, occurred most frequently in the 18th century (17·6% of the time) and least frequently in the 19th century (8%) as compared to 12% of the time in the current century. On the other hand, Type 4, which is characterized as a cold, winter-like circulation in summer, was estimated to have occurred 9·6% in the 18th century and 4·0% in the 19th century as compared to 12% in the 20th century.

Examination of the distribution in these occurrences of types within each century (Fig. 9.22) reveals interesting changes in frequency through time. For example, Types 1, 2, and 5 are estimated to have occurred most frequently throughout the first half of the 18th century. Type 3 with wetness in the Rocky Mountains and Type 4 with cold summers are estimated to have occurred more frequently in the latter half of the century. During the 19th century Type 1 is estimated to have occurred at a frequency greater than one out of three years, Type 5 is estimated to have been frequent during the first four decades, and Type 2 is estimated to have occurred during the 1820's through 1860's as well as near the end of the century. During the 20th century the types were often clustered in distinct periods of time. Type 4 predominates during the first decade, which is followed by a high occurrence of Type 2 until 1925 and then by Type 3 until 1931. The drought Types 1 and 5 became most important in the 1930's through 1960's, after which other types occurred more frequently. A comparison of Type 1 and 5 occurrences among the three centuries indicates that the frequency of drought in the 18th century was the same as in the current one but was more frequent in the 19th century by approximately 10%.

As was the case for winter, the pressure anomaly types provide a unique and precise means of summarizing the climate of the past without mapping and analyzing each yearly reconstruction. A variety of periods dominated by particular atmospheric circulation regimes can be identified and interpreted in terms of the modern climate, without obscuring other types of variation that may be mixed with them. The data on yearly occurrence of types are also available in Figs 9.17 and 9.22 for comparison with other information on past climate.

The information provided in the figures deals with half-hemisphere-wide generalizations about climate. As such, the yearly reconstructions may or may not be in agreement with data at any one location, creating apparent inconsistencies of detail. As data from more reporting climatic stations and more tree-ring stations can be incorporated in the reconstructions, the results of the estimated and actual occurrences should be increasingly in agreement.

X. Verification of Reconstructions for Summer using Independent Tree-Ring Data

A number of verifications of the reconstructions for summer have been attempted with varying degrees of success. The reconstructions themselves were more difficult to create and verify than those for winter because (1) the summer season that was used included two rather than three months, (2) the variance of pressure in summer is less than that of the winter, (3) the climatic variations of summer are not as well correlated over space as those of winter, and (4) the summer climate can affect growth more during the following year than during the current one, which leads to an uncertainty as to the placement of reconstructions in the time sequence. In addition, many response functions described in Chapter 8 exhibit smaller weights for the climate of July and August than for the climate of the three winter months, indicating that the trees do not respond as markedly to variations in summer climate.

For the purposes of this volume, only the summer verification methods are presented which differ from those already described for winter. One verification test for summer used independent tree-ring data from Alaska and Northwest Canada back to A.D. 1800 (Blasing and Fritts, 1975). This information was well dated, well replicated, and from northern tree line sites. Therefore, the Arctic tree-ring data offered a unique opportunity for an independent test of summer circulation in the North American Arctic which was outside the area covered by the 49 arid-site chronologies.

For purposes of the analysis, the narrow rings from the Arctic sites were all assumed to be indicators of anomalously cloudy, wet, cold climate, while the wide rings were assumed to be indicators of anomalously sunny, dry, mild climate. The reconstructed pressure anomaly was interpreted as a weather map in terms of the expected anomaly in storm tracks and the expected direction in wind which controlled the temperatures at the tree sites (see Blasing and Fritts, 1975). That is, the anomalous wind direction is inferred to be parallel to the isobars in the anomaly maps, with low pressure to the left and high pressure to the right.

Three characteristics of the Arctic ring-width chronologies complicated the results. (1) Frost can sometimes damage the tree and cause abrupt and persistent changes in growth; (2) the ring-width response appears to lag one to 15 or more years behind the original causal conditions of climate (LaMarche, 1974a; LaMarche and Stockton, 1974); and (3) the period used for pressure reconstruction, July and August, did not coincide exactly with the spring and summer period to which Arctic trees respond. The first two difficulties caused a lag in the growth response behind climate which filters out some of the year-to-year variations in climate, while the last created a certain amount of inconsistency in the results (Blasing and Fritts, 1975).

The test involved two checks. In the first, the mean pattern in Arctic tree growth associated with each pressure type during the 20th century was compared to those for the 19th century for years reconstructed to be the same type (Fig. 9.22). It was hoped that some consistency in growth pattern would be evident, in spite of the fact that the tree growth sometimes lagged behind climate and that some pressure types may not affect the climate of the North American Arctic. In the second test, the growth patterns in the Arctic were themselves typed and then the mean anomaly in reconstructed pressure for the years of each growth type were examined for their consistency with the patterns in the growth types.

The first test was inconclusive because pressure types such as 1, 2, and 5 exhibit weak gradients in the Alaskan area, or, as in the case of Type 3, the most characteristic years were too weakly represented to allow comparison of the two results during the period in common among the data sets, 1800-1939. The second test, which was more successful, is described in the following paragraphs.

The standardized yearly ring-width chronologies from the Arctic were normalized for 1800-1939 and anomalies of growth were typed using the procedure of Blasing (1975). The resulting growth type occurrences were not as randomly distributed through time as those of the pressure types but were confined to distinct periods, apparently because of persistence and autocorrelation in the growth sequences. However, during periods of transition two or more growth types are interspersed with one another.

The upper portion of Fig. 9.23a includes maps of the average normalized patterns for the first four growth types (a) and is labeled according to the first and last year associated with each one. Figure 9.23b includes the mean reconstructed pressure anomaly associated with the particular years of growth. The reconstructed pressure anomalies for the summer model (Table 9.1, line 3) were used first, but later the results from the minimum-sized model (Table 9.1, line 10) were applied and found to be consistent with those described in the following pages. The

first growth type is complicated by lagging effects of extreme climatic conditions occurring late in the 18th century, so the discussion will start with the second type. Growth Type 2, which occurred in years from 1812 through 1828, exhibits anomalously low values throughout Alaska and adjoining areas in Canada, except for higher than average growth near the Alaskan coast. Growth Types 3 and 4 show similar anomalies but with a larger area of higher than average growth for a number of chronologies in south Alaska and adjoining areas in Canada. It may be inferred from these patterns that during 1812-1851 conditions in the north were unfavorable to growth and thus were cold and stormy, while further south where growth was higher, conditions were warmer than average and less stormy.

During 1812-1851 (Fig. 9.23b) the North Pacific High was reconstructed to be displaced north of the positions it occupied during the calibration period for 1900-1962, and the summer storm track was also inferred to be displaced to the north. Storms were inferred to be most common in the vicinity of the Arctic coast along a path which turns southward in western Canada, at least for the intervals dominated by growth Types 2 and 3, which occurred from 1812 to 1836. This is consistent with the growth, as storms would bring cloudy weather to the north slope of Alaska, advect cold air southward and eastward from the Arctic Ocean, and bring low temperatures to the areas of low growth in the northern Arctic. The southward flowing air would become warm as it moved over central Alaska and this, in conjunction with the northward displacement of the North Pacific high pressure system, would bring sunny weather and above-normal growth along the southern coast.

Growth Type 1 in Fig. 9.23a is markedly different from growth Types 2 and 3 while the associated pressure anomalies are almost identical. One explanation for the discrepancy was that the climate changed in the last decade of the previous century and the years representing growth Type 1 were transitional to a new mode of climate. An examination of type occurrences shown in Fig. 9.22 confirmed this possibility, as pressure Types 3 and 4 dominated the reconstructions from 1770 to 1795 but occurred rarely in the following century. The anomalies associated with pressure Type 3 were somewhat higher than normal over the Bering Strait and Northwest Canada, and lower than normal over central and eastern Alaska. This is a markedly different anomaly from the pressure reconstructed for 1804-1811 shown in Fig. 9.23 and one which would be more consistent with growth Type 1. In order to test this possibility further, the available growth data associated with pressure Type 3 for the years 1790-1795 were averaged (Blasing and Fritts, 1975). The pattern was remarkably in agreement with growth Type 1 which followed during
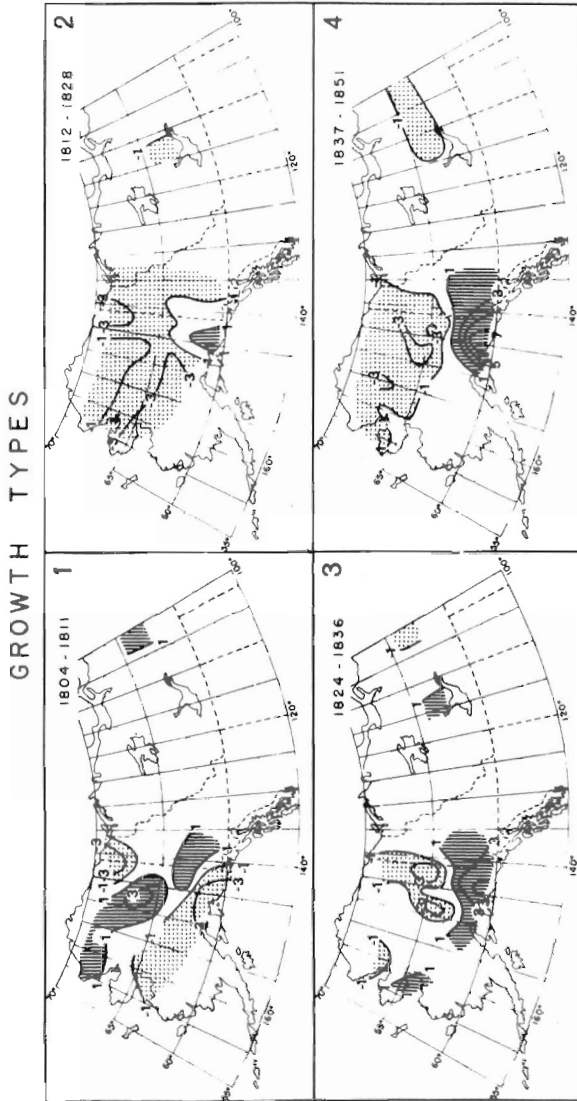
GROWTH TYPES

FIG. 9.23a

FIG. 9.23. The anomaly pattern for (a) the four Arctic tree-growth types occurring in the first half of the 19th century, and (b) the reconstructed pressure anomalies averaged for the years of that growth type from the application of the transfer function to the 49 chronologies from arid North American tree sites. The Arctic tree growth is expressed in standard deviation units as departures from the mean for the period 1800-1939. The years shown in the figure are the first and last of those included in the particular growth type. (Blasing and Fritts, 1975)
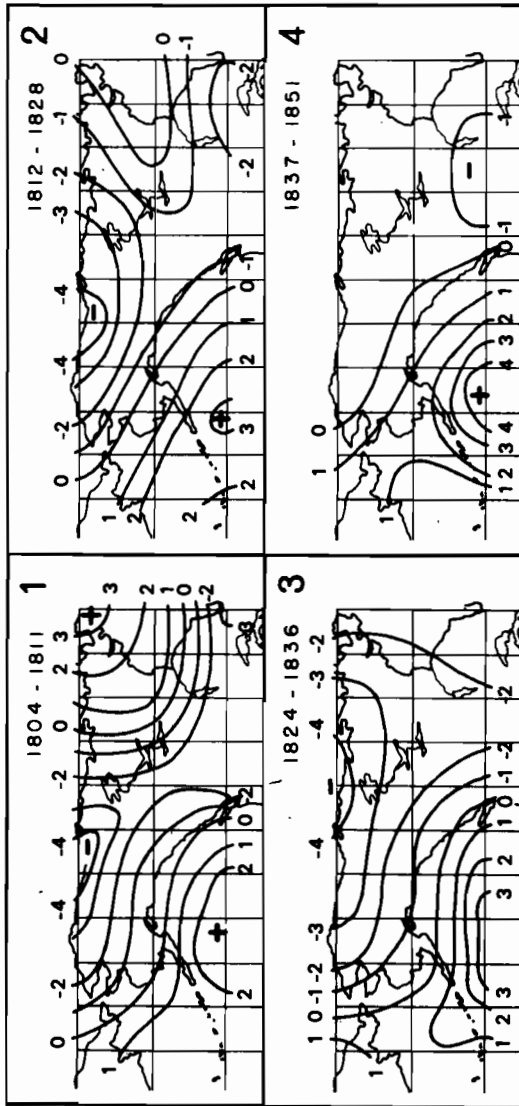
FIG. 9.23b

the 1804-1811 interval. Therefore growth Type 1 was inferred to be transitional representing a lag in growth response behind a marked change in climate.

It was therefore concluded that the growth pattern in the Arctic trees for 1804-1811 represented in part a lagging response behind a marked pattern in climate during the latter part of the 18th century and in part a transitional growth response to a new climate pattern existing for the 1804-1811 period. By 1812 (16 years after Type 3 summers were reconstructed to have occurred) the growth pattern reached a new equilibrium with the current climate, a growth pattern which persisted for approximately 40 years. However, the pressure anomalies associated with growth Type 4 (Fig. 9.23a) suggested that there was a return to normal pressure throughout the continental North American Arctic, so that this growth type might also be a transitional one.

The growth anomaly for Type 5 (Fig. 9.24a) occurred during 1845-1863 with high growth throughout Alaska, especially in the area near Anchorage. The associated pressure anomaly shows a reintensified pressure gradient resembling the prior periods with Types 1-3 with one apparent but important difference. The area of anomalously low pressure extended across the Bering Strait to Siberia so that the wind over western Alaska was from a westerly direction rather than from the northwest, a condition which might be expected to bring warmer air into the western and northern parts of the state. The influx of warmer air across the Alaskan interior is also consistent with the continuation of anomalously high growth in the area along the south coast, as occurred in growth Types 3 and 4.

Growth during the last 40 years of the 19th century (Types 6 and 7) continued high in northwest Alaska, but it decreased to the northeast and south. The anomaly in pressure reconstructed for years of growth Type 6 suggests continued westerly flow from the north Pacific Ocean, with some southward flow from the Arctic Ocean into the Mackenzie Delta where growth was average or below normal.

For the last two decades of the 19th century, which were dominated by growth Type 7, the positive anomalies of growth for northern Alaska become less marked and the inferred climate more like that of today, while negative anomalies in growth become more apparent to the south. The mean pressure anomaly for the years of Type 7 is reconstructed to be close to normal over most of Alaska. However, there appeared to be more storms and a stronger component of onshore air flow from the south than previously, which brings lower summer temperatures along the coast and warmer temperatures inland.

After the turn of the century, 1901-1914, the anomalously high
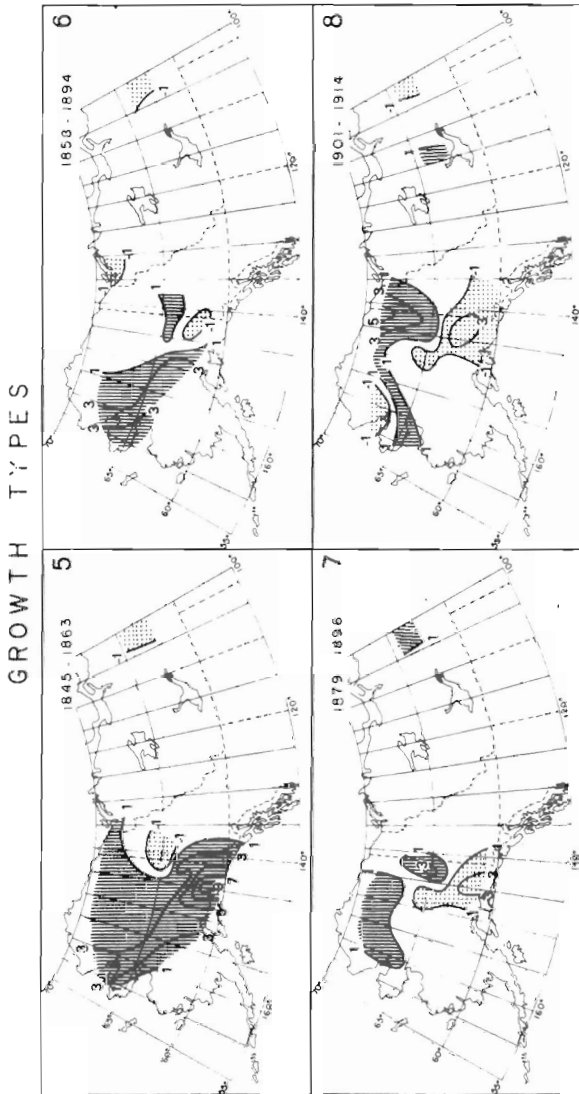
FIG. 9.24a

FIG. 9.24a and b. Same as in Fig. 9.23 but for the latter half of the 19th and early 20th century, which include the period dominated by four additional growth types. (Blasing and Fritts, 1975)
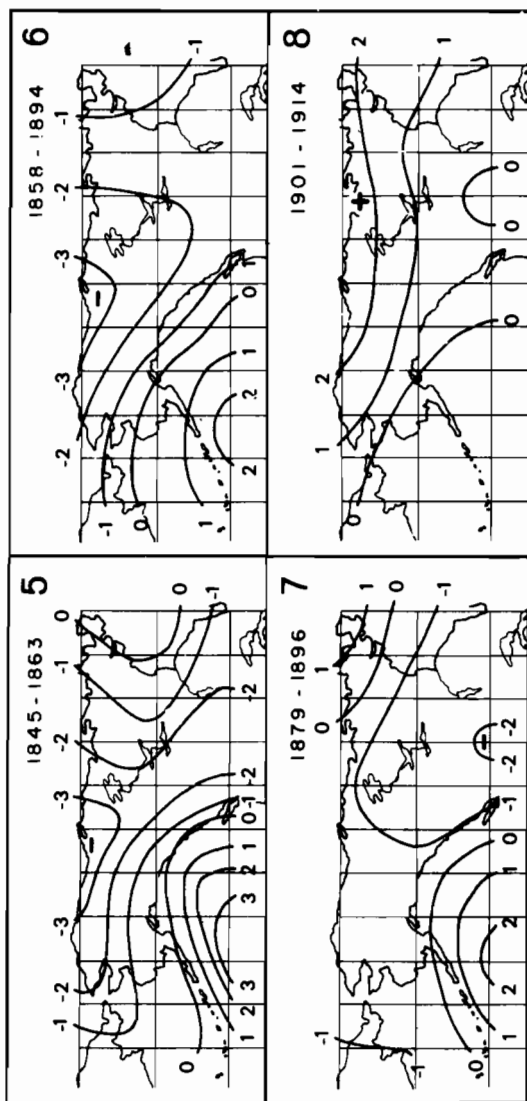
FIG. 9.24b

pressure in the Gulf of Alaska disappeared. This occurred in conjunction with continued lower than average growth in the south, colder temperatures, more storms, and increased cold air flow from the south and southeast off the Gulf of Alaska. Since the northern areas of Alaska and Canada are under a regime of anomalous southerly winds flowing over the land area, the air is warmed and temperatures become higher and more conducive to high growth. One exception to this general warming pattern in the North is the reduced growth in the northern Seward Peninsula, where coastal conditions may have counteracted any ameliorating effect of the more southerly winds.

While the above analysis is speculative, it does show how tree growth itself can be used as direct evidence of climatic variation and applied to verify or document climatic reconstructions. The Arctic tree-ring data appear to be consistent with the pressure anomalies reconstructed for the same area and period of time. Attention shall now be directed to other types of data that may be used to verify, validate, or complement dendroclimatographic reconstructions.

XI. Verification using Journals, Historical Data, and various Proxy Records of Climate

Official meteorological records and tree rings are not the only data sources available for climatic reconstruction and verification. A variety of other information is available from historical materials, journals, harvest logbooks, records of freezing and thawing of lakes, phenological observations on flowering and fruiting of trees, and a variety of chronicles. Much valuable information has been gathered from such references to climatic events, including, for example, the freezing dates of Lake Suwa and the blooming dates of cherry trees in Japan (Arakawa, 1954, 1956); sea ice data (Bergthorsson, 1962); the records of pioneers, explorers, and early forts (Lawson, 1972, 1974; Wahl and Lawson, 1970); vintage dates and other historical events in Europe (Ladurie, 1971); data from ships' logs (Lamb, 1972); and lake level and other hydrologic and geologic records (Antevs, 1952; Fritts and Cathey, 1971). Such records must be scanned critically, evaluated, and compiled by region and date to facilitate their comparison with climatic reconstructions. At present few of these data have been applied to verification of tree-ring reconstructions, and only one example from Blasing and Fritts (1975) is cited here.

Daily temperature data were obtained from Kutzbach and Wendland (personal communication) for the Russian fort at Illoolook, Unalaska Island, near modern Dutch Harbor for 1829-1833. The maximum and

R

minimum temperatures for July and August were averaged and compared to the anomalous wind inferred from the pressure field over the island as reconstructed from the arid-site tree rings. When the anomalous wind was estimated from the west–northwest, which occurred in 1829 and 1831, the observed temperatures at Illoolook were several degrees lower than during years when the anomaly was estimated from the southwest or west–southwest (Table 9.VI). For these years the reconstructed pressure anomalies were verified.

TABLE 9.VI Comparison of inferred anomalous wind direction from reconstructed pressure anomalies and mean July–August temperatures[a] for 5 years at Illoolook, Unalaska

Year	Anomalous direction of the inferred geostrophic wind	Mean summer temperature
1829	west–northwest	53·5 F
1830	southwest	58·6°F
1831	west–northwest	51·4°F
1832	west–southwest	58·1°F
1833	west–southwest	58·2°F

[a]Data courtesy of Kutzbach and Wendland, University of Wisconsin.

More and more proxy data on climate are becoming available through the work of many scientists—data which not only serve as verification but also offer additional climatic information. Some of these data are not dated to the exact year or season of occurrence. Precisely dated, continuous tree-ring evidence could provide the necessary time control, structure, and continuity to weave them into a coherent year-by-year history. In addition, the spatial patterns derived from tree rings could resolve conflicting evidence. For example, temperatures reconstructed to be anomalously high for one area and anomalously low for another would be consistent if they were on opposite sides of an anomalous low pressure trough. Northerly flow to the east of the trough would produce warm temperatures, while southerly flow to the west would produce cool temperatures.

XII. Applications to Climatological Problems

The precisely dated and objectively derived tree-ring reconstructions are expected to contribute significantly to man's understanding of climate. As mentioned above, these climatic reconstructions are unique in that they provide a continuous time sequence, and they can be used to place other less well-dated information into its proper time period and location within a coherent framework. In addition, the reconstructions are

objectively derived, not subjectively inferred, so that they provide a precision not found in most paleoclimatic data.

The temporal accuracy of the reconstructions can be of special value to climatological analysis. For example, dynamic modeling of climate (Gates and Mintz, 1975) will eventually require accurate and well-dated maps of past variations for making comparisons (Sheppard, 1966). Various hypotheses about climatic linkages to physical phenomena such as atmosphere, tidal forces, variations in solar energy output or sunspots, variations in atmospheric turbidity resulting from volcanic eruptions, and so forth, can be tested against the long climatic record derived from tree-ring analysis. In addition, hypotheses about man's possible role in changing climate may be tested by searching for analogies in the reconstructed record.

Although reliable climatic forecasts are not presently feasible, some estimates of possible future climates would be useful for planning purposes. For example, it is argued by some workers (Bryson, 1974; Lamb, 1966) that the climate has been so anomalous in recent times that the climatic statistics derived from the recent record are unrealistic and therefore do not adequately portray the expectations for the future. Thus, the tree-ring chronologies spanning a longer period of time may provide a more realistic record, and the statistics of the reconstructions can be compared to those for the shorter climatic record to identify the extent and nature of the bias in the shorter record and to adjust its stastistics accordingly.

The calibrated tree-ring record from the selected 49 sites and the pressure types reconstructed from them shown in Figs 9.17 and 9.22 can be applied to this problem. For purposes of illustration, assume that the frequencies for the 20th century pressure types in the two figures represent the known record of climate from western North America and the North Pacific. The frequencies of 20th century pressure types along with those for the reconstructions in the 18th and 19th centuries are summarized in Fig. 9.25 for both winter and summer. In the case of summer, the dashed lines indicate the actual reconstructions and the solid line the frequencies after adjustment as discussed in Section IX.

The hatched bar on the right is a mean value of the frequencies obtained by pooling the 200 years of estimates and the 62 years of actual pressure occurrences. Some marked anomalies of the 20th century are in evidence. Winter Type 4, which produces cold weather in the Plains, occurred 10% less frequently, and winter Type 2 with a cold western United States occurred 11% more frequently than would be indicated if the longer 262-year mean were used. Any decisions concerning these patterns of climate, based exclusively upon the 20th century data, would

be in error, and should be modified using the longer-term estimates. Data from the 20th century concerning pressure Types 1 and 3 are evidently more in line, as they are within 2% of the long-term estimates.
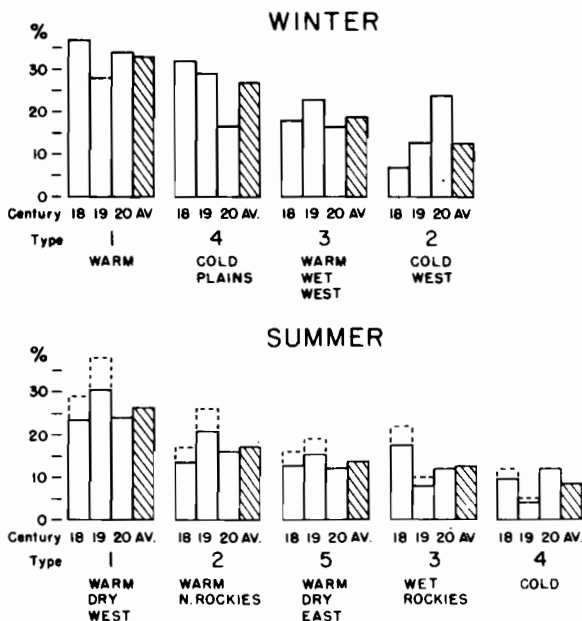
FIG. 9.25. The percent frequencies of reconstruction and occurrence for the pressure types during the individual last three centuries as compared to the averages for the 262 years spanned by the actual data and the reconstructions together. Since the 20th century data are anomalous, the longer-term averages may be better estimates of the expectations for future modes of climate.

The data for summer (Fig. 9.25) indicate that the frequencies during the 20th century are closer to the long-term estimates. However, each of the drought and warm types, Types 1, 2, and 5, exhibits a 1% to 2% lower anomaly and amount to a 5% lower drought frequency. Type 4, the cold summer type, occurred 4% more frequently.

These kinds of analyses can be used to identify the bias in the modern record, which in this example is toward warmer winters in the midcontinent, colder winters in the West, less frequent drought, and cooler temperatures in summer over the middle and eastern portions of the continent.

XIII. Present and Future Prospects of Dendroclimatology

This volume has attempted to describe the most important concepts and principles of the emerging discipline of dendroclimatology. Growth of trees has been shown to fluctuate in many ways, depending upon physical, physiological, and age variations of plant tissues as well as genetic, soil, and microclimatological variations among trees. These variations can affect growth only by limiting the rates of plant processes in one or more organs of the tree.

The details of the interrelationships are exceedingly complex, but the ring characteristics and the essential nature of the climatic relationships can be statistically measured, modeled, and the net effects of climate on growth expressed in response function form. Transfer functions can be objectively derived and applied to past tree-ring information to obtain estimates of past variations in climate.

The climatic reconstructions described require that all rings be precisely dated, that the environmental data with which they are calibrated be accurately placed in time, and that there be environmental data independent of that used in the calibration to serve as checks of the reconstructed climate.

It has also been shown that calibration need not be restricted to the specific microenvironments where tree samples were taken. In fact, it is often better to use regional averages of climate rather than specific site data for calibration, because the macroclimatic variations averaged for a region are not only highly correlated with the microclimates of the different tree sites but they are often more representative of large-scale changes in climate. In addition, the large-scale variations are more closely linked to the major variations in world climate.

The accuracy of the climatic reconstructions at any given location or time period is expected to improve as more diverse tree-ring data sets are obtained from a wider variety of species, sites, regions, and continents. In general, the greater the number of trees and sites used for a spatial sample, the greater the diversity in the tree-ring responses to climate. Similarly, the greater the areal coverage of the tree sites, the more information that can be extracted from the ring-width data on past world climate. It is no longer necessary to confine sampling to extremely arid or cold sites, and it is no longer desirable to select samples responding to the same climatic factor. The multivariate statistics perform their own selecting and scaling of anomaly variance in a way which obtains the maximum information on the calibrated variables of climate.

Data from the growth rings other than their widths are expected to add

new dimensions to climatic analysis. Such data may include the character of cells and intracellular structures, variations in wood density throughout the ring, microchemical variations from one ring to the next, fluctuations in isotopes of carbon, hydrogen, and oxygen, or possibly the residual magnetic field which is measurable from specimens of wood. In addition to the tree-ring reconstructions, other well-dated information on climate can be used, such as that available from oxygen isotope analysis of ice (Dansgaard *et al.*, 1971), the annually layered sediments in lakes and ocean basins (Swain, 1973), and layering found in certain species of corals (Buddemeier, 1974), as well as very long climatic records themselves. As long as such data can be dated to the exact year, as are tree rings, they can be entered into the multivariate equation along with the tree-ring chronologies, and together they can be used to establish past hemispheric or even worldwide climatic variations.

Usable tree-ring information appears to be available from temperate climates of both the Northern and Southern Hemispheres. The investigator must examine the appropriate species and sites for the older climatically affected trees and look for the contorted stem forms indicating general stress and old age. While at present there appears to be little success in dating ring structures in the Tropics, there are many possible species and promising habitats in that area that have not been examined; information from the Tropics is too valuable for any potential sources to be arbitrarily ruled out. Of course, the ultimate test of any sample is the crossdating and the resultant amount of calibration possible with variations in climatic factors.

Not all climatic data are equally useful in calibration, for there may be large errors and inconsistencies in poorly collected and prepared data. Such errors will contribute to inaccuracies in the calibrated relationships, and no matter how excellent the tree-ring records are, they cannot exceed the reliability of the climatic data used for calibration. Also, rain gauges, thermometers, and barometers all measure conditions at a point, and all contain some errors and local bias, and are therefore imperfect estimators of the macroclimate. As such, they may be poor recorders of those climatic variations that limit the plant and influence ring widths. Thus, many climatological, hydrological, and other environmental records now used for calibration can be averaged over space and time, or treated in some other fashion which facilitates and improves the climatic calibration.

New and improved statistical procedures will undoubtedly become available, as well as new climatological methods for attacking problems of climatic variation. Work has hardly begun on estimating future probabilities of climate or on attempts to forecast future climate. While

leadership in many of these tasks will come directly from climatologists, the dendrochronologist should be an important part of this effort because of his excellent position to utilize tree-ring data to obtain the "long" view of past climatic variations.

The primary task for the dendroclimatologist in the future will be the extension of the tree-ring record backward in time, the utilization of new species, the sampling of trees in new regions of the world, and the development of new techniques of analysis. The International Tree-Ring Data Bank which is now operational at the Laboratory of Tree-Ring Research, University of Arizona, will hopefully provide long-term archival storage as well as quick retrieval of ring measurements and the chronologies derived from them. Although the present focus of the data bank is upon ring-width measurements usable for climatic reconstructions, the designed system is sufficiently flexible to allow for storage and retrieval of all types of tree-ring materials, including those usable only for dating or for study of environmental problems not necessarily involving climate.

It is hoped that the principles and procedures described in this book will have acquainted the reader with the variety of opportunities and techniques of the field and will stimulate his research in directions unimagined at present. Tree rings offer a rather remarkable record of those past conditions affecting tree growth. It is now up to the dendroclimatologist to skillfully use the many tools at his disposal, to extract that information, and to apply it to the many problems concerned with variations in the natural and man-affected environment.

Appendix

Scientific and Common Names of Trees

Scientific Names	*Common Names*
Abies Mill.	fir
Abies amabilis (Dougl.) Forbes	Pacific silver fir
Abies concolor (Gord. and Glend.) Lindl.	white fir
Abies lasiocarpa (Hook.) Nutt.	subalpine fir
Abies magnifica A. Murr.	red fir
Abies procera Rehd.	noble fir
Acer L.	maple
Acer rubrum L.	red maple
Acer saccharum Marsh.	sugar maple
Agathis R. A. Salisbury	kauri
Alnus B. Ehrh.	alder
Amelanchier Med.	serviceberry
Araucaria A. L. Jussieu	araucaria, monkey puzzle
Artemisia L.	sagebrush
Artemisia tridentata Nutt.	big sagebrush
Austrocedrus chilensis D. Don Florin et Boutelje	ciprés, southern incense cedar (South America) [was *Libocedrus chilensis* (D. Don) Endl.]
Betula L.	birch
Carya Nutt.	hickory
Cedrus Trew	true cedar
Celtis L.	hackberry
Cercocarpus H. B. K.	mountain-mahogany
Cornus L.	dogwood
Cupressus L.	cypress
Cupressus arizona Greene	Arizona cypress
Ephedra L.	Mormon tea
Fagus L.	beech
Fagus grandifolia Ehrh.	American beech
Fagus silvatica L.	European beech
Fitzroya cupressoides (Mol.) Johnst.	àlerce
Fraxinus L.	ash
Fraxinus americana L.	white ash
Juniperus L.	juniper, cedar

Juniperus communis L.	common juniper
Juniperus occidentalis Hook	Western juniper
Juniperus osteosperma (Torr.) Little	Utah juniper
Juniperus virginiana L.	Eastern red cedar
Larix Mill.	larch
Larix decidua Mill.	European larch
Larix occidentalis Nutt.	Western larch, tamarack
Libocedrus Endl.	incense cedar
Liquidambar styraciflua L.	sweetgum
Liriodendron L.	yellow poplar, tuliptree
Opuntia Mill.	prickly pear, cholla cactus
Picea A. Dietr.	spruce
Picea abies (L.) Karst.	Norway spruce
Picea excelsa Link	[same as *Picea abies*]
Picea glauca (Moench) Voss	white spruce
Picea rubens Sarg.	red spruce
Picea sitchensis (Bong.) Carr.	Sitka spruce
Pinus L.	pine
Pinus aristata Engelm.	Rocky Mountain bristlecone pine
Pinus banksiana Lamb.	Jack pine
Pinus cembra L.	Swiss stone pine
Pinus cembroides Zucc.	Mexican pinyon pine
Pinus contorta Dougl.	lodgepole pine
Pinus echinata Mill.	shortleaf pine
Pinus edulis Engelm.	pinyon
Pinus excelsa	[same as *Picea abies*]
Pinus flexilis James.	limber pine
Pinus halepensis Mill.	Aleppo pine
Pinus jeffreyi Grev. and Balf.	Jeffrey pine
Pinus longaeva D. K. Bailey	Great Basin bristlecone pine
Pinus monophylla Torr. and Frém.	singleleaf pinyon
Pinus monticola Dougl.	Western white pine
Pinus ponderosa Laws.	ponderosa pine, western yellow pine
Pinus radiata D. Don	Monterey pine
Pinus resinosa Ait.	red pine
Pinus strobus L.	Eastern white pine
Pinus sylvestris L.	Scotch pine, Scots pine
Pinus taeda L.	loblolly pine
Pistacia L.	pistachio
Podocarpus L'Héritier ex Persoon	podocarpus
Populus L.	poplar
Populus deltoides Bartr.	Eastern cottonwood
Populus tremuloides Michx.	quaking aspen
Pseudotsuga Carr.	Douglas-fir
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir
Purshia D. C.	antelope brush, bitterbrush
Quercus L.	oak
Quercus alba L.	white oak
Quercus coccinea Muenchh.	scarlet oak
Quercus ellipsoidalis E. J. Hill	Northern pine oak

Quercus prinus L.	chestnut oak
Quercus robur L.	English oak
Quercus rubrâ L.	red oak, eastern red oak, northern red oak
Sequoia Endl.	sequoia
Sequoia gigantea (Lindl.) Decne.	[same as *Sequoiadendron giganteum*]
Sequoiadendron giganteum (Lindl.) Büchholz	giant sequoia
Sequoia sempervirens Endl.	coast redwood
Taxodium L. C. Rich	bald cypress
Thuja L.	arborvitae
Tsuga Carr.	hemlock
Tsuga canadensis (L.) Carr.	Eastern hemlock
Tsuga heterophylla Sarg.	Western hemlock
Tsuga mertensiana (Bong.) Carr.	mountain hemlock
Ulmus L.	elm
Zygophyllum L.	bean caper

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Glossary

ABSCISE. Separate by formation of a specialized tissue which forms a line of weakness.

ABSORPTIVITY. With reference to the energy balance (q.v.), the capacity of a plant to absorb radiant energy.

ACROPETAL. Direction from the midportions of a plant toward the apex. In the case of a stem, from the ground level toward the stem tip. Opposite of basipetal. (q.v.).

ACTIVE ABSORPTION. See *active transport*.

ACTIVE TRANSPORT. The movement of minerals or ions through cell membranes against a free energy gradient (q.v.) by the expenditure of metabolic energy, resulting in the accumulation of salts such as occurs in roots. Cf. *diffusion*.

ADENOSINE TRIPHOSPHATE (ATP). In living cells, a high-energy coenzyme (q.v.) which acts as a carrier of chemical energy.

AEROBIC RESPIRATION. Respiration which utilizes free oxygen and food, such as glucose, and releases energy, carbon dioxide, and water. Cf. *anaerobic respiration*.

A HORIZON. In soils, the top mineral horizon in which eluviation (q.v.) occurs. Cf. *B horizon*.

AIR MASS. A large body of air which is relatively homogeneous in temperature and moisture content.

ALBEDO. Reflectivity of a surface when viewed from above.

ALDEHYDES. Highly reactive organic compounds characterized by a specific bonding configuration of hydrogen and oxygen units.

AMPLITUDE, ECOLOGICAL. See *ecological amplitude*.

AMPLITUDES OF EIGENVECTORS. The products of eigenvectors (q.v.) and the data from which the eigenvectors were derived expressing the importance of each eigenvector in each observation set. Also referred to as *factor scores*.

AMYLASE. A plant enzyme which catalyzes the condensation - hydrolysis reaction (q.v.) involving starch and glucose.

ANAEROBIC RESPIRATION. Respiration (q.v.) which occurs in living cells in the absence of free oxygen, involving changes in chemical bonding, the formation of intermediate organic molecules, and the release of carbon dioxide. Cf. *aerobic respiration*.

ANALYSIS OF VARIANCE. A statistical procedure for measuring the variation attributable to different sources.

ANGIOSPERM. The flowering seed plants, as differentiated from gymnosperms, the nonflowering seed plants.

ANTIAUXIN. A growth regulator or hormone which inhibits the action of auxins (q.v.) and thereby inhibits cell enlargement.

ANTICYCLONE. A high pressure system in the atmosphere characterized by dry descending air and clear weather. Cf. *cyclone*.

APEX. The tip or pointed end of an organ or plant part, such as the tip of a root, shoot, leaf, or bud.

APICAL DOMINANCE. Inhibition of lateral bud growth by vigorously growing apices of a plant, usually attributed to hormones produced by the growing tissues.

APICAL MERISTEM. The tissue at the tips of stems and roots composed of small, thin-walled cells which are capable of dividing and differentiating into the various tissues of the stem and root.

ASSIMILATION. The utilization of carbohydrates, fats, and proteins to synthesize the protoplasm, cell walls, and numerous other substances making up the enzyme systems, pigments, and structures of an organism.

ATP. Adenosine triphosphate (q.v.).

AUTOCORRELATION COEFFICIENT. A statistic describing serial dependence or association in a time series with previous conditions or states. See *serial correlation*.

AUTOCORRELATION FUNCTION. The result of computing the autocorrelation coefficients (q.v.) from one to a prescribed number of lags and then plotting these coefficients as a function of lag.

AUTOREGRESSION. A regression (q.v.) in which one value in a time series is regressed upon one or more variables which precede it in time.

AUXIN. A plant growth regulator or hormone which is responsible for cell enlargement.

AVERAGE. Mean (q.v.).

BAR. Unit of atmospheric pressure equal to 1,000,000 dynes per square centimeter (about 14·50 pounds per square inch).

BASIPETAL. Direction from the apex toward the midportions. In the case of a stem, from stem tips toward the ground level. Opposite of acropetal. (q.v.).

B HORIZON. In soils, a mineral horizon below the A horizon (q.v.) in which illuviation (q.v.) occurs.

BOLE. The trunk or stem of a tree.

BORDERED PITS. In conifers, specialized thin areas in the walls of tracheids (q.v.) surrounded by a raised lip.

BUTTRESS ROOT. A root which has elongated vertically, been exposed to the atmosphere, and taken on some of the characteristics of a stem.

C-3 PLANTS. Plants which carry on respiration which involves light energy.

C-4 PLANTS. Plants which carry on respiration which is not affected by light.

CALIBRATION. In dendroclimatology, the process of obtaining a transfer function (q.v.) or response function (q.v.) which can be used to estimate one or more predictand (q.v.) variables from a set of predictors (q.v.).

CAMBIAL INITIALS. The nonvacuolated cells within the cambium from which all elements of the radial file (q.v.) are derived by cell division.

CAMBIUM. A thin layer of meristematic cells (q.v.) such as the vascular cambium (q.v.) and the cork cambium (q.v.) formed in stems and roots.

CANONICAL ANALYSIS. A multivariate statistical technique which includes both canonical correlation (q.v.) and canonical regression (q.v.).

CANONICAL CORRELATION. A statistical technique designed to specify orthogonal (q.v.) modes of intercorrelation between two sets of variables.

CANONICAL REGRESSION. Determination of a set of regression coefficients from a canonical correlation (q.v.) which are used to estimate values of one set of variables from values of another. Cf. *regression*.

CARBON ASSIMILATION. Photosynthesis (q.v.).

CASPARIAN STRIP. A layer of suberin (q.v.) deposited on the radial and horizontally oriented walls of the endodermis which is impervious to the movement of water along the cell wall.

CELL SAP. The solution of water and dissolved substances found in the vacuoles (q.v.) of living cells.

CELLULOSE. The primary framework substance in a plant cell wall.

CHINOOK. See *foehn wind*.

CHLORENCHYMA. Green chlorophyll-containing tissues found in plants.

CHLOROPHYLL. The green pigment in plant cells which is necessary for the trapping of light energy used in the process of photosynthesis (q.v.)

CHLOROPLASTS. Chlorophyll-containing bodies within the cytoplasm (q.v.) of chlorenchyma (q.v.) cells.

C HORIZON. In soils, the lowermost horizon which includes undifferentiated parent material (q.v.).

CHRONOLOGY. Ring-width chronology (q.v.).

CHRONOLOGY BUILDING. The dating and processing of ring widths in many trees from a given region or site to produce long homogeneous ring-width chronologies used for crossdating and for deducing past climate.

CLIMATE. The aggregate of weather, including all of meteorological phenomena occurring over a relatively long period of time. Cf. *weather*.

CLIMATE SYSTEM. The properties and processes that are responsible for climate and its variations. The *properties* are classified as thermal, kinetic, aqueous, and static, while the *processes* include precipitation, evaporation, radiation, and the transfer of heat, mass, and momentum.

CLIMATIC STATE. The average, variability, and other statistics of climatic variables over a specified period of time in a specified domain of the earth–atmosphere system.

CLIMATOGRAPHY. The mapping of climatic patterns. Cf. *dendroclimatography* and *synoptic climatology*.

COEFFICIENT. In an equation, a constant number by which a variable is multiplied.

COENZYME. A substance whose presence is necessary for the activity of an enzyme.

COHERENCY. An estimate of association between two time series (analogous to the square of the correlation coefficient [q.v.]) expressed as a function of frequency. Also called *coherence*.

COLLOID. A suspension of molecule aggregates (such as cytoplasm [q.v.]) which is made up of particles that cannot readily diffuse through membranes (q.v.).

COMPANION CELL. A small specialized cell in the phloem associated with a large, thin-walled sieve tube and containing its nucleus.

COMPLACENT. A dendrochronological term referring to the lack of ring-width variability, which indicates that the growth of a particular tree is relatively unaffected by variations in climate.

COMPONENT VARIANCES. In analysis of variance (q.v.), the estimates of variances attributable to and partitioned into each source of variation.

COMPRESSION WOOD. The name given reaction wood (q.v.) which in coniferous species occurs on the lower side of the leaning stems and lateral branches. Cf. *tension wood*.

CONCENTRATION. The relative number of molecules of a given substance per unit of volume or weight.

CONDENSATION. The plant process in which molecules of soluble substances such as glucose combine with one another in the presence of an enzyme to form water and

insoluble and chemically more complex substances such as starch; the reverse of hydrolysis (q.v.).

CONDENSATION–HYDROLYSIS REACTION. A class of reversible chemical reactions usually involving a change in solubility of the reactants but no change in their chemically bound energy. See also *condensation* and *hydrolysis*.

CONIFERS. The cone-bearing gymnosperms (q.v.)

CORK CAMBIUM. A thin cylinder of meristematic tissue in the outer bark which produces the cork. As the girth of the stem increases and the outer bark exfoliates, new cork cambia differentiate from beneath the younger tissue inside the bark.

CORRELATION. Association of two variables without implying the presence or the direction of dependence. Cf. *regression* and *coupling*.

CORRELATION COEFFICIENT. A statistic which expresses the amount of interdependence or association between two data sets. It ranges in values from $+1$, which indicates perfect and direct association, to -1, which indicates perfect and inverse association. A value of 0 indicates a complete lack of interdependence.

CORTEX. Parenchyma (q.v.) tissue found in young stems and roots which lies outside the vascular tissues and inside the epidermis.

COUPLING. The degree of cause-and-effect linkage between elements of a system, that is, the influence which one phenomenon has upon another. Cf. *correlation*.

CROSSDATING. The procedure of matching ring-width variations and other structural characteristics among trees that have grown in nearby areas, allowing the identification of the exact year in which each ring was formed.

CROSS POWER SPECTRUM ANALYSIS. A means of studying covariance between two time series expressed as a function of frequency. Cf. *power spectrum analysis* and *coherency*.

CUTICLE. A layer of wax formed on the external surface of the epidermis in many plants.

CUTIN. A water repellant waxy substance that forms the chief ingredient of the cuticle (q.v.). Cf. *suberin*.

CYCLONE. A storm or low pressure system carried in the general circulation of the atmosphere and characterized by counterclockwise motion (in the Northern Hemisphere) and by ascending air. Cf. *anticyclone*.

CYTOPLASM. In plants, the protoplasm of the cell exclusive of the nucleus, bounded by the cell wall on the outside and usually by a vacuole on the inside. It may include membranes (q.v.), plastids (q.v.), and a variety of other bodies.

DECIDUOUS. Foliage-shedding, as opposed to evergreen.

DEDUCTION. A conclusion drawn by reasoning from facts or premises, often involving a series of inferences (q.v.)

DEGREES OF FREEDOM. A statistical term referring to the number of items in a sample that can vary independently of one another.

DENDROCHRONOLOGY. The science that deals with the dating and study of annual growth layers in wood.

DENDROCLIMATOGRAPHY. A subfield of dendrochronology (q.v.) which utilizes dated tree rings to reconstruct and map the spatial variations in climate.

DENDROCLIMATOLOGY. A subfield of dendrochronology (q.v.) which utilizes dated tree rings to reconstruct and study past and present climate.

DENDROECOLOGY. A subfield of dendrochronology (q.v.) which utilizes dated tree rings to study ecological problems and the environment.

DENDROGEOMORPHOLOGY. A subfield of dendrochronology (q.v.) which utilizes dated tree rings to study land forms and geomorphic processes.

DENDROGRAPH. An instrument that continuously records size changes in stems of trees. Cf. *dendrometer*.

DENDROHYDROLOGY. A subfield of dendrochronology (q.v.) which utilizes dated tree rings to study hydrologic problems, such as river flow and flooding history.

DENDROMETER. An instrument that is used to measure the size of tree stems. Cf. *dendrograph*.

DEPENDENT DATA. Data used to obtain a calibration (q.v.).

DEWPOINT. Temperature of the air when water begins to condense.

DIAGONAL MATRIX. A square matrix (q.v.) with values along the main diagonal, and zeros on the off-diagonal elements (q.v.).

DIFFERENTIALLY PERMEABLE MEMBRANE. A membrane which varies in its permeability to various molecules and can therefore regulate the relative movement of substances within a plant.

DIFFERENTIATION. The process by which the young growing cells take on the characteristics of the tissue of which they will become a part. Also referred to as *maturation*.

DIFFUSE-POROUS WOODS. Certain angiosperms (q.v.), such as *Fagus*, *Acer*, and *Liriodendron*, in which vessels are of approximately the same diameter throughout the earlywood and latewood portions of the ring, as differentiated from ring-porous (q.v.) angiosperms.

DIFFUSION. The net movement of molecules (or ions) of a given substance from a region of high free energy (q.v.) of that substance to a region of low free energy of that substance. Cf. *mass movement*.

DIGESTION. Hydrolysis (q.v.).

DORMANCY. A condition within plants which prevents growth from occurring even though other physiological processes are active and environmental conditions are favorable. Dormancy may be classified as *temporary* (lasting a few days or a few weeks) or *permanent* (lasting for periods of many weeks or months).

DOUBLE-MASS ANALYSIS. A means of comparing several precipitation records to identify inhomogeneities due to station relocations and other causes.

EARLYWOOD. The wood produced in the annual ring during the early part of the growing season, characterized by large thin-walled cells. Earlywood is more porous than latewood (q.v.) and often lighter in color. Sometimes referred to as *springwood*.

ECOLOGICAL AMPLITUDE. The range of habitats over which a species may grow and reproduce.

ECOTYPE. A genetic variation within a species caused by isolation and environmental selection.

EFFECTIVE SAMPLE SIZE. The number of items in a time series which are independent of each other.

EIGENVALUES. A set of scalars or coefficients (q.v.) which are proportional to the amount of variance reduced by each eigenvector (principal component [q.v.]).

EIGENVECTORS. A set of orthogonal (q.v.) variables which are transformations representing the modes of uncorrelated behavior of a data set. There can be as many eigenvectors as there are variables in the original data set, but the transformations can be ranked from the most important ones which account for a large portion of the variance in the original data, and the least important ones which express only minor variations and orthogonality constraints in the original data. By discarding the smaller unimportant eigenvectors, it is possible to reduce

the number of variables in a system. Also referred to as *principal components*. Cf. *amplitudes of eigenvectors*.

ELEMENT. In regard to a matrix (q.v.), the individual value of datum defined as being located in a particular row and column of a matrix.

ELUVIATION. In soils, the leaching or loss of minerals from a soil horizon (q.v.). Cf. *illuviation*.

EMISSIVITY. In plants, the ability to emit radiation.

ENDODERMIS. A sheath of cells most commonly occurring inside the cortex of roots but outside the vascular tissue of xylem and phloem, often with radially and horizontally oriented walls impregnated with suberin (q.v.) which form a layer referred to as the *casparian strip*.

ENERGY BALANCE. The disposition of energy within a given system such as a column of soil and the atmosphere above it, determined by rates of inflow and outflow, sources and sinks, and transformations of energy.

ENVIRONMENT. A general term which includes all phenomena affecting or impinging on an organism. Cf. *operational environment* and *potential environment*.

ENVIRONMENTAL FACTORS. The specific phenomena which are entering into an operational relationship with an organism at a given time. Cf. *operational environment* and *potential environment*.

EPIDERMIS. In plants, the single-cell tissue originating from the meristem which forms the outside layer covering leaves, young stems, young roots, flowers, and young fruits. As the young stem enlarges, the epidermis ruptures and is replaced by the cork produced in the bark.

EQUALLY PROBABLE CLASSES. Groups chosen so that each one has an equal likelihood of occurring.

ESTIMATES. The numerical solutions of a statistical regression equation in which the values of the predictors (q.v.) representing the statistical input of the system have been substituted into the equation to obtain values (the estimates) of the predictand (q.v.). These are compared to actual values of the predictand to evaluate the degree of calibration that has been obtained.

EVAPOTRANSPIRATION. The loss of water due to both evaporation from soil and transpiration (q.v.).

EXPLAINED VARIANCE. Variance reduced (q.v.).

EXPONENTIAL FUNCTION. A nonlinear mathematical relationship in which one variable changes as a function of a second variable which is an exponent term associated with a constant.

FACTOR SCORES. Amplitudes (q.v.).

FALSE RING. A change in cell structure within an annual growth layer which resembles the boundary of a true annual ring, making it appear to be two or more growth layers instead of one. Also referred to as *intra-annual growth band*.

FASCICLE. A small number or bundle such as the bundles of needles in many *Pinus* species.

FIBERS. In angiosperms, elongated and relatively narrow cells with thick walls.

FIELD CAPACITY. The amount of moisture held in a particular soil which has been thoroughly wetted and then allowed to drain for several days until the rate of drainage has become very slow.

FILTERS. As used in this text, a set of numerical weights which are applied to a time series to emphasize variations at certain frequencies. When only the long-term or low-frequency variations are retained the weights are referred to as a *low-pass filter*. When only the short-term or high-frequency variations are retained, the weights are referred to as a *high-pass filter*.

FIRST DIFFERENCES. The sequence of values from a time series obtained by subtracting the value of each item in a time series from its immediate successor.

FIRST-ORDER AUTOCORRELATION. The statistical association (correlation [q.v.]) of each value in a time series with the value of its immediate predecessor.

FOEHN WIND. A warm dry wind blowing down the side of a mountain. Same as *chinook*.

FOOD. As used in this text, food refers only to organic molecules classed as carbohydrates, fats, or proteins which contain chemically bound energy that can be released by oxidation (q.v.).

FREE ENERGY. As in diffusion (q.v.), the molecular energy capable of doing work involving concentration (the relative number of molecules for a substance) and the molecular activity (kinetic energy).

FREE ENERGY GRADIENT. The ratio of the difference in free energy of a given substance between two points and the distance between these points, governing the rate of diffusion. Cf. *diffusion*.

FRONT A narrow zone of discontinuity between two air masses (q.v.) of different character.

FROST RING. Distorted xylem tissue damaged by freezing in the growing season during which the cells of the tissue were being formed.

FUSIFORM INITIALS. Elongated, spindle-shaped cells which make up approximately 90% of the cambium (q.v.) and which give rise to the longitudinally arranged cells in the xylem and phloem. Growth in the stem in a radial direction occurs by division of the fusiform initials throughout the entire length of the cell and by formation of the new wall along a tangential plan.

GENERATING PROCESS. The manner in which a time series (q.v.) such as ring width is generated by the growth-controlling factors; sometimes represented by a mathematical function.

GENOTYPE. Hereditary potential controlled by genes. Cf. *phenotype*.

GIBBERELLIN. A plant growth regulator or hormone which affects stem elongation.

GOODNESS OF FIT. The closeness of statistical estimates to the actual predictand data. Cf. *variance reduced*.

GRAND PERIOD OF GROWTH. The interval within the growing season when growth occurs most rapidly, excluding the period of increasing growth rate at the beginning of the season and the period of decreasing growth rate at the end of the season.

GRAVITATIONAL WATER. Water within a soil in excess of field capacity (q.v.) which percolates downward due to the pull of gravity.

GROSS PHOTOSYNTHESIS. The total amount of glucose formed or carbon dioxide utilized in photosynthesis without regard to the glucose utilized and carbon dioxide released by respiration. Cf. *net photosynthesis*.

GROWTH REGULATORS. Organic compounds produced in small amounts which promote, inhibit, or qualitatively modify growth of plants. Types of hormones (q.v.).

GUARD CELLS. Two cells which surround each stomate (q.v.), causing it to open or close. Walls of the guard cells are thicker near the pore opening than on the side away from the pore, and the two cells arch away from each other as the volume of the guard cells increases, opening the pore.

GUTTATION. The discharging or exudation of water droplets from turgid leaves.

GYMNOSPERM. The nonflowering seed plants, as differentiated from angiosperms, the flowering seed plants.

HEARTWOOD. The darker colored central portion of a stem in which the wood rays (q.v.) are dead, as differentiated from the lighter colored sapwood.

HEMICELLULOSE. An important carbohydrate constituent of xylem cell walls.

HIGH-FREQUENCY VARIANCE. In this text, all variations in ring width that are of shorter duration than eight years (representing cycles and other variations with wavelengths or durations of eight years or less). Cf. *low-frequency variance*.

HIGH-PASS FILTER. See *filters*.

HORMONES. A class of organic compounds produced in small amounts which promote, inhibit, or qualitatively modify growth, development, and life activities of plants. Cf. *growth regulators*.

HYDROLYSIS. The plant process in which relatively complex insoluble substances are converted to smaller soluble ones in the presence of enzymes, as in the conversion of starch to glucose; the reverse of the process of condensation (q.v.).

HYDROSTATIC. Relating to the pressure from overlying or confined liquids.

HYPOTHESIS. An inference (q.v.) to be tested.

ILLUVIATION. In soils, the accumulation of minerals in a soil horizon (q.v.). Cf. *eluviation*.

INCREMENT CORER. A field tool used to bore and extract a thin cylinder of wood from tree stems.

INDEPENDENT DATA. Data not used for calibration (q.v.) which can be used as verification of reconstructions. Verification is established when the estimates from the independent predictor (q.v.) set resemble the predictands (q.v.) of the independent data set.

INFERENCE. A generalization derived from given information usually including a number of facts.

INHIBITOR. A growth regulator or hormone which reduces or stops growth and can induce either temporary or permanent dormancy.

INTERACTION. The influence of a factor upon the effect of another which differs from the individual or mean effects of the two factors.

INTRA-ANNUAL GROWTH BAND. False ring (q.v.).

ION. An electrically charged atom or group of atoms.

JUVENILE WOOD. Relatively thin-walled lignified xylem tissue which is low in density and is formed in young trees or in tissues located near the stem apex.

KININ. A growth regulator or hormone which promotes cell division.

KRUMMHOLZ. Gnarled and stunted trees which grow in exposed sites usually near the upper elevational tree line.

LAPSE RATE. The rate of change of air temperature per unit increase in altitude.

LATENT HEAT. The heat absorbed when water evaporates.

LATEWOOD. Dense and often dark wood produced in the annual ring during the later part of the growing season, characterized by small, thick-walled cells. Also referred to as *summerwood*. Cf. *earlywood*.

LEAST SQUARES. A numerical method for fitting a function, such as a straight line, to a set of data in such a way that the sum of squares of the residuals (q.v.) is minimized.

LENTICELS. Ruptures in the bark of a stem through which substances such as water vapor, oxygen, and carbon dioxide can move.

LIGNIN. A material added to the thickening walls of living xylem cells after cell enlargement has ceased, which gives wood its hardness and increases its density.

LOCALLY ABSENT RING. A growth ring which is discontinuous around the stem so that it is absent along certain radii; also referred to as *partial* or *missing ring*.

LOW-FREQUENCY VARIANCE. In this text, all variations in ring width that last longer than eight years (represented by cycles and other variations with

wavelengths or durations greater than eight years). Cf. *trend* and *high-frequency variance*.

LOW-PASS FILTER. See *filters*.

MACROCLIMATE. The aggregate of climatic conditions for a region, often based upon 30 or more years of observation. Cf. *microclimate*.

MASS MOVEMENT. The transfer of molecules or particles by flow from one place to another driven by application of some external force, as opposed to diffusion (q.v.).

MATRIX. An array of data ordered in rows and columns. Cf. *element*.

MATRIX POTENTIAL (Ψm). The water potential forces attributed to surface phenomena; as opposed to osmotic potential (q.v.) and pressure potential (q.v.).

MATURATION. Differentiation (q.v.)

MEAN. The average; the value that is closest to all values in a data set.

MEAN SENSITIVITY. A statistic measuring the mean relative change between adjacent ring widths; that is, the average relative difference from one ring width to the next. Cf. *sensitivity*.

MEAN STANDARDIZED INDICES. Ring-width chronology (q.v.).

MEMBRANE. A thin layer lying along the outer limits of living protoplasm (inside the cell walls) and along various other boundaries, such as between protoplasm and vacuole. It may vary in its permeability to different molecules. Cf. *differentially permeable membrane*.

MERISTEM. A plant tissue composed of small thin-walled cells that are capable of dividing. Meristematic tissue is found in all buds, root tips, and growing regions including the cambia. Cf. *apical meristem*.

MESOPHYLL. In plants, all cells located between the upper and lower epidermis of a leaf.

MICROCLIMATE. The aggregate of meteorological conditions within a localized site occurring over a period of time. Cf. *macroclimate*.

MICROENVIRONMENT. A localized environment such as that surrounding a leaf, bud, or root.

MICROMETEOROLOGY. The meteorological conditions of a localized site or the study thereof. Cf. *microclimate*.

MIDDLE LAMELLA. A cementing layer between cell walls in plants.

MISSING RING. Locally absent ring (q.v.) or partial ring.

MODEL. A statement, equation, or diagram which represents a basic set of facts and their interrelationships. They can range from extremely simple preconceived notions to highly complex systems.

MOTHER CELL. A derivative of the initial cell of a cambium that can still divide.

MOVING AVERAGES. Averages of overlapping segments of a time series usually calculated at regular intervals in the time sequence. Also referred to as *running means*.

MULTINODAL. Having the capacity to produce several series of leaves during one season's growth, as occurs in *Pinus halepensis*, *P. echinata*, and *P. taeda*.

MULTIPLE CORRELATION. The correlation coefficient calculated from a multiple regression (q.v.) relationship.

MULTIPLE REGRESSION. A regression (q.v.) involving more than one predictor variable. The multiple regression coefficients describe the relative effect of each predictor (q.v.) variable upon the predictand (q.v.), adjusting for the intercorrelations between the predictor variables.

NET PHOTOSYNTHESIS. Gross photosynthesis (q.v.) minus respiration (q.v.),

expressing the net increase in glucose and the net utilization of carbon dioxide.

NOISE. In this text, the random, residual (q.v.), or background variation in a time series that cannot be attributed to a detectable quality, pattern, or variation, as opposed to signal (q.v.), which represents meaningful information such as the ring-width variations attributed to climate, environment, or biological conditions.

NORMAL DISTRIBUTION. A bell-shaped distribution of data which closely resembles the normal density function with the mean value corresponding to the point at which the distribution function is a maximum and with approximately two-thirds of the data within a distance of one standard deviation (q.v.) on each side of the mean (q.v.).

NORMALIZED DATA. Standard normal variates (q.v.).

NUTRIENT. In a botanical context, mineral salts which are essential in small amounts for the normal growth and survival of the plant. They are not considered foods in this text, because they are not a significant source of energy.

NUCLEUS. The dense portion of the protoplasm which contains the hereditary material.

OPERATIONAL ENVIRONMENT. The environmental phenomena which are actually entering into a relationship with an organism at a particular time. The specific phenomena which enter such operational relationships are considered environmental factors (q.v.).

OROGRAPHIC. Relating to mountains or elevational relief.

ORTHOGONAL. Uncorrelated, independent of one another.

OSMOSIS. Diffusion (q.v.) of water through a differentially peremable membrane (q.v.). The process by which water moves into and out the living protoplasm of cells.

OSMOTIC POTENTIAL (Ψs) The water potential (q.v.) forces which are due only to substances dissolved in the water.

OXIDATION. A class of chemical reactions which releases energy stored in food molecules; the reverse of reduction (q.v.) in which molecules increase in energy.

OXIDATION–REDUCTION REACTION. A general class of chemical reactions in which there is a change in energy.

PARAMETER. A particular variable or constant.

PARENCHYMA. A plant tissue made up of living thin-walled, and vacuolated cells.

PARENT MATERIAL. In soils, the undifferentiated weathered rock material from which a soil develops.

PARTIAL RING. Locally absent (q.v.) or missing ring.

PERMANENT WILTING POINT. The moisture content of a drying soil at the time plants first become permanently wilted, including moisture that is generally unavailable to the plant.

PHELLEM. The technical term for cork cells which are differentiated from the cork cambium and are impregnated with suberin (q.v..

PHENOLOGY. The changing appearance or condition of an organism, often associated with its yearly cycle, such as the breaking of dormancy, beginning of growth, enlargement, flowering, fruiting, and onset of dormancy.

PHENOTYPE. Observable characteristics of an organism that result from its heredity. Cf. *genotype*.

PHLOEM. In trees, the region containing food-conducting tissue in the bark.

PHOTOPERIOD. The length of day or period of illumination, which can influence certain phenological conditions such as flowering and dormancy in plants.

PHOTO RESPIRATION. Respiration pathway involving light energy. Occurs in C-3 plants.

PHOTOSYNTHATE. Glucose, the food product of photosynthesis, sometimes including certain chemically altered fragments of glucose.

PHOTOSYNTHESIS. The process by which sugar (glucose) is manufactured from carbon dioxide and water by the chlorophyll-containing tissues (chlorenchyma of plants in the presence of light, and oxygen is released as a by-product. Also referred to as *carbon assimilation.*

PHYSIOLOGICAL PRECONDITIONING. The induction of internal metabolic conditions which can influence the biochemical reactions and other processes of a plant during later stages in its life cycle.

PHYSIOLOGICAL SEASONS. In plants, periods of varying physiological activity during the year, usually determined by the climatic regime which preconditions and governs the processes, conditions, and structures of the plant.

PITH. In plants, the soft, thin-walled tissue at the center of the stem made up of parenchyma with unlignified cell walls.

PLASTIDS. Specialized bodies such as the chloroplasts (q.v.) contained in the cytoplasm (q.v.) of a cell.

POLYSACCHARIDES. A carbohydrate made up of several sugar molecules, a substance produced early in the development of the cell wall matrix of plants.

POTENTIAL ENVIRONMENT. Environmental phenomena which are capable of entering into a reaction with an organism but have not yet done so. Cf. *operational environment.*

POWER SPECTRUM ANALYSIS. A technique for studying the distribution of variance in a time series as a function of frequency.

PREDICTAND. In stastistics, the variable or variables of a system which are predicted (estimated, reconstructed). Cf. *predictor.*

PREDICTION. Estimates of conditions or data, not necessarily made for the future or forward in time. Cf. *reconstruction* and *retrodiction.*

PREDICTOR. In statistics, the input variable or variables of a system, values of which are used to obtain prediction (estimates, reconstructions) of the predictands (q.v.).

PRESSURE POTENTIAL (Ψp). The positive water potential forces attributed to pressure exerted on a cell wall which results in cell turgor.

PRINCIPAL COMPONENTS. Eigenvectors (q.v.)

PRINCIPLE. A general truth or essential nature of a phenomenon ascertained from experience and usually including one or more inferences (q.v.).

PRODUCT MEAN. A statistic useful for verification with independent data which takes into account both the sign and magnitude of the departure from the calibration mean; computed from the product of the departures of actual and estimated values from the mean value, with positive and negative products averaged separately.

PROTOPLASM. The viscous colloidal substance making up the living portion of the cell including the cytoplasm (q.v.) and nucleus (q.v.). The protoplasm is surrounded by a differentially permeable plasma membrane and, in plants, by a more or less rigid cell wall.

PROXY. In this text, a substitute record.

RADIAL FILE. A row or tier of cells such as the tracheids which arise from the division of a single cambial initial.

RAYS. Wood rays (q.v.).

RE Reduction of error (q.v.).

REACTION WOOD. Anomalous cells formed in the xylem of leaning stems and lateral

branches, often associated with an eccentric growth ring. In coniferous species, the reaction wood occurs on the lower side of the lean, and is referred to as *compression wood*; in angiosperm species it occurs on the upper side of the lean and is referred to as *tension wood*.

RECIPROCAL FILTERS. A pair of filters (q.v.) which have been designed to pass variance at opposite ends of the frequency range.

RECONSTRUCTION. As used in this text, statistical estimates or deductions of past conditions or events derived from various types of evidence, especially those from well-dated and replicated ring-width chronologies, Cf. *retrodiction* and *prediction*.

REDUCTION. A class of chemical reactions in which molecules gain chemical energy generally derived from ATP (q.v.); the reverse of oxidation (q.v.) in which molecules lose energy.

REDUCTION of ERROR (RE). A statistic useful for verification with independent data, having possible values ranging from $+1 \cdot 0$ to minus infinity. If it is applied to the dependent data set, the result is equivalent to the square of the correlation coefficient (q.v.) which measures the percent variance calibrated (q.v.) by the relationship.

REGRESSION. A general statistical term often represented by an equation which describes relationships where the values of one or more variables are expressed as a function of other variables. Cf. *correlation*.

RELEASE. In trees, a marked increase in growth due to removal of competitors. Cf. *suppression*.

REPRODUCTIVE BUDS. Buds that can produce stems with flowers, fruits, and seeds as well as leaves. Cf. *vegetative buds*.

REPRODUCTIVE ORGANS. In plants, the flowers, fruits, and seeds, as differentiated from the vegetative organs (q.v.).

RESIDUAL. The difference between an observation of actual data and an estimate (q.v.) obtained by applying a given function to the data set. The residuals represent the noise (q.v.) of the system and any signal not accounted for by the functional relationship. Cf. *least squares*.

RESIN DUCT Long, narrow, intercellular channels in conifers surrounded by parenchyma and filled with resin.

RESPIRATION. A series of biochemical reactions which release the chemical energy stored in food such as that in the glucose molecule. Cf. *aerobic respiration* and *anaerobic respiration*.

RESPONSE FUNCTION. In this text, a statistical calibration equation which expresses the separate relative effects of several climatic factors on ring width. Climatic factors often are average temperature and total precipitation during each month of a 14-month period prior to and concurrent with the period of growth. A weight is associated with each factor which describes how the tree "responds" to variations in that climatic factor. Cf. *transfer function*.

RETRODICTION. A term proposed for statistical estimations made backward in time, as opposed to the term *prediction* (q.v.) implying estimates made forward in time.

RIDGE. In the atmosphere, an elongated high pressure area which is commonly formed at altitudes of several kilometers above the earth's surface. Cf. *trough*.

RING-POROUS WOODS. Certain angiosperms (q.v.), such as *Ulmus, Fraxinus,* and *Quercus,* in which the vessels in the earlywood are markedly wider than those in the latewood, as differentiated from diffuse-porous (q.v.) angiosperms.

RING-WIDTH CHRONOLOGY The averaged standardized ring-width indices from a number of trees sampled from a particular site which can be used for crossdating and deducing past climate. Also called *mean standardized indices* and *chronology*.

RING-WIDTH INDICES. The transformed values of ring widths after standardization
(q.v.) which have a mean of 1·0 (or 100) and a variance that is relatively
homogeneous through time. Also referred to as *standardized ring-width chronology*.

ROOT CAP. A structure which covers the apical meristem (q.v.) of a root.

ROOT/SHOOT RATIO. The amount of roots relative to the amount of shoots.

RUNNING MEANS. Moving averages (q.v.)

SAPWOOD. The lighter colored outer water-conducting portion of the tree stem with
living ray tissue, as differentiated from the darker dead heartwood portion in the
center of the stem.

SENSIBLE HEAT. Heat added or lost when there is a temperature change.

SENSITIVITY. A dendrochronological term referring to the presence of ring-width
variability in the radial direction within a tree which indicates that the growth
response of the particular tree is "sensitive" to variations in climate. Opposite of
complacency (q.v.). Cf. *mean sensitivity*.

SERIAL CORRELATION. The correlation between successive values in a time series
(autocorrelation) or lagged correlation between two time series.

SIEVE TUBES. Large, nonwoody, thin-walled living phloem cells which are involved in
translocation of organic substances throughout a tree. Cf. *companion cells*.

SIGMOID CURVE. A cumulative curve of growth in the shape of a prostate *S*.

SIGNAL. In this text, a detectable quality, pattern, or variation in a time series such as
ring widths which can be attributed to meaningful information on climate,
environment, or biological conditions of the trees, as opposed to the background
variations or noise (q.v.) which provide no useful information about the trees and
their environment.

SIGN TEST. A count of agreement or disagreement between signs, plus or minus, for two
series of numbers and the statistical test used to determine whether the number of
agreements is significantly different from the number of disagreements.

SITE SELECTION. Selection of tree-ring samples from limiting sites to maximize the
information or signal contained in the rings and to minimize the undesirable
variations representing noise.

SOIL HORIZON. A more or less distinct layer in a soil profile (q.v.) characterized by its
morphological, physical, chemical, and mineralogical properties.

SOIL PROFILE. The vertical assemblage of soil horizons (q.v.) from the soil surface
down to the lowermost layer of undifferentiated unweathered material.

SOLUM, The portion of the soil represented by the A and B horizons (q.v.).

SPIKE TOP. The dead terminal branch of a tree, which may remain intact for many
years. A feature characteristic of some extremely old, stress-site trees.

SPRINGWOOD. Earlywood (q.v.).

STANDARD DEVIATION. The mean scatter of a population of numbers from the
population mean. The square root of the variance (q.v.). Cf. *normal distribution*.

STANDARD ERROR. An estimate of how much a particular statistic of a sampled
population, such as the mean, can vary from its "true" theoretical value based on
the entire population as represented by the statistical universe (q.v.).

STANDARD NORMAL VARIATES. A transformation converting a set of data to a
population with a mean of zero and a standard deviation of 1·0 obtained by
subtracting the mean and dividing by the standard deviation of the original data.
Also referred to as *normalized data*.

STANDARDIZATION. The removal of the effects of increasing tree age on ring widths
and their conversion to a time series of ring-width indices (q.v.) with a mean of 1·0
(or 100) and with a variance relatively homogeneous through time.

STANDARDIZED RING-WIDTH CHRONOLOGY. Ring-width indices (q.v.).

STATISTICAL UNIVERSE. A theoretical term referring to an entire population including all data, as opposed to the subset of that population represented by a sample. Since entire populations can rarely be measured, statistics derived from samples are used to estimate the theoretical values of entire populations. Cf. *standard error*.

STATISTICS. Any kind of numerical data, but most often applied to values used to describe characteristics of populations.

STOMATES. Microscopic holes in the epidermis of plants, through which diffusion (q.v.) of gasses such as water vapor, carbon dioxide, and oxygen occurs. Two cells called guard cells (q.v.) surround each stomate and govern its size.

SUBERIN. A fatty or waxy water-repellant substance which is usually found in the endodermis and cork. Cf. *cutin*.

SUMMERWOOD. Latewood (q.v.).

SUPPRESSION. In trees, a marked reduction in growth due to crowding or shading from neighboring trees. Cf. *release*.

SURROGATE. A substitute.

SYNOPTIC CLIMATOLOGY. A term applied to studies of climate in which the general circulation of the atmosphere must be considered over both space and time. Cf. *climatography*.

SYSTEM (NATURAL SYSTEM). A portion of the universe separated from its surroundings by recognizable boundaries and including one or more substances, any chemical reactions and interactions, as well as other processes affecting them.

TALUS SLOPE. A slope of disintegrated rock and earth material that accumulates at the base of cliffs and exposed rock surfaces.

TENSION WOOD. The name given to reaction wood (q.v.) which in angiosperm species occurs on the upper side of leaning stems and lateral branches. Cf. *compression wood*.

TEXTURE. In soils, the relative amounts of sand, silt, and clay.

TIME SERIES. A set of data representing a regular sequence of occurrences or events which are indexed as a function of time.

TRACHEIDS. In gymnosperms, dead, vertically oriented xylem cells with relatively thick lignified (q.v.) walls which may be perforated by bordered pits. (q.v.).

TRANSFER FUNCTION. A set of weights applied to ring-width index values to obtain estimates of climate. Growth records are "transferred" into reconstructions of climate. Cf. *response function*.

TRANSLOCATION. The long distance transport by mass movement (q.v.) of organic and inorganic substances in the phloem and xylem from one part of the plant to another, as contrasted with molecular diffusion (q.v.) of solutes and water from cell to cell.

TRANSMISSIVITY. The ability to transmit energy through a structure.

TRANSPIRATION. The loss of water by evaporation from the surfaces of all parts of the exposed plant, including leaves, stems, flowers, and fruits.

TREND. Extremely low-frequency variance (q.v.) with wavelengths which are greater than the length of the time series. Trend in a ring-width series results from such things as the changing growth potential of the tree due to increasing age, successional development in the forest community, geological changes, or very gradual changes in climate.

TROUGH. An elongated low pressure area which is commonly formed at altitudes several kilometers above the earth's surface. Cf. *ridge*.

TURGOR. The outward pressure exerted on the walls of living cells resulting from the

pressure potential developed within them.

UNINODAL. Producing only one series of leaves each year as occurs in many *Pinus* species. Cf. *multinodal*.

VACUOLE. The central portion of a living cell containing water and dissolved substances referred to as cell sap (q.v.).

VAPOR PRESSURE DEFICIT. The difference between the actual vapor pressure of the air and the vapor pressure of an atmosphere at the same temperature that is saturated with water.

VARIABLE. In this text, a characteristic, feature, or factor which can assume different values in successive individual cases.

VARIANCE. The square of the mean scatter of a statistical population of numbers from the population mean. The square of the standard deviation (q.v.).

VARIANCE CALIBRATED. Variance reduced (q.v.).

VARIANCE REDUCED. The difference between the mean scatter or variance (q.v.) of a data set and the residual (q.v.) variance, representing the departure of the data from a statistical relationship or representation of the data; for example, variance reduced by regression or by eigenvectors (principal components) of the data set. Sometimes called *explained variance*. Cf. *goodness of fit*.

VASCULAR CAMBIUM. The thin cylinder of meristematic tissue (q.v.) between the wood and the bark which produces xylem (q.v.) on the inside and phloem (q.v.) on the outside.

VASCULAR TISSUE. The xylem (q.v.) and phloem (q.v.).

VEGETATIVE BUDS. Buds that can produce only stems and leaves. Cf. *reproductive buds*.

VEGETATIVE ORGANS. In plants, the roots, stems, and leaves, as differentiated from the reproductive organs (q.v.).

VERIFICATION. The proof of validity of results by comparing actual independent climatic data to reconstructions of climate.

VESSEL Large tube-like water-conducting element in the wood of angiosperms (hardwoods) in contrast to the smaller tracheid (q.v.) found in gymnosperms (q.v.).

VISCOSITY. The property of a fluid that resists internal flow because of strong cohesive forces among the molecules.

WATER BALANCE. The rates of movement and pathways governing the inflow, outflow, and water status in a system such as a plant.

WATER POTENTIAL (Ψ). The difference in free energy (q.v.) of water in the plant, soil, or atmospheric system under consideration and that of pure water at atmospheric pressure. Cf. *osmotic potential*.

WEATHER. All observable meteorological phenomena which vary over time scales of minutes to days, including precipitation, heat, temperature, light, wind, clouds, and related factors that influence the environments of the biosphere. Cf. *climate*.

WOOD RAYS. Thin-walled cells in the xylem (q.v.) forming lines or ribbons radiating from the pith (q.v.).

XYLEM. The water-conducting tissue of plants which makes up the wood cylinder of a tree inside the bark and surrounding the pith.

XYLEM RAYS. Wood rays (q.v.).

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