II. SCIENTIFIC BASIS OF DENDROCHRONOLOGY

A. Biological Basis of Dendrochronology

1. What are tree rings?

i. Relevant Structural Properties

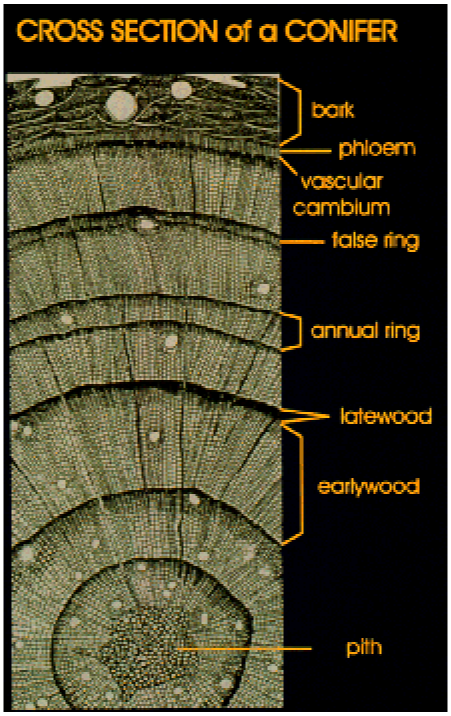

Figure 5.

Tree rings are the new layers of wood formed each year on the outside of the existing wood of trees. The rings can be seen in cross sections of tree trunks. In *conifers* such as *Pinus, Juniperus, Cedrus*, for example the boundary between one ring and the next is marked by the contrast between small thick-walled *latewood* cells formed at the end of one growing season, and larger thin-walled *earlywood* cells formed at the beginning of the next growing season. In *hardwoods* (such as *Quercus* or *Pistacia*) wood anatomy is more complex. Whereas most of the volume of coniferous wood is made up of one cell type, *tracheids*, several cell types constitute large fractions of the volume of hardwood timber. In species such as *Quercus*, for example, the cells (called *vessels*) have a large enough diameter in the earlywood (the first part of the ring) to be visible to the unaided eye and are commonly used as an indicator of the ring boundary (Figure 6). Such species are said to have *ring-porous* structure. In other species, such as *Salix* and *Populus*, no vessels are this big and there is no concentration of them at the very beginning of the ring, making ring identification more difficult. Species like this are called *diffuse-porous* (Figure 7). It should be remembered that rings are not confined to the stem, but that the layers of new wood they represent are found throughout the woody parts of the plant. See 'A good look at wood's structure' by R.L.Gray and R.A.Parham (1982) for further details.

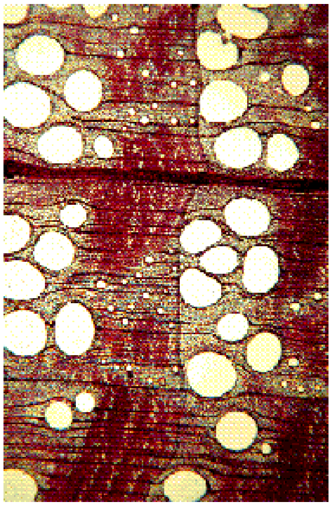

Figure 6. Red oak (*Quercus rubra*) tree rings. The large vesssels in the earlywood indicate this is a ring-porous angiosperm tree).

Figure 7. Sugar maple tree rings (*Acer succharum*) . The small vessels throughout the entire tree ring indicates this is a diffuse-porous angiosperm species.

ii. Determining that Tree Rings are Annual

Annual tree rings are found where there is a single major period of dormancy (a time when no growth occurs) and a single major period of wood growth per year. These conditions apply to most trees in the middle and high latitudes, and to some in the tropics. The major period of dormancy may be the winter, in middle and high latitudes, and the dry season in tropical regions. In semi-arid and arid regions such as the lower elevations of the American southwest and the Near East, there are species which produce wood whenever sufficient moisture is available and may produce more than one ring per year, or perhaps no ring in a given year. This is known to occur in some *Acacias*. Thus it is necessary to check that tree rings are annual in a particular species and region. This has been done for the major tree species of the middle and high latitudes by observing growth directly through a number of methods. The existence of common patterns of broad and narrow rings may also be an indication of annual ring formation, when linked to specific knowledge of local environmental conditions.

2. Crossdating and why it is possible

The chemical composition, size, and structure of an annual tree ring constitutes a record of conditions in the tree’s environment at the time the ring was being formed. The processes of cell division, enlargement, and maturation that determine the size and internal structure of the annual ring are subject to environmental control. When a factor (for example, moisture supply) is the one that most limits one or more of these processes to a similar extent in most of the individual trees at one location, or over a larger region it may be observed. For example, interannual variation in precipitation can result in characteristic patterns of broad and narrow rings in trees as much as 1,000 kilometers apart in southwestern North America. Such patterns are also found in regions with short, cool, moist summers, such as some high mountains and at high latitudes. Here variations in summer temperatures produce fluctuations in ring width or wood density. If the common pattern of tree-ring properties is strong enough and a sufficiently long series of rings is available in each case, it is possible to match the ring pattern of wood of unknown age against dated wood and thus attribute each growth ring in the sample of unknown age to a calendar year. This technique, called *crossdating*, was developed early in the twentieth century by Andrew E. Douglass. Its application to fields including paleoclimatology, ecology, hydrology and archaeology is known as *dendrochronology*, a name derived from the Greek words for Atree≅ and Aknowing the time.≅ Details of the technique of crossdating applicable in semi-arid regions are given in Stokes and Smiley's book 'Introduction to Tree-Ring Dating' (1968).

3. Which Trees Can be Used?

Trees that form the distinct, reliably annual rings (whose properties record year-to-year climate fluctuations) are found throughout forests outside the tropical regions (Figure 8). Trees close to the limits of their distribution tend to yield particularly strong records of past year-to-year climate variability, because in such places they are responding to conditions that are extreme for them. A few cases of trees from tropical regions showing datable annual rings provide a basis for current efforts to extend dendrochronology into these regions. Trees at middle and high latitudes may live from several hundred to, in a few species, several thousand years. Their wood may be preserved in peat or other sediments, by cold dry conditions, or by incorporation

Figure 8. The famous tree-ring specimen from Broken Flute Cave in northern Arizona. Notice the distinct annual rings.

in buildings or artifacts. This permits the establishment of cross-dated and replicated tree-ring measurement series, called *chronologies*, that are longer that the maximum life span of an individual tree.

Figure 9. Bristlecone pines are the oldest known trees in the world. This is one located in the White Mountains of eastern California.

The longest continuous examples of such chronologies extend over most of the Holocene period (roughly the past 10,000 years), notably for bristlecone pine (*Pinus longaeva*) in the White Mountains of California and for oaks (*Quercus* spp.) in western Europe (Figure 9). Networks of tree-ring chronologies based on ring width, and recently on wood density, exist for North America, Europe, Morocco, New Zealand, Tasmania, the western Himalayas, and temperate South America, and more are being prepared for Siberia and temperate Asia. Such a network typically contains 10 to 250 climatically sensitive tree-ring chronologies, each containing series from two radii each from 10 to 40 trees of one species. Before these are combined into a site chronology, non-climatic variation such as biological growth trend is removed from the measurements. Biological growth trend is the tendency for rings to be larger close to the pith and smaller close to the bark. Most of these networks provide useful climatic information for 250 to 500 years. The small number of climate-sensitive tree-ring chronologies with lengths of 1,000 years or more is increasing rapidly, with recent additions from Tasmania, southern South America, the Polar Urals, Scandinavia, the southeastern United States, the Sierra Nevada (California), New Mexico, Morocco, and the eastern Mediterranean region. However, choosing trees to build a chronology is not simply a matter of finding old trees. Of course, if the aim of the collection is to gain a representative sample of the landscape or forest, the criteria appropriate to that study should be used, for example some kind of stratified random sample design. If, however, the aim is to establish a tree-ring chronology for purposes of dating or climate study, the criteria mentioned here should be used. There are several levels of decision to be made when building a tree-ring chronology:

i. Species Selection

To be useful for dendrochronology, a tree species' wood should show *anatomically distinct annual rings* (Figure 10). This means that the ring boundary should be clear. There are two major problems that may make a ring boundary unclear, or lead to mistaken identification of ring boundaries. The first is that the ring boundary may not be sharp. The second is that so-called *false rings*, or intra-annual bands, may be present (Figure 11). These are produced in conifers when weather within a growth season results in a band of latewood-type cells (small with thick walls) preceding a band of earlywood type cells (larger with thin walls) and then a final layer of latewood cells. Careful microscopic examination of a suitably prepared specimen will allow the false ring to be identified because there will be a gradual transition to earlywood cell types, rather than the sharp transition seen in true rings. Some groups of tree species are more likely to have false rings than other tree species. There should be a high degree of *circuit uniformity*, that is, the relative year-to year variations in ring width should be consistent all around the tree. A good example of the examination of species suitability for dendrochronology in a new region is found in P.W.Dunwiddie's (1979) paper 'Dendrochronological studies of indigenous New Zealand trees'.

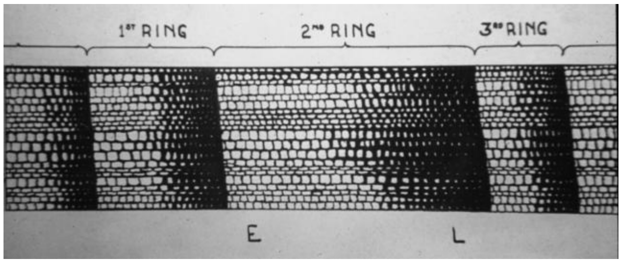

Figure 10. Distinct annual rings.

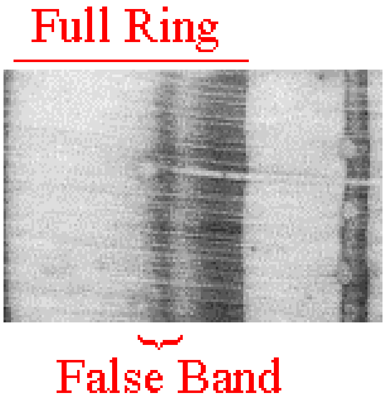

Figure 11.

ii. Site Selection

The strength of the climatic influence on tree growth, and hence the strength and reliability of crossdating, depends heavily on the conditions under which the tree is growing. In general, sites where a single climatic factor is the main limiting factor for growth rates are to be preferred (Figure 12 and 13). These sites are usually near the limits of the species geographical, elevational, or ecological distribution. For example, in trees whose ring growth is limited by moisture availability, a site on a freely draining slope is normally to be preferred over valley-bottom or poorly drained sites, although there are circumstances in which valley bottom trees may be useful. For trees limited by temperature-related factors, a north facing slope (in the Northern Hemisphere) and higher elevation will probably result in stronger crossdating, although in some conditions a valley bottom where temperature is affected by cold air drainage may yield trees more limited by climate.

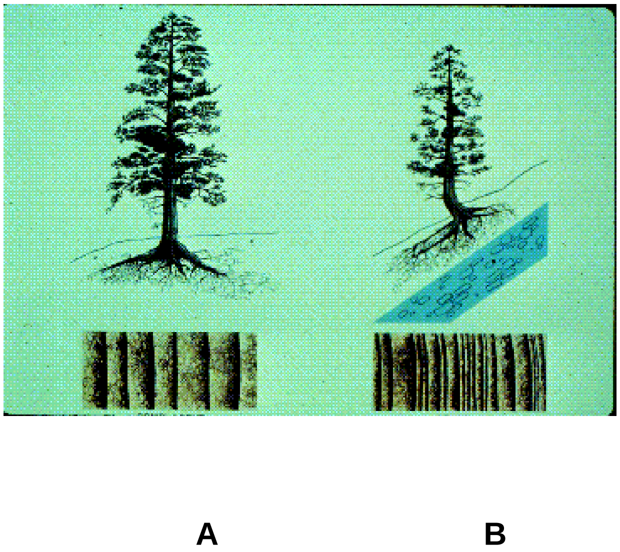

Figure 12. A. A tree growing in poorly-drained, mesic (wet) site does not produce tree-rings especially sensitive to variability in rainfall. B. A tree growing in a xeric environment where precipitation limits growth produces more variable and sensitive tree-ring series.

Figure 13. *Quercus aegilops* in northern Jordan growing on xeric site.

iii. Tree Selection

The best trees to use in a tree-ring chronology will have tree-ring records that are sensitive to year-to-year variations in the environment, and will have many rings. The methods for identifying such trees vary according to site types. For example, in semi-arid regions such as the American southwest and much of the Near East, such trees (which we will call old, sensitive trees) will resemble an upturned carrot (Figure 14). That is, they will have strong taper, perhaps a single dead leader surrounded by living secondary leaders (a 'spike top'), and may well show spiral grain. They will be found in open stands, so that the influence of the strong climate variability producing cross-dating is not diluted by inter-tree and other biological interactions. Such places, along with steep rock outcrops, often contain old trees and downed wood because their openness or other features protect them against the spread of fire. They will often be amongst the smaller trees of a species in a region, rather than the larger. Generally, trees which appear to have been used or damaged by people (coppiced, pollarded, used for animal browse, etc.) are to be avoided, as are those with heart rot.

iv. The Need for Replication

Figure 14. An old Douglas-fir (*Pseudotsuga menziesii*) growing in the Santa Catalina Mountains north of Tucson, Arizona. Notice the spike top and the spiral shape of the trunk.

There are many influences on the formation of the annual ring. Some are unique to the individual tree, or even to one side of a tree. For example the death of a neighboring tree may result in a reduction of competition for light and nutrients and produce a surge in growth in nearby survivors. Others are specific to the forest stand, such as changes in silviculture or a change in water table. In dendrochronology we are interested, at least at first when building chronologies, in the influences of climate that are common to many trees at several sites in a region, all responding to the same regional climate, and hence showing common, but not identical, patterns of tree ring growth. We need to identify and extract this common pattern. Because the climate influence is common to all trees of a species in a region growing on ecologically similar sites, we can extract it by sampling many trees at several sites, thus averaging out the variation special to each tree or stand and strengthening the record of the common pattern. There is one other important need for replication. In many cases, trees living under climatic stress may not always form a complete layer of new wood in every year. This produces *missing* or *partially-missing rings*. If we take enough samples from enough sites we increase our chances of finding a tree, or even a sample which does have a ring in such a year. The fewer samples we take, the greater the risk of remaining ignorant of a missing ring.

4. Scientific Basis of Major Applications

i. Applications Based on Felling or Death Dates

If the bark is still present, or if there is other good evidence that the outermost ring on a sample was the last one formed before the death of the tree, we can give a death date to the tree. If the last ring is complete, the death occurred in the following dormant season. If the last ring is incomplete, we may be able to estimate in which part of the growth season death (usually by felling) occurred. As we can assign each ring to a precise calendar year by cross-dating, we can build a picture of felling dates, of death by disease or pest, or as a result of some other environmental change. This is the dendrochronological application of most interest to archaeologists.

ii. Applications Based on Recruitment Dates

Here, it is necessary to get a sample from as close to the soil as possible in order to get as close as possible to the time at which the tree was a seedling. Using tree-ring dating, it is possible to get recruitment dates not only from living trees, but also from remnant wood preserved in the environment. This has been used extensively in studies of elevational and latitudinal tree-line movement.

ii. Applications Based on Scars and Reaction Wood

Wound tissue is formed in trees in response to damage caused by fires (Figure 15), rock falls and ice or rocks carried by floods. This wound tissue may then be dated dendrochronologically, and , using an appropriate sampling scheme, the temporal and spatial extent of past events may be reconstructed. Similarly, ground movements cause trees to tilt, and then to produce reaction wood, which can also be dated, a feature of use to geomorphologists in dating landslides and earthquakes. The case study on fire history (R.Touchan) will provide an example of an application based on dating scars.

Figure 15. A cross section from a Douglas-fir found in Bandelier National Monument, Santa Fe, New Mexico. The cross-section shows many fire scars marked with arrows.

iv. The Twin Concepts of Signal and Noise

When using tree-rings as a record of past climate, we need to remove the influence of site and other ecological factors from the record, leaving the regional climate signal. As indicated above (under the topic of 'the need for replication'), the climate *signal* may be strengthened by replication and averaging, so that the common signal among trees is strengthened while the factors affecting only individuals (*noise*) are averaged out.

v. Applications to the Study of the Atmosphere and Climate

The many thousand year long chronologies of bristlecone pine in North America and oaks in Europe made possible the calibration of the radiocarbon time scale, an achievement of great importance to many aspects of research on the climate of the Holocene. This permitted the discovery of hitherto unknown variations in atmospheric carbon-14 and opened up a whole new realm of geophysical investigation which some scientists believe will improve our understanding of the interaction between solar variability and climate. In addition to the radionuclide carbon-14, the stable isotopes of carbon, hydrogen, and oxygen in tree rings have been used to study climatic conditions. Most tree-ring studies of past climate have not used isotopes, but ring width and, recently, maximum latewood density. Long bristlecone pine chronologies were used by LaMarche to study century-scale climate fluctuation over the past 5,000 years. This was based on the inference that groups of decades with smaller rings in bristlecone pine growing near its upper elevational limit were associated with cooler periods, while small annual rings in the same species at its lower limit indicated a severe shortage of moisture. The confidence that could be placed in tree rings as records of climate was increased by Fritts in establishing the nature of the physiologic mechanisms controlling tree-ring formation and variability. In 1956, Edmund Schulman reported large regional patterns of ring-width variability in the semiarid regions of North America. His survey also revealed the great longevity of bristlecone pines. Further sampling and more sophisticated analyses by others established the existence of synoptic-scale (many hundreds or a few thousand kilometers across) inter-annual variation in tree-ring widths. This has been exploited using techniques from multivariate statistics to reconstruct synoptic-scale variation in temperature, precipitation, and sea-level pressure anomalies for recent centuries, notably in western North America and in Europe.

This method has great power because reconstructed annual or seasonal maps for the past century or so can be tested directly against the instrumental record (thermometers and rain guages) or other data for the same years. Other such reconstructions, usually of regional means or single-station records, have been made in many regions. These and other reconstructions have cast light on the potential climatic role of explosive volcanic eruptions, the Southern Oscillation, and solar variability. They also provide a basis for comparing recent variability with that of preindustrial times. Similar networks of tree-ring records have been used to reconstruct the flow of rivers and the extent and frequency of droughts.

In all these cases it is necessary to select species, sites and trees carefully, to work with replicated cross-dated material, and to perform two other steps, *standardization* and *averaging*. Standardization is a mathematical step designed to remove non-climatic age-and geometric change from the tree-ring series for an individual sample. The simplest possible line is fit to the series of tree-ring measurements, and usually the measurement for each ring is divided by the value for that year of the fit line to produce a time series of *indices*. The indices for each sample are then averaged for the whole site collection to produce the site chronology referred to above. These and other techniques are used to isolate and strengthen the climate signal at the expense of the non-climatic noise. The paper by Fritts et al (1980) on 'Past climate reconstructed from tree rings' is an example of the reconstruction of seasonal maps of climate on a large spatial scale. The paper by Hughes and Brown '(1992) Drought frequency in central California since 101 B.C. recorded in giant sequoia tree rings' is an example of a simpler approach to placing the recent frequency of extreme droughts in a long-term context. The case study on southern Jordan by R. Touchan is an example of another practical application of tree-ring reconstruction of past conditions.

vi. Applications Based on Removing Climate Signal

There are other cases where the climate information in the tree rings may be regarded as noise rather than signal. For example, we may wish to identify the impact of pollution, or forest insect population outbreaks, on radial growth. One way to do this, in the case of the study of insect outbreaks, is to identify the host tree species, and another non-host tree species, preferably found at the same sites, that has a similar climate response. The difference between the tree-ring chronologies of these species will be greatest when the host species' growth is affected by a large population of insects, and so the past history of such outbreaks may be reconstructed.

vii. Measurements Other than Ring Width

Much additional information may be extracted from tree rings by making additional measurements, such as wood microanatomy, wood microdensitometry (Figure 16 and 17), stable isotopic rations, and other wood chemistry analyses, according to the needs of the particular project.

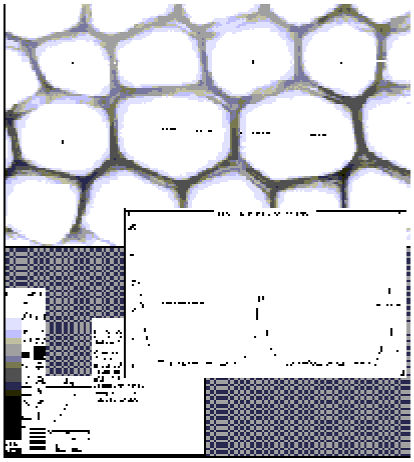

Figure 16. Cell sizes and cell wall thickness measured on an image analysis.

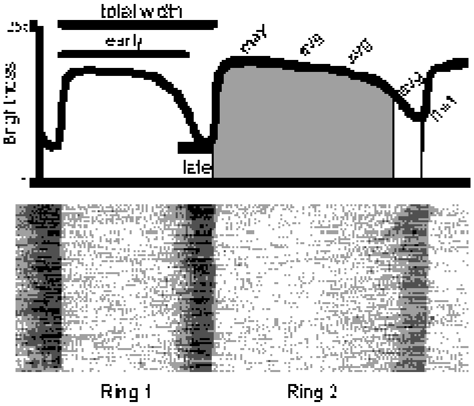

Figure 17. A diagram showing the technique of image analysis to measure wood density.

B. Sample Preparation and Crossdating Techniques

1. Sample Preparation

Sample preparation is a very important step in dendrochronological research. It is the best way to illustrate the anatomical characteristics desired for study. We use sample preparation for cores and cross sections. In this section we will illustrate both.

i. Cores

We take cores from a sample tree by using increment borers (Figure 18 and 19). Core preparation should take the following into consideration:

a. The cores should be air dried for a few days before being placed into slotted mounts, so that they will not shrink and pull apart in the mount as they dry.

Figure 18. A researcher is coring a tree using increment borer.

Figure 19.

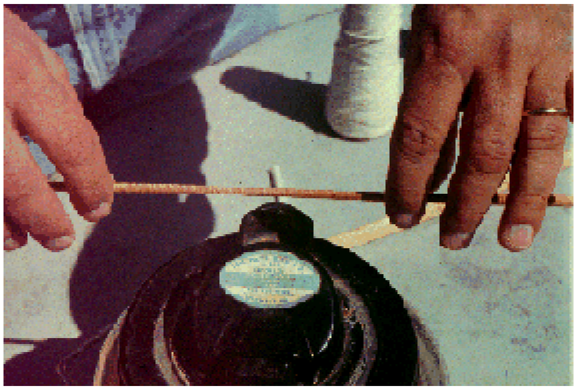

Figure 20. Straightening a twisted core over a jet of steam.

b. Check if the core is twisted. Sometimes the extracted core could be twisted or broken if there is dirt or resin inside the borer or if the cutting tip of the borer is dull. To do that you need to examine the sides of the core where there is a shiny line caused by reflections from the walls of tracheids. These lines should continue along the sides of the core;

they will show if the core is twisted. To straighten a twisted core, hold the core on either side of the twisted part and place it in a jet of steam, while gently untwisting the core (Figure 20). Remove the core from the steam while still holding it in the untwisted position and hold it until it cools.

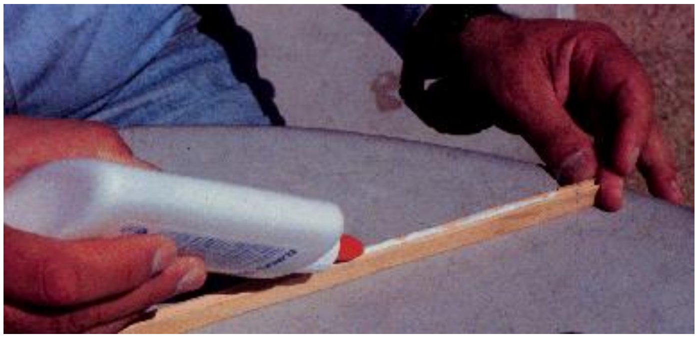
Figure 21. Spreading a glue inside the grooved wooden mount.

c. Mount the cores with the tracheids aligned vertically so that a sanded surface will be a transverse section. If we do not align the tracheids in this way, the cells and the ring boundaries are very difficult to see after surfacing (Figure 21 and 22).

d. The mounted cores should be wrapped tightly with a string and stored until the glue dries (Figure 23).

e. Sand the core either by hand or with a belt sander. Start with medium-grade sandpaper such as 100 or 220 grit, and continue through 320, 360 and 400 grit (Figure 24). A finely sanded surface is very important for crossdating because it will make visible the details in ring structure, such as ring boundaries, microrings, and diagnostic characteristics such as frost damage, false rings, and injuries.


Figure 22. Mounting an increment core.


Figure 23. Wrapping the core with a string to hold the core in place until the glue is dry.

Figure 24. Sanding the core.

ii. Cross-sections

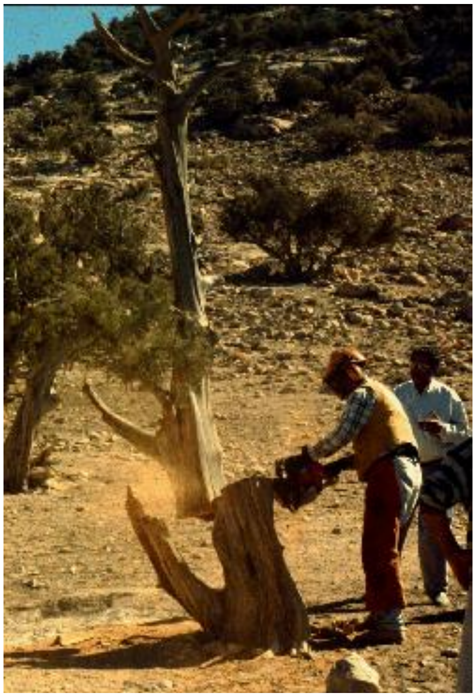

Figure 25. Using a chainsaw to obtain a cross section from *Juniperus phoenicia* in southern Jordan.

We usually prefer to sample trees by taking increment cores instead of cross sections because cutting a cross section means destroying the tree. However, there may be times when taking a cross section is necessary. For example, to establish crossdating in a new region it is necessary to obtain cross sections from several trees, particularly for genera such as juniper in semi-arid regions where experience has taught us to expect frequent partially absent rings (Figure 25). Sampling hardwood trees, such as oak, may some times force dendrochronologists to take cross sections instead of increment cores because it is difficult to insert increment borers in some hardwood trees. Obtaining cross sections is also crucial for some research studies, such as developing fire history or flood event chronologies. In the last two cases, however, most of the samples usually are taken from dead trees in the form of stumps, logs or snags.

If the cross section is not fairly smooth and level, is must be cut by a bandsaw to create a level surface for sanding (Figure 26). The cross section should be sanded using very coarse progressively through finer grades of sanding belts (60 through 400 grit) mounted on electrical hand sanders (Figure 27). When sanding is finished, ring boundaries and cell walls will be very clear and visible for crossdating.

Figure 26. Cutting a sample with bandsaw.

Figure 27. Before sanding the sample. Notice that the ring boundaries are not distinct.

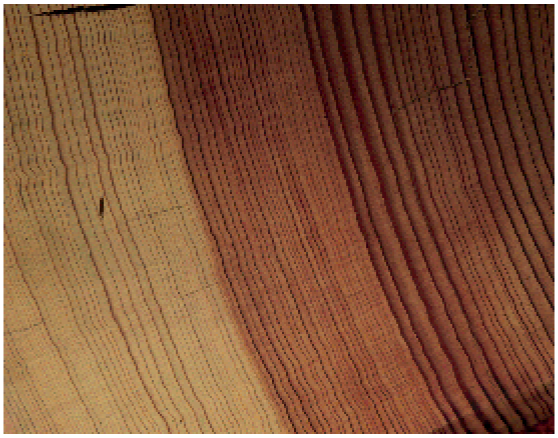

Figure 28. After sanding the sample. Notice the distinct annual rings.

2. Crossdating Technique (Skeleton Plots)

Dr. A. E. Douglass invented the technique of crossdating by means of skeleton plots (Figure 28) A skeleton plot is a graphical illustration of tree-ring widths. It is a technique that aids the dendrochronologist in relating groups of specimens to each other by matching ring patterns and determining the exact date for each ring (See

Stokes and Smiley book). This simple technique requires an experienced person with microscope, pencil and graph paper. This technique is faster than methods requiring ring measurements, but in some cases where the samples are complacent (tree-ring growth varies little from one year to the next) it is better to measure the samples and view the plots overlaid on a light table to determine the exact dates. See the text by Stokes and Smiley and the publication by Thomas Swetnam for detailed information on the technique of crossdating by skeleton plot.

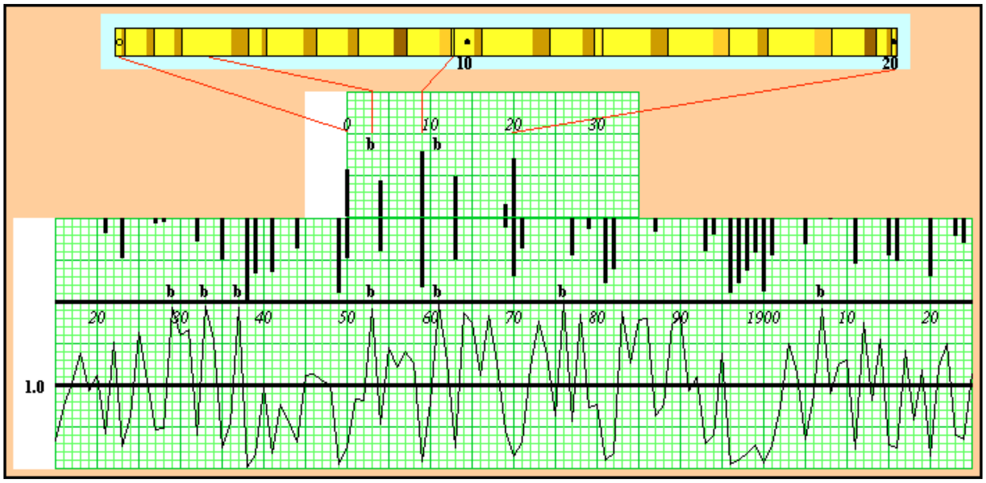

Figure 29. Using the skeleton plot technique for cross-dating.

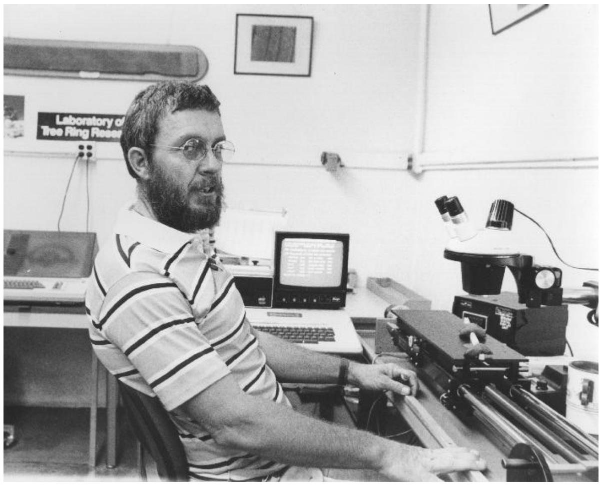

Figure 30. A researcher at the LTRR using the sliding-stage micrometer/ microcomputer for measuring tree rings.

3. Ring Widths Measurements

In some applications, all the information needed is contained in the dates. In many cases however, tree-ring width measurement is needed. After we determine the exact calendar year for each ring, we measure the annual tree-ring widths. Several machines have been used to provide efficient and precise measurements. The LTRR uses the sliding-stage micrometer interfaced with a microcomputer (Robinson and Evans 1980) and the Velmex System (Krusic) (Figure 29).

The surfaced and dated specimen is placed on a traveling stage under a binocular microscope with a cross-hair in one eye piece. The stage is moved by a manual mechanism so that the ring boundary is aligned with the cross-hair. The sample is moved to the next ring boundary and the ring width is transmitted to a computer by pressing a button.

4. Standardization

Generally, the average annual ring width decreases as the tree get older and the circumference of the tree increases (Figure 31). The rate of decrease in each tree is related to aging, genetic potential for growth, bole geometry, site conditions, and stand history (Swetnam, 1988). In addition, neighboring trees may have very different overall rates of growth, but share the same patterns of relative year-to year change. Standardization is the statistical procedure for adjusting for these nonclimatic influences and combining the ring-width information from the individual trees into a representative tree-ring index of growth at the site. The most important aspects of standardization are summarized below:

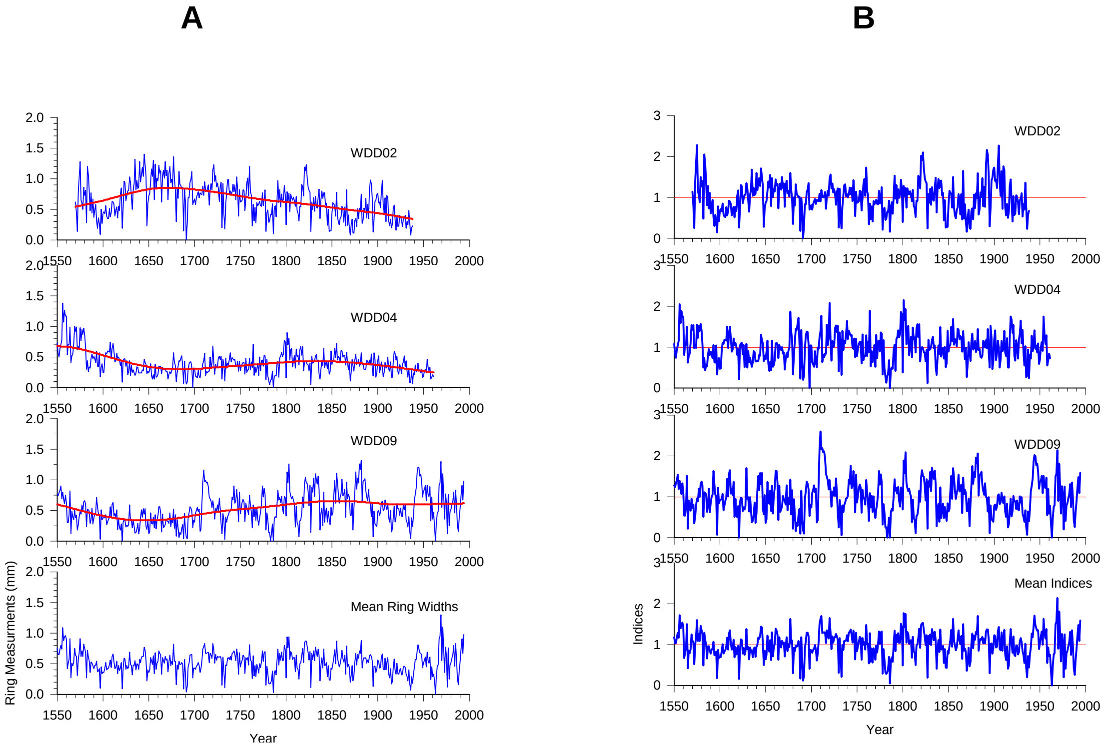

Figure 31. A. Non-standardized series. B. Standardized series

the primary reasons for standardizing ring widths are:

a. <u>Remove age-related trends</u>. Usually this is a trend of decreasing ring width with increasing age or size of tree, and after a tree reaches a certain age is related to the laying down of an approximately constant volume of annual wood increment on an expanding circumference. The trend is typically removed by fitting a modified negative exponential curve or a straight line with a negative slope.

b. <u>Remove other non-climatic, or individualistic growth trends</u> The ring widths of some trees, particularly from the forest interior, may contain stand-related low-frequency variations that may not be represented by a monotonically decreasing age curve. In such cases a cubic smoothing spline has been found to be useful in standardization (Cook and Peters 1981).

c. <u>Transform all series to a common mean, i.e., remove absolute differences in ring widths so that relative variations are emphasized</u>. After a curve as been fit to represent the age trend in ring width, that trend is generally removed by the ratio method. Each ring-width value (W_t) is divided by the value of the trend line (Y_t) for that year. This procedure will produce an index of a tree growth (I_t) as a variation in environmental factors (Fritts 1987, Swetnam 1988, Dean 1997).

$$I_t = W_t/Y_t$$

The means of I_t for the various cores are all equal to 1.0 by this ration detrending method.

d. <u>Homogenize and stabilize the variance of the series</u> Experience has shown that variance of ring width generally increases with increasing mean ring width. Since the variance trend is age or size related, it is desireable to remove the trend before using the data for environmental interpretation. The ratio-method of detrending fortunately has the benefit of tending to reduce or remove this dependence of variance on mean, and thus tends to reduce variance trend from individual core indices. An additional source of trend in variance in the site chronology is the changing sample size over time. The site chronology is basically a mean value function of the indices from the individual cores or trees. As the sample size increases, this mean mean value function more precisely estimates the common growth signal. Accordingly the variance of the site chronology tends to decrease with increasing sample size. The tree-ring standardization program ARSTAN has an option for the user to adjust for variance trend. The method essential consists of removing series-length trend in absolute departures of the site index from the long-term mean (Cook and Kairiukstis 1990).

e. Combine the ring-width information from multiple cores or trees. The indices, I_t, for the individual cores or trees are averaged together to form a “site chronology.” The average can be a simple arithmetic mean or a robust mean. The site chronology is therefore statistically a mean-value function, and the sample size varies over time depending on the number of trees available.

5. Assessing quality of chronology

The quality of a tree-ring chronology usually is judged from statistics that measure the strength of the common signal in the individual ring-width indices. One widely used measure of strength of common signal is the average correlation between pairs of core indices, or mean between-tree correlation, $\bar{r}_{bt}$, where the correlations are computed for some common period for the available overlap for each pair of series. Because a site chronology is an average over trees, the common signal is enhanced as the sample size (number of trees) becomes greater. Thus a high-quality chronology has both high betwee-tree correlation and high sample size. These traits would tend to reduce the noise component in the average over trees.

Statistical theory of random numbers has been used to derive an assessment statistic called the expressed population signal (EPS), which depends on sample size and mean between-tree correlation, and indicates how closely the tree ring chronology based on the given sample size might be expected to approximate the unknown theoretical chronology based on an infinite number of trees at the site. The EPS and a related statistic, the subsample signal strength (SSS) are frequently used to assess not only the overall quality of the chronology, but how far back in time the chronology is useful before the sample size becomes to low to capture the true tree-ring signal at the site (Wigley et al. 1984). The EPS is computed as follows

$$\mathrm{EPS} = \frac{\bar{r}_{bt}}{\bar{r}_{bt} + \left(1 - \bar{r}_{bt}\right)/n}$$

where $\bar{r}_{bt}$ is the mean between-tree correlation and n is the sample size, or number of trees. EPS can be computed for each year of the chronology, and reaches a maximum when sample size n is largest. The SSS is most often used to describe how closely the chronology based on a subset of trees approximates the chronology based on the full sample size. SSS can be directly computed as

$$\mathrm{SSS} = \frac{\mathrm{EPS}(n)}{\mathrm{EPS}_{\max}}$$

where $\mathrm{EPS}(n)$ is the expressed population signal when the chronology comprises n trees and $\mathrm{EPS}_{\max}$ is the expressed population at maximum sample size. As a rule of thumb, a climatic reconstruction is usually deemed unreliable when SSS of the tree-ring chronology drops below 0.85.

C. Applications

A set of papers illustrating hydroclimatic applications of tree-ring data are included as attachments. It should be emphasized that these examples focus heavily on semi-arid regions, in keeping with the nature and geographical setting of the course. All of these applications involve statistical reconstruction of some variable related to drought or water supply. **These variables include precipitation, drought indices, and streamflow**. As such, the applications share a common set of general steps, which are outlined below.

1. Selection of the hydroclimatic variable whose long-term history is of interest

This variable is referred to as the predictand, or the variable to be “predicted” or “reconstructed” from tree rings. The choice of variable usually depends on the purpose of the study. For example, a water management agency might be most interested in getting estimates of annual flow of a river, while an agricultural user employing dryland farming might be more interested in seasonal total precipitation.

The quality of the predictand variable is important, as the variable should be driven by natural climatic variability rather than the influence of man. Thus gaged river flow from upstream reaches above major reservoirs is often preferred for streamflow reconstruction. Precipitation and temperature variables are sometimes subjected to homogeneity testing to eliminate from consideration records unduly distorted by station moves and other factors.

2. Assessment of the hydrologic or climatic system governing behavior of the hydroclimatic variable

For a streamflow reconstruction, this step might involve review of papers dealing with the water balance of the region, or delineating where the runoff to the stream originates. For a climatic reconstruction, the synoptic climatology of the region is of interest.

3. Selection of tree-ring chronologies to be used in reconstructing the variable.

The initial selection is usually based on geography: sites are preferred from the region under the same climatological influence as the variable to be reconstructed. For example, tree-ring sites for a streamflow reconstruction are preferred from the runoff producing mountains of the watershed.

4. Exploratory analysis to identify the season and climatic variables most important to the tree-ring series, and possibly using this information to screen the tree-ring series

Response-function analysis (Fritts 1976) is typically performted to identify the primary months or seasons of important climatic influence on the tree-ring chronologies. In its simplest form response function analysis is identical to correlation analysis, in which product-moment correlations between the tree-ring chronology and seasonal or monthly climate variables are computed and graphed. The pattern of correlations indicates the important seasonal components. More complicated formas of response-function analysis include principal components transformation of the climatic variables before statistical correlation with the tree-ring chronology.

5. Selection of a form of statistical model to reconstruct the hydroclimatic variable

Almost always the model of choice for dendrohydrologic and dendroclimatic reconstruction has been linear regression. In the simplest case, an arithmetic average over all tree-ring chronologies in a region might be used as a predictor of streamflow, precipitation, or some other variable. The model is often extended to multiple linear regression, in which individual chronologies are entered stepwise or by some other selection method as predictors in the model. A more complicated extension is the principal-components reduction of the set of tree-ring time series into a smaller set of orthogonal variables to be used as predictors in the model.

It should be noted that recently models other than linear regression have gained attention in hydroclimatic reconstruction. Examples are binary classification trees (Meko and Baisan 2001) and neural networks (Zhang et al. 1999; Woodhouse 1999).

6. Calibration and Validation of the reconstruction model

Calibration is the “tuning” of the parameters of the model to achieve greatest possible accuracy of reconstruction in the period of overlap between the tree-ring predictand and the predictand. In regression models, a least squares approach is used such that the sum of squares of errors (observed minus predicted values) is minimized. Validation is the checking of the ability of the model to reproduce values of the predictand outside the period used to calibrate the model. Two general approaches are taken to validation – split-sample and cross-validation.

a) split-sample. The data is subdivided into two segments (e.g., first half and second half); the model is calibrated on one segment and validated on the other; the calibration and validation segments are exchanged and the process repeated. Split sample is generally used when available overlap of hydroclimatic and tree-ring data is large (e.g., greater than 60 years).

b) cross-validation (Michaelsen 1987). This is an iterative process in which the model for an *N*-year overlap of climate and tree rings is calibrated repeatly *N* times, each time dropping a different data observation from the calibration and using the calibrated model to predict the “left out” observation. The aggregate series of predictions for the left-out observations is treated as predictions based on independent data.

Accuracy of the reconstruction model is measured by a variety of statistics. Most commonly, the calibraton accuracy is summarized by the regression R^2, possibly adjusted for number of predictors in the model, and by the standard error of the estimate (SE). The validation accuracy is most often summarized by the root-mean-square error of validation ($RMSE_v$) and the reduction of error statistic (RE) (Gordon 1982; Meko and Graybill 1995; Meko et al. 2001}.

7. Application of the model to generate the long-term reconstruction

The reconstruction is generated simply by multiplying the predictors (e.g., tree-ring chronologies) by the regression weights estimated in calibrating the model. Sometimes a set of "subperiod" models is generated for different periods of the tree-ring record depending on which sites are available. In that case, each model is used to reconstruct the predictand variable for a particular target period, and the individual segments are spliced together to form a final continuous reconstruction.

8. Assessment of time series features of the reconstruction

Different statistical tools are used for assessing the reconstruction, depending on the objective. For hydroclimatic reconstructions, runs analysis (Meko et al. 1995) and spectral analysis (Cook et al. 1999) are frequently applied to study the recurrence properties of drought. Most assessment begins with plotting the reconstruction and its confidence band, which ideally is based on the root-mean-square-error of validation. Features outside a specified confidence band (e.g., 95%) around the long-term mean are most deserving of attention. Monte Carlo approaches have been used to incorporate the uncertainty into analysis of drought properties of the reconstruction. Examples of such an approach can be found in the attached papers on reconstruction of streamflow in California (Meko et al. 2001), and precipitation in Jordan (Touchan et al. 1999, 2003).

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