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Chronometric Dating in Archaeology

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Chapter 2

Dendrochronology

JEFFREY S. DEAN

ABSTRACT

Dendrochronology, the science that uses tree rings for dating past events and reconstructing past environmental conditions, has undergone a period of explosive growth in the last three decades. From a discipline of limited topical and geographic scope, dendrochronology has been transformed into a global phenomenon relevant to a broad range of subjects. Firmly grounded in the principle of crossdating—using aspects of ring morphology to identify contemporaneous rings in different trees—dendrochronology provides absolute dates accurate to the calendar year and qualitative and quantitative reconstructions of environmental variations on seasonal to century scales. Archaeological applications of dendrochronology fall into three categories: chronological, behavioral, and environmental. Chronological analysis involves the dating of both concrete and abstract units of archaeological analysis. Archaeological tree-ring collections provide a broad spectrum of information on past human behavior including the treatment of trees as a natural resource and wood as a raw material, sources of timbers, season of wood procurement, and numerous specific wood use practices. Archaeologically-relevant environmental information derives from site species assemblages, geologic dating, and the dendroclimatic analysis of archaeological tree-ring sequences. Further expansion of the geographic compass and topical relevance of dendrochronology can be expected as scholars from around the globe pursue the ramifications of this technique.

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INTRODUCTION

Thirty years ago, in Brothwell and Higgs' *Science in Archaeology*, Bryant Bannister (1963) summarized the state of dendrochronology poised on the threshold of an era of unprecedented growth and expansion. Since then, the field has been transformed from a somewhat parochial discipline focused on archaeological dating and rudimentary climatic analysis of limited geographic scope to a global phenomenon applicable to an astonishing range of research topics. In 1963, a handful of dendrochronological operations existed in the United States and Europe. Today, more than 100 tree-ring programs cover all areas of the globe. The magnitude of this transformation is exemplified by the contrast between the First International Dendroclimatic Workshop in 1974, which was attended by 30 scholars from nine European and North American countries, and the 1994 International Conference on Tree Rings, Environment, and Humanity, which involved 332 participants from 35 countries (Dean *et al.* 1996). Bannister's article, therefore, provides an excellent benchmark for assessing the discipline's progress during the last three decades.

DENDROCHRONOLOGY

Bannister's (1963: 161) definition of dendrochronology—"the method of employing tree-rings as a measurement of time . . . and . . . the process of inferring past environmental conditions that existed when the rings were being formed . . ."—is as apt today as then. It captures the two principal components of dendrochronology, the dating of past events and the reconstruction of past environmental conditions. The range of phenomena subsumed under these categories, however, has expanded immensely since 1963. Where dating once was restricted primarily to archaeological contexts, it now applies to a broad spectrum of human and natural events including construction episodes, tree modification, volcanic eruptions, earthquakes, alluvial deposition and erosion, floods, forest fires, arboreal insect infestations, plant community establishment and dieback, and radioisotopic fluctuations. Once restricted to climate, dendrochronological reconstruction now encompasses many additional environmental factors, such as streamflow, flood frequency and intensity, plant community composition and distribution, wildfire frequency and intensity, alluvial hydrology, and glacier advances and retreats.

HISTORICAL BACKGROUND

Although knowledge of the growth layers in trees originated in antiquity, the first recorded use of tree rings in a dendrochronological sense occurred in 1737 when Duhamel and Buffon used a prominent frost damaged ring as a

marker of the year 1709 in northern Europe. Alexander C. Twining in Connecticut in 1827 (Studhalter 1955) and Charles Babbage in England in 1838 (Heizer 1956) suggested that sequences of wide and narrow rings could be used to date past events and reconstruct climate, although neither of them pursued these insights. Later in the nineteenth century, Jacob Kuechler in Texas (Stallings 1937), J.C. Kapteyn in Germany and the Netherlands (Schulman 1937), and O. Shvedov in Russia (Eckstein and Wrobel 1983) independently used matched tree-ring sequences for dating natural events and making inferences about climate. It remained, however, for Andrew Ellicott Douglass to develop his own recognition of ring-width correspondences among different trees into the science of dendrochronology (Webb 1983).

Around the turn of the century, Douglass, an astronomer at the Lowell Observatory in Flagstaff, Arizona, was frustrated in his efforts to relate the earth's climate to sunspot activity by the lack of meteorological data long enough to reveal cycles comparable to the 22-year sunspot cycle. In 1904, he initiated a study of rings in local ponderosa pine trees as potential climatic records long enough to be related to the sunspot cycle. He discovered that different trees exhibited identical patterns of ring-width variability and realized that these commonalities indicated external climatic control of tree growth over a wide area. By 1914, he had used the correspondences in ring width to construct a 500-year composite chronology of the variability common to the pines of the area and had established a positive correlation between ring width and the precipitation of the preceding winter (Douglass 1914).

Stimulated by the interest of archaeologists, Douglass devoted much of the next 15 years to building a tree-ring chronology long enough to date wood samples from the prehistoric sites that dot the Southwestern landscape. In 1929, the Whipple Ruin at Show Low, Arizona, yielded a fragment of charred wood whose rings bridged the gap between the dated living tree sequence and a 585-year "floating" chronology composed of samples from prehistoric archaeological sites (Douglass 1929; Haury 1962). This achievement allowed Douglass to assign calendar dates to these sites, the first independent dating of archaeological sites in the world.

Douglass' success inspired the application of dendrochronology in other regions including the North American Arctic (Giddings 1941) and Great Plains (Weakly 1940), Scandinavia (Høeg 1944; Schulman 1944), and southern Germany (Huber 1941). World War II terminated this nascent expansion, and momentum was not regained until long after the end of hostilities. Beginning around 1960, dendrochronology experienced a renaissance that continues to accelerate as new applications of the method are developed and it is expanded into new regions. Driven primarily by interests in archaeological dating, climate reconstruction, and calibration of the radiocarbon time scale, this explosive growth began in northern Europe and expanded around the world. Today, validated tree-ring chronologies have been developed everywhere but in tropical Africa, and research is being pursued wherever conditions permit. The range of topics and methods encompassed by modern dendrochronology is exemplified by the proceedings of the 1994 international conference in Tucson (Dean *et al.* 1996).

CONCEPTS AND PRINCIPLES

The concepts and principles that underlie dendrochronology (Baillie 1982, 1995; Bannister 1963; Dean 1986; Eckstein *et al.* 1984; Fritts 1976; Glock 1937; Schweingruber 1988) are well known, and only salient features and new developments are discussed here.

The layers of woody growth that sheathe a tree's trunk beneath the bark appear in cross section as a series of concentric "rings" around the pith at the center. A ring is composed of a light-colored inner band (earlywood) and a dark outer band (latewood) whose abrupt termination marks the outer boundary of the ring (Fig. 2.1). Occasionally, bands of latewood within the earlywood form "false" or "double" rings, which are distinguished from true rings by indefinite outer boundaries. In the trees used in dendrochronology, the progression of rings from pith to circumference establishes an unalterable temporal order, and the production of but one ring per year provides the incremental regularity necessary to establish a fixed time scale.

More than 180 tree and shrub species (Grissino-Mayer 1995) possess the attributes necessary for successful tree-ring analysis: visible and unambiguous ring definition, the production of a set number of rings per unit of time (one ring per year), a substantial proportion of radial growth controlled by one or a small number of external environmental factors (usually climate), and the existence of morphological features (e.g., width, density) that allow the environmental "signal" to be extracted from ring sequences.

Two types of ring series, which represent end points on a continuum of variation, are recognized (Fig. 2.2). *Complacent* series display little between-ring variation and are produced when the factors that regulate growth vary little from year to year. Sensitive series are characterized by high between-ring variability that results from annual fluctuations in the environmental factors that limit growth. Sensitive series are the fundamental data source of dendrochronology. Both complacent and sensitive ring series exhibit a characteristic *age trend* in which individual rings become progressively smaller from the pith to the circumference independently of between-ring variability.

Crossdating, the matching of patterns of ring variation among trees, is the one immutable principle of tree-ring science (Fig. 2.2). Any analysis that does not employ rigorous, replicable crossdating is not dendrochronological in nature; counting rings does not afford the comparative validation necessary to produce absolutely dated ring sequences. Crossdating is defined as the "existence of characteristics in tree-ring structure that permit the identification in many different trees of rings that were formed contemporaneously with one another" (Dean 1986: 133–134). Although the first recorded instance of crossdating, that of Duhamel and Buffon in 1737, involved the intertree

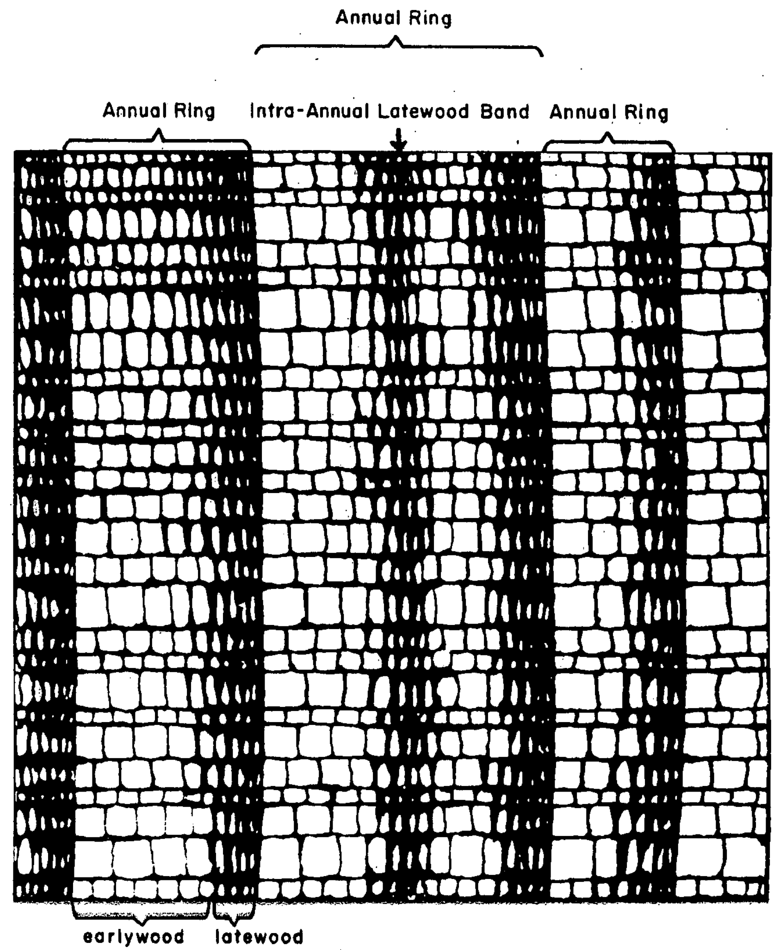

Figure 2.1. Transverse section of coniferous ring series showing dendrochronologically important features of ring morphology including cell structure, annual rings, earlywood and latewood, and intra-annular growth bands (false rings).

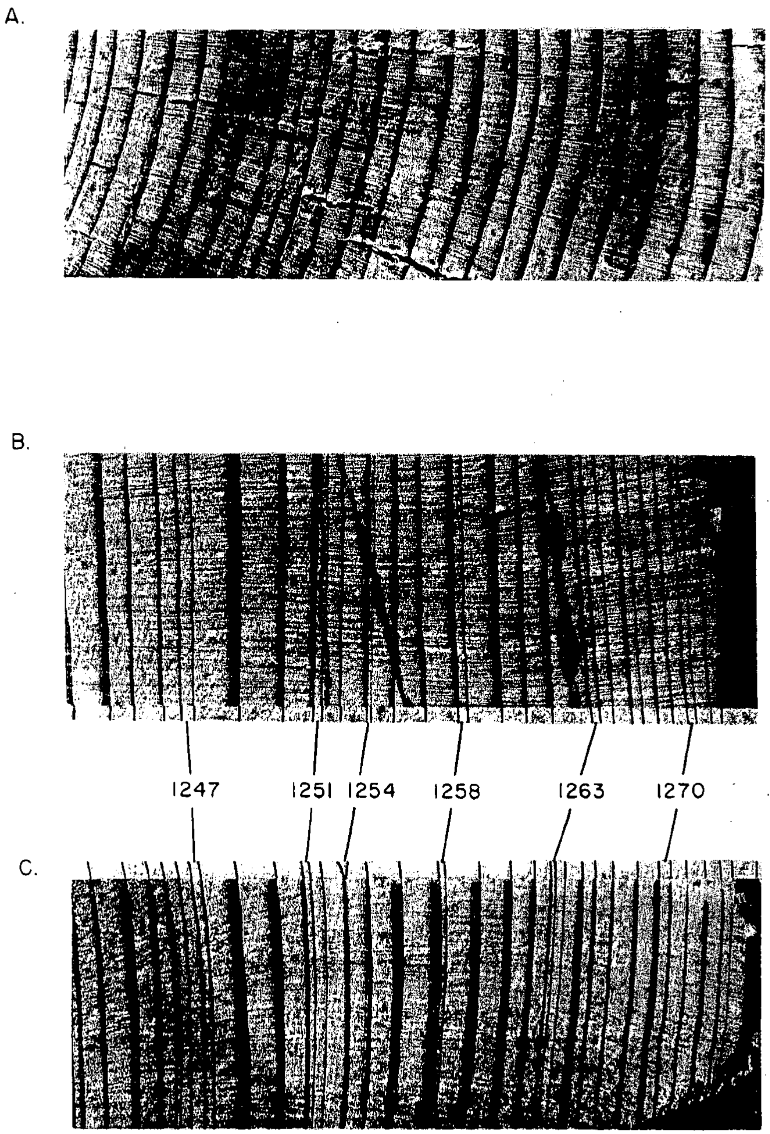

Figure 2.2. Complacent (A) and sensitive (B and C) ring series illustrating crossdating between sensitive series.

matching of frost damaged rings, the most commonly used indicators are covariation in ring widths or densities among different trees. Although other phenomena can be used for limited crossdating, only width and density covary consistently enough over large enough areas to support regional scale dendrochronological research. The fact that ring widths and densities crossdate over large areas specifies a spatial scale of external control that can only be climatic in nature, a condition that underlies most environmental reconstruction based on tree rings.

Ring-width crossdating is expressed primarily in the narrow rings, which reflect external conditions that limit tree growth over wide areas, rather than in larger rings, which are more affected by local factors or the physiological capacities of individual trees. The climatic variables that control radial growth vary considerably depending on large scale climatic patterns (Fritts 1976). Precipitation is the principle limiting factor in arid regions, temperature is the major limiting factor in cold habitats, and combinations of these and other variables control growth in intermediate climate regimes. As a result, the climatic signal in tree rings is weaker and crossdating is more difficult in intermediate environments than in those where radial growth is governed by a single strong factor. Ring density exhibits climatically controlled variation that is independent of ring-width variability and can be used for crossdating even when ring-widths are uselessly complacent.

Strict implementation of crossdating is necessary for three reasons. First, crossdating assigns exact calendar dates to all the rings in a sequence when the date of only one ring is known. Second, a ring series of unknown age can be dated by finding the unique place at which it crossdates with a sequence of known date. When such a match is achieved, each ring in the previously undated sample is assigned to the year in which it was grown. Third, crossdating is the only certain means of detecting the absence of rings from a sequence or the presence of "false" rings, which render ring counts too low or too high, respectively. Ring absence occurs when external stresses limit growth to such a small part of the tree that any sample from the tree is unlikely to contain that ring (Glock 1937: 43–51). False rings are caused by conditions that stimulate the production of one or more additional bands of earlywood cells after latewood cells have begun to form but before the tree stops growing for the year (Glock *et al.* 1960). Careful crossdating against a dated sequence indicates points on a sample at which expected small rings do not occur (locally absent rings) or points at which extra rings (false rings) appear. Thus, crossdating establishes the actual number of true rings in a sample as well as specifies the exact calendar date of each of those rings.

The second basic principal of dendrochronology, *chronology building* is the process of constructing long, absolutely dated ring sequences from many individual crossdated ring series (Fig. 2.3). Chronology building produces composite ring sequences that are longer than any of their individual compo-

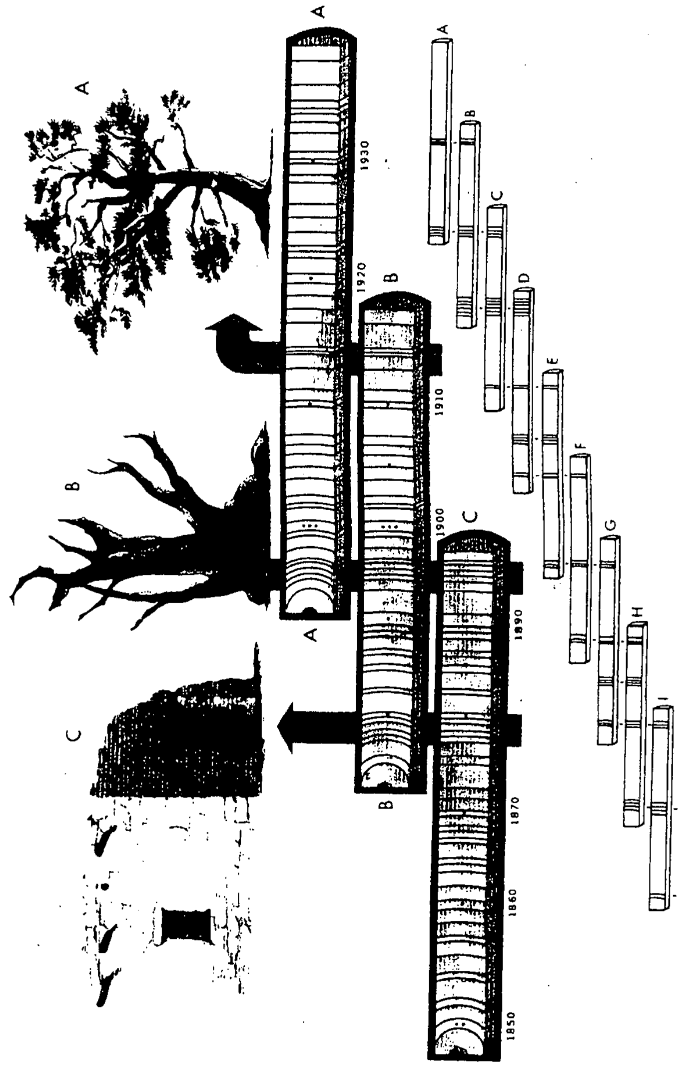

Figure 2.3. Chronology building: the construction of a composite tree-ring chronology from progressively older crossdated ring sequences representing, from youngest to oldest, living trees, dead tree remnants, and ancient human structures.

nents. Furthermore, combining ring records enhances the variability common to many trees and reduces variability due to individual tree or local habitat factors. Composite tree-ring chronologies serve as standards for dating samples of unknown age and as bases for reconstructing past environmental variability.

Tree-ring chronologies are anchored in time by samples from living trees, the year of sampling providing a date for the latest ring in the sequence. Chronologies are extended beyond the range of living trees by crossdating in ring series from progressively older deadwood, archaeological, or geologic samples (Figure 2.3). Long chronologies usually are constructed in pieces as "floating" segments (ring sequences that do not overlap with others) are linked to each other or to the dated, living-tree segments.

The area subsumed by a particular tree-ring chronology varies as a function of the geographic compass of the factors that regulate tree growth. The general Southwestern chronology extends from western California to central New Mexico and from central Utah to northern Mexico. The bald-cypress chronology in the southeastern United States covers the area from the Mississippi River to the Atlantic Ocean and from North Carolina to northern Florida. The western European sequence extends from Northern Ireland to the Carpathian Mountains (Pilcher *et al.* 1984) and may eventually be linked with the eastern Mediterranean chronology south of the Alps (Kuniholm 1995; Kuniholm *et al.* 1996). More localized crossdating exists in other areas including temperate North America, southern South America, the British Isles, northern and eastern Europe, the Mediterranean Basin, southern Africa, temperate and tropical Asia, Australia, Tasmania, and New Zealand.

TECHNIQUES

Although the basic concepts and principles of dendrochronology have remained constant since the inception of the discipline, the *methods* used to analyze rings and ring series, document crossdating, build chronologies, and extract environmental information have changed dramatically. Once the data categories (e.g., ring width, ring density, fire scars, frost rings) have been chosen, technical development furthers five general objectives: data capture (measurement), data equalization (standardization), data comparison (crossdating), data consolidation (chronology building), and environmental reconstruction.

Data Categories

A major change since 1963 has been the development of an attribute of ring morphology other than width as a basis for tree-ring analysis. Faced with complacent ring-width series, researchers in France turned to ring density as a potential source of crossdatable variability (Polge 1963). The discoveries that density variations existed in trees with uniform ring widths and that these variations could be matched from tree to tree opened an avenue of dendrochronological inquiry that is now routinely used throughout the world. Similar advances have been made in recognizing and characterizing other aspects of ring morphology (e.g., fire, flood, frost, and insect damage) that can be matched among different trees. Usually, these attributes supplement ring width and density correspondences that actually validate the crossdating.

Data Capture

Both qualitative and quantitative methods are used to record ring-width variations and crossdate ring series. Whatever technique is used for dating, quantitative measurements are the ultimate record of ring-width variability. Measurements capture the full range of variation and can be statistically manipulated and evaluated. Several different devices that measure ring widths to the nearest 0.01 mm and store the data on computer disks currently are in use. Density data are more difficult to acquire. Radiodensitometry (Parker 1971; Schweingruber 1988: 58–73), which uses densitometers to analyze X-radiographs of ring sequences, places severe restrictions on sample collection and preparation and is cumbersome, expensive, and of limited applicability to samples with small rings and to charcoal. Recent advances in sample collection and preparation methods and in X-ray and densitometric technology have simplified the process, but it still remains a costly procedure of restricted applicability. Currently, image analysis technology is being used to develop automated electronic "work stations" that extract both width and density data from wood samples or CRT images and perform routine data analyses (Schweingruber 1988: 55; Sheppard and Graumlich 1996).

Standardization

Accurate dating and environmental reconstruction rest on maximizing the variability common to the trees of a region (signal) by eliminating as much of the noncommon variability (noise) as possible. This objective is achieved in two ways. First, averaging data from at least two cores from each of at least ten trees reduces within—and between—tree variability at a growth site. Second, various standardization (normalization) procedures are used to remove idiosyncratic variability from individual ring series and reduce between-sample differences.

Standardization minimizes variability that is unique to individual trees and growth sites. Variability of this sort results from individual trees' physiological capabilities, local site conditions that modulate climatic influences, changes in site conditions, and a host of specific traumatic events that affect individual trees. These factors can cause growth surges, suppressions, or other

anomalies that obscure the environmental signal. The individual tree attributes that most commonly must be removed are the age trend from large to small rings, which is not related to climate, and between-tree differences in mean ring width, which must be adjusted to prevent the variability in samples with large rings from swamping that in samples with small rings.

Ring-width standardization methods have changed considerably since 1963 when techniques developed by Douglass and his colleagues still prevailed. These techniques involved manually fitting a trend line to the plotted ring widths and calculating the percentage departure of each ring from the trend line to produce a sequence of ring-width *indices* with a mean $\approx$1.0 and a unique standard deviation (Bannister 1963; Schulman 1956: 29–30). This procedure removes the growth trend and other low frequency variations, emphasizes between-ring variability, and converts all sequences to the same scale. The advent of computers and statistical advances after 1960 allowed the laborious standardization process to be automated (Cook and Holmes 1986; Graybill 1979, 1982), which in turn permitted the rapid processing of many samples. Standardization programs mathematically fit trend lines of appropriate forms to the ring-width series and calculate the indices. Because these techniques minimize potentially important low frequency variations, much attention has been devoted to developing methods that preserve this range of variability. While polynomial curves proved somewhat unsatisfactory (Blasing *et al.* 1983), spline-functions (Blasing *et al.* 1983; Cook and Peters 1981; Sheppard 1993), Box-Jenkins modeling (Biondi and Swetnam 1987), and other time series techniques preserve a broad spectrum of climate-related tree-ring variability. Continuing efforts to retain long term variability include the search for new curve-fitting and data consolidation methods (Sheppard 1993) and the use of ring widths from long series with little trend. Density series are standardized in much the same way (Schweingruber 1988: 85–87).

Crossdating

Two basic approaches to crossdating exist, visual-graphical and statistical. The first involves the visual comparison of wood samples themselves or of graphical representations of ring variability. The second involves computing mathematical measures of crossdating between quantified ring series data that usually are expressed in terms of probability distributions.

In regions characterized by width-sensitive ring series, visual-graphical methods commonly are used to establish crossdating, which subsequently can be quantified through measuring and statistical comparison. Most archaeological and geological tree-ring dating in North America is done visually or with *skeleton plots*. Skeleton plotting (Bannister 1963: 167; Dean 1986: 142; Glock 1937; Stokes and Smiley 1968) is a subjective, graphical means of quickly recording, at a standard scale, aspects of ring-width variability relevant to crossdating, that is, the sequence and relative sizes of small rings. A representative subset of samples is measured for chronology building and dendroclimatic reconstruction. Alternatively, crossdating can be established by visually comparing plotted ring widths or indices.

In regions characterized by more complacent tree growth, statistical techniques are used to establish crossdating. The first quantitative crossdating technique was developed in the 1930s by Huber (Huber *et al.* 1949) in southern Germany. This method involves a statistic, W (the "gleichläufigkeitswert" or coefficient of parallel variation), that is based on the percentage of cases in which the ring widths in paired series increase or decrease together. In the United States, Gladwin (1940) developed a technique based on the percentage of cases in which rings in matched samples exceed or fall below the mean together as a quantitative alternative to the "Douglass Method" (skeleton plotting). Gladwin's method, however, does not specify probabilities for putative matches, and it has been rejected as a crossdating technique.

As might be expected, the use of computers led to the development of several crossdating programs to supplement the visual and graphical procedures. Programs SNCHR (Eckstein and Bauch 1969) and CATRAS (Aniol 1983) employ versions of Huber's W statistic. Pearsonian correlation forms the basis of several crossdating programs. The most commonly used of these is CROS (Baillie 1982: 82–85, 1995: 20–21; Baillie and Pilcher 1973; Pilcher and Baillie 1987), which uses a modification of Student's *t* to evaluate the probability of each of a series of correlation coefficients for successive matches between a dated chronology and a sequence of unknown age moved forward in one year increments. Usually, only one match point produces a significant *t* value, thereby dating the unknown sample. CATRAS (Aniol 1983), which employs *t* evaluations of correlations as well as the W statistic, also is widely used. COFECHA (Holmes 1986), a program for checking and verifying crossdating, also can be used to date samples of unknown age. Matches indicated by these (and other) statistical techniques cannot be uncritically accepted but must be checked and validated against the wood itself (Baillie 1982: 85; Schweingruber 1988: 78).

The chief weakness of all computer crossdating programs is their inability to deal effectively with measurement sequences that have missing values, caused by the absence of rings from the samples, or extra values, caused by the measurement of false rings. Either condition destroys the synchroneity between master chronology and undated sample that is necessary to produce significant correlation coefficients. COFECHA attempts to circumvent this problem by calculating coefficients for overlaps of short chronology segments incremented in both directions, but it still misses matches when many values are absent from the unknown samples. For this reason, statistical dating techniques are seldom used in regions, such as western North America, where ring absence is common.

Density crossdating is established by both visual comparison of plotted values and statistical techniques similar to those used on ring widths.

Chronology Building

Composite tree-ring chronologies are constructed subjectively or mathematically. The visual averaging of skeleton plots is adequate for building chronologies designed purely for dating samples of unknown age. Statistical analyses, however, require quantitative chronologies, which are produced by averaging ring widths, indices, or density values for each year over a number of samples to produce sequences of mean values. Although a fairly straightforward process, considerable attention has been given to preserving in the final chronology important statistical attributes and the full range of climatic information (Cook *et al.* 1995; Cook and Holmes 1986; Sheppard 1993).

Environmental Reconstruction

No aspect of dendrochronology has undergone a greater transformation since 1963 than the derivation of environmental information from tree-ring data (Fritts 1976). Before 1960, dendroclimatic analysis consisted of the laborious construction of climate sensitive ring-width chronologies, the occasional use of correlation to document relationships between ring widths and various climatic parameters, and the inference of relative climatic variability from the ring sequences. This approach is epitomized by Edmund Schulman's (1956) monumental book *Dendroclimatic Changes in Semiarid America*, which is the culmination of years of painstaking work by this dedicated scholar and many colleagues.

In the 1960s, the development of computers capable of handling complex mathematical manipulations and huge quantities of tree-ring and meteorological data revolutionized dendroclimatology and fostered two types of environmental reconstruction. *Qualitative* reconstructions (Dean and Robinson 1977; Fritts 1965; Jacoby *et al.* 1996; Lara and Villalba 1993), which estimate relative variations in climate from tree-ring data, carry on the tradition of Douglass and Schulman. *Quantitative* reconstructions use mathematical relationships between environment and ring attributes to retrodict variability in specific environmental parameters in appropriate units of measurement, such as inches or millimeters of precipitation (D'Arrigo and Jacoby 1991; Fritts 1977; Hughes *et al.* 1994; Rose *et al.* 1981; Stahle and Cleaveland 1992), degrees (Briffa *et al.* 1990; Fritts 1977; Graumlich 1993; Shiyatov *et al.* 1996) or degree days (Jacoby *et al.* 1985) of temperature, millibars of atmospheric pressure (Fritts 1971; Hirschboeck *et al.* 1996), various measures of streamflow (Cleaveland and Stahle 1989; Graybill 1989; Stockton 1975), drought indices (Cook *et al.* 1996; Meko *et al.* 1980; Rose 1994; Stockton and Meko 1975; Van West 1994), and others. Response and transfer functions, regression analysis, autoregressive modeling, spectral analysis, and numerical modeling (Fritts *et al.* 1991) are used to calibrate ring and climatic variability, verify these relationships, and reconstruct annual and seasonal values of specific climatic parameters. In addition, dendroclimatology illuminates large and small scale temporal (Dean 1988; Jacoby et al. 1985) and spatial (Dean and Robinson 1977; Fritts 1965, 1971, 1991; Fritts and Shao 1992) patterns in climate including phenomena such as the Medieval Warm Period (Graybill and Shiyatov 1992; Hughes and Diaz 1994), the Little Ice Age (Briffa *et al.* 1990; Jacoby *et al.* 1985), El Niño-Southern Oscillation (ENSO) (D'Arrigo and Jacoby 1991; Lough and Fritts 1985; Swetnam and Betancourt 1990; Woodhouse 1993), and Global Climate Change (Jacoby and D'Arrigo 1995). Many of these reconstructions are invaluable to archaeology in their contribution to better understanding cultural ecology, sociocultural evolution, and human adaptive behavior (Dean 1988; Plog *et al.* 1988).

A major development since 1963 has been the investigation of measures of climatic variability other than ring width. Density attributes have been used to reconstruct a variety of climatic variables (Briffa *et al.* 1990; Cleaveland 1986). Where widths generally reflect precipitation of a twelve-month period prior to and including the current growing season (Fritts 1976), density is more sensitive to rainfall and temperature of the growing season itself (Cleaveland 1986; Parker and Henoch 1971), and the two phenomena can be used together to apprehend a broader spectrum of climatic variability. Recently, between-ring variability in isotopic content has been used to reconstruct past climatic fluctuations (Leavitt 1994; Lipp *et al.* 1996; Switsur *et al.* 1996).

In addition to qualitative and quantitative reconstructions, tree-ring evidence has been used to identify and date individual extreme or episodic events that could have impacted human groups. Among these occurrences are droughts (Van West 1994), floods (McCord 1996), hurricanes (Reams and Van Deusen 1996), and killing frosts (Stahle 1990).

ARCHAEOLOGICAL TREE-RING ANALYSIS

Dendrochronology provides three different kinds of information germane to archaeology: chronological, behavioral, and environmental (Dean 1986, 1996a). *Chronological* analysis uses tree rings to date archaeological phenomena ranging from concrete entities (e.g., pithouses, pueblos, cabins, churches, ships) to conceptual units (e.g., phases, periods, artifact types, design styles). A tree-ring date is an absolute calendric placement of the outermost ring on a sample achieved by crossdating the sample's ring series with a dated master chronology. These dates are accurate to the year and have no associated statistical error. Under ideal circumstances, the outermost-ring date specifies the year in which the tree was felled for use by the inhabitants of the site. Within the limits established by archaeological dating theory, the date can be applied to the feature with which the sample is associated. The accurate dating of features also dates associated time-sensitive materials, such as ceramics, that can then be used for the temporal placement of sites that lack tree-ring dates. In this fashion, dendrochronology can become the foundation for detailed local and regional archaeological chronologies, such as those in the American Southwest where tree-ring dated ceramic types and styles specify intervals as short as 25 years (Breternitz 1966).

Another chronological application of dendrochronology is as a standard for rectifying other chronometric systems characterized by less accuracy, precision, and resolution. Dendrochronology has been instrumental in calibrating the radiocarbon time scale (Taylor 1987) and archaeomagnetic curves (Sternberg and McGuire 1990). These comparisons enhance the chronometric attributes of the other dating systems and improve understanding of the dates and how to apply them to archaeological phenomena.

Analyzing archaeological tree-ring materials as collections of artifacts produces information on a wide range of past human *behavior* including treatment of trees as a natural resource, use of wood as a raw material, seasonal timing of tree felling, sources of wood, tools and techniques of tree felling and wood modification, differential use of species, use of dead wood, reuse of timbers salvaged from older structures, stockpiling, structure remodeling and repair, and others.

Dendrochronology produces three types of *environmental* information: that provided by comparing past species assemblages with modern plant communities, that yielded by tree-ring analysis of geological samples, and that derived from dendroclimatic analysis of tree-ring chronologies.

APPLICATIONS

The explosive growth of dendrochronology over the last thirty years significantly expanded existing applications of the method and generated numerous new applications, many of them only dimly imaginable in 1963. These applications encompass a wide range of subjects including paleoenvironment, climatic reconstruction, climate modeling, global change, alluvial geology and hydrology, volcanology, glaciology, oceanography, botany, forestry, ecology, chronometry, history, art history, anthropology, archaeology, and others. Rather than attempt to summarize all these developments here, I present a sample of applications pertinent to archaeology as it is most broadly conceived, the attempt to understand past and present human behavior and the processes of sociocultural stability, change, and evolution.

Chronological Applications

In 1963, active archaeological tree-ring dating was confined to the U.S. Southwest and Great Plains, western Europe, and Russia, having lapsed in

Alaska. The subsequent global expansion of dendrochronology has enormous archaeological potential, which has been partially realized in western North America, Europe, Siberia, and the eastern Mediterranean where systematic archaeological tree-ring dating has become routine.

An important consequence of the expansion has been the construction of extremely long (>1000 years) tree-ring chronologies of great potential for archaeological dating. The bristlecone pine sequence from the North American Great Basin reaches 8,700 years into the past with earlier floating segments that may eventually extend it beyond 10,000 years (Ferguson *et al.* 1985). The 7,272-year western European sequence (Pilcher *et al.* 1984) has been extended into the 10,000-year range (Becker 1993). The eastern Mediterranean chronology, which at present consists of a dated series and several floating segments, has the potential to reach beyond 7,000 BC (Kuniholm 1995). Southwestern chronologies extend back to 322 BC with floating segments that may allow further extension. In Europe, archaeological or subfossil tree-ring chronologies, some discontinuous, with segments longer than 1,000 years have been constructed in the eastern midlands of England (Laxton and Litton 1988), the Netherlands (Jansma 1996), France (Girardclos *et al.* 1996; Lambert *et al.* 1996), and Poland (Krąpiec 1996). Long living-tree chronologies include a 3,622-year alerce sequence from Chile (Lara and Villalba 1993), a 3,220-year sequoia sequence from California (Brown *et al.* 1994), several multimillennial bristlecone pine series from the Great Basin, a 1,600-year baldcypress sequence from the southeastern U.S. (Stahle *et al.* 1988), a 1,555-year Scots pine sequence from Fennoscandia (Briffa *et al.* 1990), a 1,210-year Huon pine sequence from Tasmania (Cook *et al.* 1992), and 1000+-year sequences from Morocco, the Polar Urals (Graybill and Shiyatov 1992), and various areas in Europe.

A principal global application of tree-ring chronology building has been the calibration of the radiocarbon time scale, which involves the evaluation of radiocarbon determinations from absolutely dated wood samples. Initially, this effort focused on giant sequoias from California, but it soon progressed to the older bristlecone pines, which eventually produced a series of calibrations extending beyond 6,000 BC (Damon *et al.* 1974; Klein *et al.* 1982; Suess 1970). This research demonstrated that radiocarbon dating systematically underestimates the true ages of materials older than 2000 years and that ^{14}C dates must be corrected. Increasing the ages of radiocarbon-dated European sites relative to the fixed Egyptian calendric chronology had implications for Old World prehistory (Renfrew 1973) that caused some archaeologists to question the global validity of the bristlecone pine calibration. The desire to independently test this calibration was an important stimulus to the development of the western European tree-ring chronology. When the radiocarbon analysis of dated European samples (Pearson *et al.* 1986; Stuiver and Kra 1986; Stuiver *et al.* 1993) confirmed the bristlecone calibration, efforts turned to lengthening both chronologies to extend the calibration further back in time. On a smaller

geographic scale, burned clay samples from tree-ring dated archaeological contexts are used to calibrate archaeomagnetic dating systems. This approach has allowed the construction and refinement of the Southwestern archaeomagnetic curve, which traces the movement of the virtual geomagnetic pole during the last millennium (Sternberg and McGuire 1990). The dendrochronological calibration of radiocarbon and archaeomagnetic dating techniques provides more accurate and precise independent dates for archaeological contexts that lack datable tree-ring materials.

Direct chronological contributions to archaeology fall into two categories: theory and practice. Dendrochronology has been instrumental in refining archaeological dating theory both in general and as it applies to specific dating techniques. Because dendrochronology lacks the internal variability (chronometric noise) inherent in other dating systems, the consideration of tree-ring dating elucidates external sources of uncertainty and error. Except for pioneering efforts by Haury (1934, 1935) and Smiley (1955, 1961), most contributions to dating theory postdate 1963. Bannister (1962, 1963) codified possible associations between dated materials and archaeological phenomena, delineated different types of potential error inherent in dating situations, and specified the conditions for successful archaeological tree-ring dating. Dean (1969) clarified the special attributes of tree-ring dates and the assumptions that underlie archaeological tree-ring dating. Baillie elucidated the temporal limits that tree-ring dates place on associated archaeological materials (Baillie 1982) and examined recurring problems in the application of archaeological tree-ring dates (Baillie 1995: 57–68). Dean (1978) elaborated the attributes of tree-ring dating into a consideration of assumptions, principles, and procedures for conceptualizing and evaluating independent dates and assessing the impact of past human behavior on dating. Ahlstrom (1985) developed a scheme for characterizing and comparing chronometric systems and dates and clarified the most powerful tool in evaluating independent dates, clustering.

Practical archaeological dating applications involve time scales ranging from seasons to millennia and spatial scales ranging from individual structures to regions. Many innovative studies of individual sites and the implications of the results for issues including social structure and organization, processes and rates of site establishment, growth, decline, and abandonment, internal and external relationships, and the identification and timing of specific events have been accomplished since 1963. Outstanding examples include chronological studies of the inhabited pueblos of Walpi (Ahlstrom *et al.* 1991) and Acoma (Robinson 1990), 13th-century cliff dwellings in northeastern Arizona (Dean 1969), the 9th century Duckfoot Site in southern Colorado (Lightfoot 1992), Neolithic lake dwellings in Germany (Billamboz 1996) and Switzerland (Tercier *et al.* 1996), Neolithic wooden trackways in England (Hillam *et al.* 1990; Morgan *et al.* 1987), Viking burial ships in southern Norway (Bonde and Christensen 1993), the settlement of Haithabu in Schleswig-Hollstein (Eckstein 1978), the medieval city of Novgorod southeast of St. Petersburg (Kolchin 1967), the Hanseatic town of Lübeck (Wrobel 1994) and Trier Cathedral (Hollstein 1980) in Germany, and the Tudor warship the *Mary Rose* (Bridge and Dobbs 1996).

Multisite studies illuminate the temporal and spatial patterning of settlement and interrelationships among contemporaneous communities. Examples include Bannister's (1965) analysis of 9th-12th century towns in Chaco Canyon, Harrill and Breternitz's (1976) comparison of site construction episodes in Johnson Canyon in southeastern Colorado, Towner's (1992) work on historical Navajo settlement and intergroup relations in northwestern New Mexico, Schlanger *et al.*'s (1993) study of prehistoric regional settlement dynamics in the Four Corners area of the Southwest, and Hurni and Orcel's (1996) and Tercier *et al.*'s (1996) analyses of the spatial patterning of dates from, respectively, medieval buildings and Neolithic sites in Switzerland.

Akin to the dating of individual sites is the dating of particular wooden artifacts including utensils, containers, furniture, statues, figurines, and the backing panels of paintings. In the Old World (Baillie 1995: 45–56; Baillie *et al.* 1985; Eckstein *et al.* 1986; Lavier and Lambert 1996), tree-ring dating not only places particular art objects in time but helps evaluate the status of pieces of questionable authenticity. In the New World, artifact dating has involved objects ranging from Eskimo wooden masks, containers, and tools (Giddings 1941) to historic religious paintings from New Mexico (Wroth 1982).

Behavioral Applications

Following Robinson's (1967) lead, the use of tree-ring sample collections to infer various aspects of past human behavior has proliferated. Wood procurement activities are revealed by various attributes of archaeological tree-ring samples. The abundance of fir and spruce beams in Chaco Canyon sites documents the prehistoric long-distance (>50 km) transport of thousands of timbers from surrounding mountains (Betancourt *et al.* 1986). In northern Europe, geographic affinities indicated by the strength of crossdating between archaeological ring series and various local master chronologies show that timber was imported from the eastern Baltic region and Belgium into, respectively, Hanseatic cities in northern Europe (Bonde *et al.* 1994) and the medieval Dutch town of 's-Hertogenbosch (Jansma 1992) and specify eastern Baltic sources for art-historical timbers in England and Flanders (Baillie *et al.* 1985).

Four tree-cutting seasons are indicated by diagnostic combinations of dates and complete and incomplete terminal—the last ring grown by a tree before death—rings (Dean and Warren 1983: 229–230). A suite of incomplete terminal rings dated to a single year indicates cutting during the summer growing season; a set of complete terminal rings dated to the same year specifies cutting during the winter between growing seasons; a mix of complete and

incomplete terminal rings dated to the same year indicates felling in the late summer or early fall when some trees had ceased growth (complete) and others had not (incomplete); complete terminal rings dated to one year and incomplete terminal rings dated to the following year specify tree cutting in the spring when some trees had started to grow (incomplete) and some had not (complete). In the northern Southwest, terminal ring data indicate (1) a general shift from spring to fall wood procurement after AD 800 (Robinson 1967: 73–88), (2) autumn tree cutting at Betatakin and year-round felling at Kiet Siel (Dean 1969), (3) spring wood procurement at Chetro Ketl (Dean and Warren 1983: 229–230), and (4) summer and fall wood procurement at, respectively, Navajo summer and winter sheep corrals (Russell and Dean 1985). These results illuminate several aspects of human behavior: (1) a shift of wood procurement away from the spring planting season as agriculture became more important, (2) tighter social integration at Betatakin than at Kiet Siel, (3) a scale of social organization at Chetro Ketl that allowed major wood procurement activities during the planting season, and (4) confirmation of the Navajo biseasonal herding pattern. In Europe, incomplete terminal rings confirm that the famous Oseberg ship burial in southern Norway occurred in the summer of AD 834 (Bonde and Christensen 1993).

Modification traces on archaeological tree-ring samples provide data on the tools and techniques used in tree felling, debarking, limb removal, length reduction, and shaping. Tool marks allowed Wrobel (1994) to develop chronologies for wood working techniques, carpenters' marks, and ornamental styles in Hanseatic Lübeck, Germany. Dates from modified beams from northeastern Arizona place the replacement of girdling and burning by stone-ax cutting at about AD 600 (Robinson 1967: 27–42), a technological change that allowed important architectural developments. Similarly, the shift from groundstone to metal woodworking implements after the arrival of European colonists in the Southwest is evident in metal-tool marks on post-AD 1600 beams from pueblos and Navajo sites. Archaeological tree-ring collections specify prehistoric Southwestern bark removal practices ranging from retention in the Kayenta region (Dean 1969) to careful debarking with stone tools in Chaco Canyon (Dean and Warren 1983: 228–229) to allowing cambium-eating beetle larvae to loosen the bark at Mesa Verde (Graham 1965). Shaping of timbers is evident in the removal of the taper to produce cylindrical beams at Casas Grandes, Chihuahua, in the 14th century (Scott 1966: 35–37), in the squaring of timbers by Spanish builders after AD 1600 in the U.S. Southwest (Douglass 1929: 738), and in the manufacture of specialized structural elements for the *Mary Rose* in 16th-century England (Bridge and Dobbs 1996).

Differential use of species is indicated by the distribution of species among functional contexts. In the Southwest, for example, decay- and insect-resistant juniper was preferred for posts and other elements that came in contact with the ground, while other species more commonly were used as roof timbers.

Date distributions from individual contexts provide information on several different wood use practices. Stockpiling is evident when large numbers of logs cut in a particular year can be shown not to have been used until some years later as at Betatakin (Dean 1969: 77) and Chetro Ketl (Dean and Warren 1983). Early dates often indicate the reuse of elements salvaged from older, abandoned structures. Physical attributes of the timbers often confirm this inference as in Room 6 at Betatakin where older beams had been cut to fit other rooms, were more heavily weathered than freshly cut timbers, and were broken off rather than ax cut (Dean 1969: 65). Similar date distributions, combined with beam attributes diagnostic of natural tree death (extreme weathering, spiral grain, presence of the root crown, and diminished growth toward the end of the ring series) indicate the use of wooden elements from long dead trees. Deadwood commonly was used for fuel, for split-log "shakes" (Dean 1969: 144), in Navajo corrals (Russell and Dean 1985), and in Eskimo sites where driftwood was the primary source of timber (Giddings 1941). Finally, late dates may indicate the repair of an existing building, an inference that can be confirmed by evidence for later acquisition of the timbers, such as differential weathering or smoke blackening, or for attendant architectural modifications. For example, the contrasts between 1230s dates from smoke blackened timbers and 1930s dates from unsmoked logs identify modern repair of a prehistoric kiva at Spruce Tree House on Mesa Verde.

Finally, tree-ring data provide information on human use of living trees. Dated stone ax cut limb stubs on old living trees reveal that the 13th century AD occupants of Mesa Verde bent young Douglas-fir trees parallel the ground and then harvested the limbs that grew vertically from the horizontal trunks (Nichols and Smith 1965). The removal of bark from living trees by humans often leaves scars that illuminate the purpose, date, and seasonal timing of this activity. Numerous partially peeled trees testify to the use of the inner bark of ponderosa pine trees as a "starvation" food by Native Americans in western North America over the last few centuries (Martorano 1988; Swetnam 1984). Other bark removal activities, such as securing raw material for artifacts and blazing trails or surveys, also have been dendrochronologically identified and dated.

Environmental Information

If the preferential selection of species by the occupants of a site can be characterized or discounted, similarities in or differences between the species in the site and the modern plant community can indicate persistence or change in the local environment since the site was occupied. Numerous aspen beams in Kiet Siel, a cliff dwelling in an area presently devoid of such trees, specify a major environmental shift since the site was occupied at the end of the 13th century AD (Dean 1969: 148). In contrast, identical prehistoric and modern species assemblages show that such a transformation did not occur at Betatakin, only four miles away in the same canyon system (Dean 1969: 81).

Human impact on local or regional environments also can be inferred from archaeological tree-ring collections. Changing species dominance through time at Kiet Siel reveals a steady deforestation of the locality as increasingly less accessible species were procured for construction beams between AD 1250 and 1286 (Dean 1969: 148). Increasing use of spruce and fir beams after A.D. 1030 in Chaco Canyon indicates regional resource depletion that eventually required the importation of logs from high elevation forests 75 kilometers from the canyon (Betancourt *et al.* 1986). Similarly, dendrochronological sourcing studies indicate that the depletion of local wood supplies led to the medieval importation of timber into the southern Baltic region (Bonde *et al.* 1994), the Netherlands (Jansma 1992), and England (Baillie *et al.* 1985).

Geological dendrochronology also elucidates behaviorally relevant environmental variability. Perhaps the most well known geologic study is the placement of an eruption of Sunset Crater in northern Arizona at AD 1064 by dating prehistoric structures containing Sunset ash (Breternitz 1967) and tree-growth effects of the ashfall in wood from nearby archaeological sites (Smiley 1958). On a larger scale, inferred growth responses to the global cooling caused by the ejection of large quantities of dust into the atmosphere have been used to identify possible eruptions (Baillie 1995: 73–121). Frost-damaged bristlecone pine rings in the Great Basin (La Marche and Hirschboeck 1984) and tree-growth anomalies in Ireland (Baillie 1989a, 1989b, 1994) and Anatolia (Kuniholm *et al.* 1996) have been used in combination with other paleoenvironmental indicators and historical records to refine the dating of major known eruptions (such as those attributed to Santorini around 1628 BC, Hekla 3 around 1159 BC, and an unknown source around AD 536) and to suggest the existence of previously undocumented eruptions (Baillie 1996). Tree-ring evidence also has been used to identify earthquakes (Jacoby *et al.* 1992) and landscape alterations (Heikkinen 1994) that may have impacted human groups. Equally significant is the construction of high resolution alluvial chronologies through the tree-ring dating of living and dead trees buried in floodplain sediments on the Colorado Plateau (Dean 1988; Karlstrom 1988) and elsewhere (Alestalo 1971; Becker 1975; Shroder 1980). The Colorado Plateau sequences allow the reconstruction of alluvial depositional and hydrologic conditions and processes that directly affected agriculture productivity and the survival of human populations in the region (Plog *et al.* 1988).

Archaeologically important environmental information also resides in the ring width and density variation that allows the dendroclimatic reconstruction of past environmental variability (Fritts 1976). A network of 25 climate sensitive chronologies was used for qualitative reconstructions that measure relative variability in climate from AD 680 to 1989 at each of the stations and across the Southwest (Dean and Funkhouser 1995; Dean and Robinson 1977). Combining dendroclimatic retrodictions with reconstructions of other environmental phenomena reveals the temporal and spatial patterning in a broad spectrum of environmental variability (Baillie 1996: 135–148; Dean *et al.* 1985; Diaz *et al.* 1989). These reconstructions are rich sources of hypotheses about human adaptive behavior to be tested against archaeological data on local (Dean *et al.* 1978) and regional (Plog *et al.* 1988) scales of analysis.

Quantitative dendroclimatic reconstructions at local (Lebo 1991; Rose 1994; Rose *et al.* 1981; Van West 1994) and regional (Briffa *et al.* 1990; Fritts and Shao 1992) scales illuminate past climatic variations that affected human populations. Annual crop production reconstructions in the Southwest (Burns 1983; Van West 1994; Van West and Altschul 1994) measure the effects of climatic variability on cultural production and storage systems. Dendrohydrologic reconstructions of annual and seasonal streamflow in the Salt River (Graybill 1989) reveal low and high flows that would have impacted prehistoric Hohokam irrigation agriculture through, respectively, deficient water supplies or the flooding of canal systems (Nials *et al.* 1989).

The burgeoning field of dendroecology uses tree-ring data to elucidate phenomena such as changes in the composition and distribution of plant communities, air pollution, and CO_2 enrichment of the atmosphere. An aspect of dendroecology particularly relevant to human behavior is the use of dated fire scars in trees to reconstruct the frequency, intensity, and extent of past forest fires. These efforts have produced detailed fire histories for numerous areas in western North America, the most impressive of which is a 3,000-year record for Sequoia National Park, California (Swetnam 1993). Obviously, the rate and intensity of natural wildfires is potentially important to human populations, and in many areas humans set fires to prepare fields, control undergrowth, or enhance natural productivity. Equally interesting are human behavioral impacts on natural fire regimes. Reduced fire frequencies resulting from both grazing (Savage and Swetnam 1990) and fire suppression (Dieterich 1980) are visible in dendroecological fire histories.

FUTURE PROSPECTS

Based on the growing level of interest in dendrochronology around the world, it is safe to predict that the discipline will continue to expand its geographic scope and its relevance to an even broader spectrum of scientific enquiry. An easily projectable trend is the construction of ring chronologies in areas hitherto unexplored or thought to be unsuitable for tree-ring studies. Paramount among the former are vast areas of Asia where studies in China, Siberia, and the Tibetan uplands are beginning to tap a huge dendrochronological potential. The latter include the South American and southeast Asian tropics

and wet areas of Australia, New Zealand, and Tasmania where, against all expectations, crossdatable ring records have been discovered. These developments have enormous archaeological potential in terms of both site dating and climatic reconstruction, particularly in China, Siberia, the Near East, northern Africa, South America, and the Arctic. In addition to the chronological and environmental improvements occasioned by this expansion will be the development of new behavioral applications, which are limited only by the archaeologists' imagination and skill.

A number of future developments can be predicted for the practice of dendrochronology. The ongoing search for additional relevant attributes of ring morphology is likely to establish the dendrochronological potential of several density measures, density and width characteristics of earlywood and latewood, cell size and wall thickness, pore size in deciduous species, and others (Evans *et al.* 1996; Tardif 1996). Refined sample collection and preparation methods along with advances in radiography and densitometry will make the analysis of density variables simpler, more efficient, and less costly. Image analysis, which captures both width and density data from samples or CRT images, underlies the development of integrated work stations capable of capturing, storing, and analyzing a broad spectrum of tree-ring data.

Expectable developments in the analysis of tree-ring data include the refinement of curve fitting procedures and data equalization techniques to remove nonclimate related variability while preserving the full spectrum of frequency and amplitude attributes of tree-growth response to climatic and other exogenous factors. Similarly, improved collection, preparation, and extractive procedures will advance analysis of the contents of rings, such as radioactive and stable isotopes and trace elements. These developments undoubtedly will improve the resolution of the dendrochronological calibration of the radiocarbon time scale through the use of smaller, more temporally discrete samples (Stuiver 1993). At the same time, automated crossdating routines are continually being perfected, and they may eventually be able to deal with missing and false rings.

Important developments can be expected in dendroclimatic reconstruction, one of the most active components of tree-ring science due to its relevance to climate modeling and large scale natural and anthropogenic climate processes such as ENSO, atmospheric CO_2 enrichment, and global change. The use of very large tree-ring data arrays of continental or even hemispherical extent (Briffa *et al.* 1996; Cook *et al.* 1996; Meko *et al.* 1993) will illuminate extremely large scale climatic variations (Fritts 1991; Hirschboeck *et al.* 1996), while tightly focused studies will elucidate fine-grained, locality-level variability in various climatic parameters. New mathematical techniques of maximizing and characterizing the climate signal in tree rings and of producing climatic reconstructions that preserve the full range of variability in past climate are being developed, tested, and applied (Van Deusen and Reams 1996). Mechanistic models of climatic effects on the formation, growth, and maturation of individual cells and rings will clarify climate-growth relationships and allow better dendroclimatic retrodictions (Fritts *et al.* 1991). Improved reconstructions resulting from these efforts will, of course, enhance understanding of culture-environment interactions on spatial scales ranging from localities to regions and temporal scales ranging from seasons to millennia.

A clear trend in dendrochronology that undoubtedly will persist is the increasing global interaction and cooperation among practitioners of the science. Growth in the geographic scale of dendrochronological investigation will stimulate concomitant growth in the sharing of data and techniques among scientists from the regions involved. A manifestation of this trend is the International Tree-Ring Data Base (ITRDB), a cooperative effort to pool dendrochronological data, chronologies, reconstructions, references, and analysis programs and make them available to interested parties. These data can be accessed through the World Data Center for Paleoclimatology at the National Oceanic and Atmospheric Administration's National Geophysical Data Center in Boulder, Colorado. A further indication of this cooperative effort is the ITRDB Forum for Dendrochronologists, an e-mail network that facilitates the rapid dissemination of information among workers and allows important issues to be raised and debated in a timely fashion. This interaction has pinpointed and resolved numerous problems and differences in tree-ring practice, exposed the strengths and weaknesses of different approaches and methods, and fostered attempts at systematizing and standardizing the principles and procedures of dendrochronology. Enhanced cooperation, the sharing of data, methods, and results, and lively debate of pertinent issues will strengthen dendrochronology's stature as a science of growing relevance to a host of concerns that face humankind today.

The bright future of the discipline, however, should not be allowed to obscure some problems that will become increasingly vexatious as the method is expanded. Several archaeologically relevant problems must be seriously addressed (Dean 1996a). First is the necessity to develop acceptable procedures for evaluating dates that are challenged on historical, archaeological, geological, or other grounds. Such challenges would involve only a tiny fraction of the dates derived and would entail the statistical and visual inspection of quantified ring attribute data *and* of the actual samples or of representations of the samples such as photographs. Since dating and verification require access to the samples, the second problem is providing for the preservation and curation of wood and charcoal samples. In addition to maintaining samples for inspection, such collections are valuable research resources for a gamut of not always foreseeable studies. Third, a standard nomenclature is necessary to characterize and compare tree-ring dates so that they can be related to the archaeological or other contexts with which they are associated. Fourth, a real need exists to develop criteria for characterizing and ranking date clusters, the most powerful

indicators of the dating of past events. Fifth is the need for formal principles for identifying anomalous dates, that is, dates that do not apply to the archaeological materials with which they are associated. Finally, since past human behavior toward trees and wood is the foremost cause of dating anomalies, it is necessary to develop general and specific models of human wood use behavior (Dean 1996b).

CONCLUSION

Although problems exist, they are being seriously addressed by the world dendrochronological community, and progress can be expected on all fronts. The carefully controlled expansion of tree-ring science into all areas of the globe, its application to an ever broader range of past and present phenomena, and its unparalleled utility as a source of baseline data for measuring current environmental excursions and predicting future variations endow dendrochronology with a bright future. In all likelihood, the next thirty years will produce changes and progress equal to those accomplished since Bannister's landmark paper of 1963.

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Chapter 3

Radiocarbon Dating

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ABSTRACT

This chapter reviews the basic elements of the radiocarbon (^{14}C) dating method and summarizes three generations of ^{14}C studies in archaeology. It considers in greater detail several major advances in ^{14}C research including the extension of the calibration of the ^{14}C time scale into the late Pleistocene, further detailed characterization of Holocene short-term perturbations (de Vries effects), and the development of accelerator mass spectrometry.

INTRODUCTION

Radiocarbon (^{14}C) dating, now in its fifth decade of general use, continues to be the most widely employed method of inferring chronometric age for late Pleistocene and Holocene age materials. An international conference held in 1990 and resulting volume, *Radiocarbon After Four Decades: An Interdisciplinary Perspective* (Taylor *et al.* 1992) summarized the major contributions that ^{14}C had made as a dating and biological and environmental tracer isotope over its first 40 years. The overall influence of the ^{14}C method is eloquently reflected in a statement nominating Willard F. Libby (1908–1980) for the 1960 Nobel Prize in chemistry: "Seldom has a single discovery in chemistry [^{14}C dating] had such an impact on the thinking in so many fields of human endeavor" (Nobel Foundation 1964).

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