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Archaeological Tree-Ring Dating at the Millennium

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Tree-ring analysis provides chronological, environmental, and behavioral data to a wide variety of disciplines related to archaeology including architectural analysis, climatology, ecology, history, hydrology, resource economics, volcanology, and others. The pace of worldwide archaeological tree-ring research has accelerated in the last two decades, and significant contributions have recently been made in archaeological chronology and chronometry, paleoenvironmental reconstruction, and the study of human behavior in both the Old and New Worlds. This paper reviews a sample of recent contributions to tree-ring method, theory, and data, and makes some suggestions for future lines of research.

KEY WORDS: dendrochronology; dendroclimatology; crossdating; tree-ring dating.

INTRODUCTION

Archaeology is a multidisciplinary social science that routinely adopts analytical techniques from disparate fields of inquiry to answer questions about human behavior and material culture in the prehistoric, historic, and recent past. Dendrochronology, literally "the study of tree time," is a multidisciplinary science that provides chronological and environmental data to an astonishing variety of archaeologically relevant fields of inquiry, including architectural analysis, biology, climatology, economics, ecology, fire history, forestry, geology, history, hydrology, pollution studies, political science, resource economics, sociology, volcanology, and other disciplines. Tree rings are also used to calibrate radiocarbon dates (see Taylor, 2000) and to confirm the veracity of other chronometric dating techniques, including archaeomagnetic (see Eighmy, 2000), historic (Towner, 2000), obsidian hydration (see Beck and Jones, 2000), and luminescence dates (see Feathers, 2000), as well as chronologic sequences derived from seriation (see Blinman, 2000) and stratigraphic analysis (see Stein, 2000).

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The analytic and interpretive utility of tree-ring dating stems from the fact that it can inform archaeological research in three broad arenas: chronometric, environmental, and behavioral (Dean, 1996a). The chronometric aspect of tree-ring dating has the longest history and is the most commonly known—tree rings can be used to date objects, features, and sites. By extension, tree-ring dates also can be used to date more abstract archaeological entities such as periods, stages, phases, and styles. The environmental aspect of modern tree-ring dating today enjoys the most worldwide application, as tree rings can be used to reconstruct numerous environmental variables, including temperature, precipitation, stream flow, drought severity, fire frequency and intensity, insect infestation, atmospheric circulation patterns, and others. The behavioral aspect of tree-ring dating has a shorter and more restricted pedigree, but the analysis of tree-ring dates and associated attributes within their archaeological contexts allows archaeologists to make inferences regarding wood-use practices, trade, and other economic variables. Note, however, that a critical disparity exists in the data of interest to these different aspects. Archaeologists concerned with the chronological and behavioral aspects of tree-ring dating are interested only in the date provided for the last ring on a specimen; archaeologists concerned with environmental reconstructions are interested in data from all the rings in a given tree-ring series.

Given the explosion in archaeologically relevant tree-ring research in the last decade, an overview is clearly warranted. The multidisciplinary nature of both archaeology and dendrochronology make it difficult to cleanly compartmentalize the myriad recent publications that may be of interest to archaeologists in both the New and Old Worlds. In addition, my experience is limited to archaeological dendrochronology of the New World, though I have more than a passing familiarity with certain aspects of Old World, and specifically European, archaeological dendrochronology. Recent contributions to dendroclimatology are considered only if they have direct bearing on archaeological research, though references and data sources are provided for the reader interested in such reconstructions. With these biases in mind, and after reviewing key concepts in the derivation of tree-ring dates and their interpretation, this paper offers an evaluation of the state of archaeological tree-ring dating at the millennium.

METHODS AND PRINCIPLES OF DENDROCHRONOLOGY

Crossdating

The fundamental principle of dendrochronology is crossdating (Fig. 1), which is classically defined as "the procedure of matching ring width variations . . . among trees that have grown in nearby areas, allowing the identification of the exact year in which each ring formed" (Fritts, 1976, p. 534). Fritts and Swetnam (1989, p. 121) added that crossdating is a procedure that "utilizes the presence and absence of

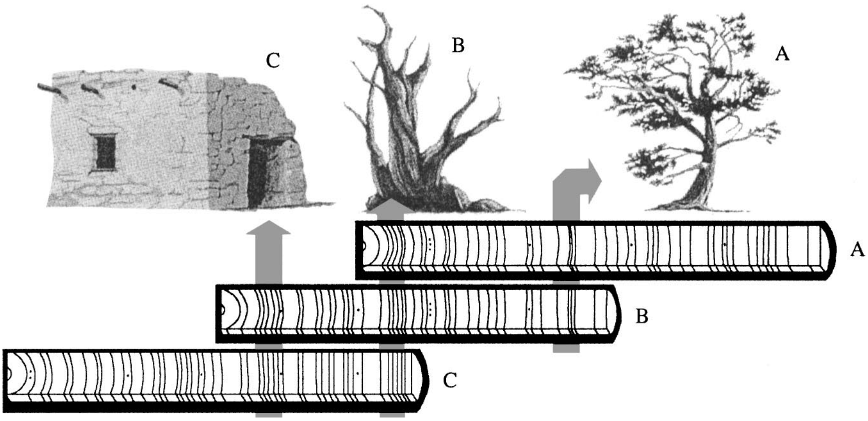

Fig. 1. The principle of crossdating and the basic method of chronology construction. Dendrochronologists analyze tree-ring specimens and crossdate patterned ring-width variations going back further and further in time, from living trees to dead snags and prehistoric beams. (Courtesy of the Laboratory of Tree-Ring Research, University of Arizona, Tucson.)

[ring] synchrony from different cores and trees to identify the growth rings that may be misinterpreted" (Fritts and Swetnam, 1989, p. 121). It is well known that many tree species add one growth ring per year. The problem for dendrochronologists is that in particularly stressful years many tree species will either fail to produce a ring, which leads to a "missing ring," or produce an incomplete, or "locally absent ring," "lens," or "moon ring" (Krapiec, 1999; see Fig. 2). To complicate matters further, certain tree species may produce a "double" or "false" ring; when the earlywood cells (i.e., those in the ring that are larger, thin walled, and therefore lighter) are being produced during a growing season, and particularly stressful climatic conditions return and lead to a general decrease in the rate of tree growth, a band of latewood cells (i.e., those that are smaller, thicker walled, and therefore darker) will be produced. If and when favorable conditions return during that growing season, earlywood cell production will begin anew, and the normal band of latewood cells will be created at the end of the growing season (Jacoby, 2000a). The key to distinguishing between double or false rings and annual rings lies in the nature of the transition between the latewood and earlywood cells: in a false or double ring the transition is gradual due to the phasing in and out of favorable growing conditions (Fig. 3). In an annual tree ring, the transition from one ring's latewood to the next ring's earlywood is abrupt because ring production actually stopped for some period of time, typically during winter.

The parameters used in crossdating differ depending on geographic and climatological variables and their effects on tree growth, as well as the research questions of interest. Most commonly, crossdating is performed on ring-width variation, but successful crossdating has been accomplished using variations in ring density,

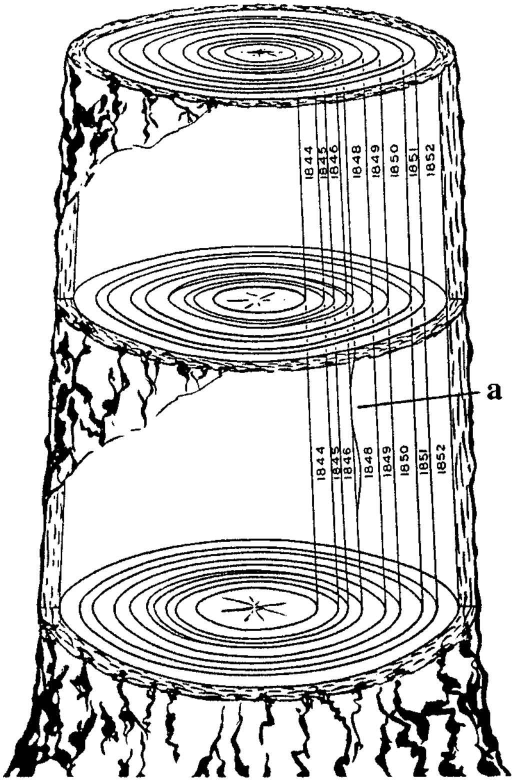

Fig. 2. Schematic cross-section of a tree stem showing a "locally absent" ring for A.D. 1847. If a dendrochronologist cores the tree at radius **a**, the ring for A.D. 1847 will be deemed "missing" and will be identifiable as such only when that core is compared to those taken from higher up the stem. (Courtesy of the Laboratory of Tree-Ring Research, University of Arizona, Tucson.)

distribution of multiple growth bands, the isotopic content of rings, and frost and fire scars (Dean, 1996a). Crossdating is possible because trees growing in the same (variously defined) regions and under the right conditions record the same *climate signal* in their rings. Although their growth patterns may differ in absolute size, the relative size of rings in trees from the same stand or region will often be the same, because the climate signal affects them all the same way. Other factors (e.g. competition, insect infestation, accidents, etc.) may have an effect as well.

In the arid American Southwest, where tree species tend to be stressed by water deficits rather than temperature extremes, ring-width variation is pronounced enough that crossdating can be performed using a visual, analog technique developed in the early part of this century by Andrew Ellicott Douglass of the University

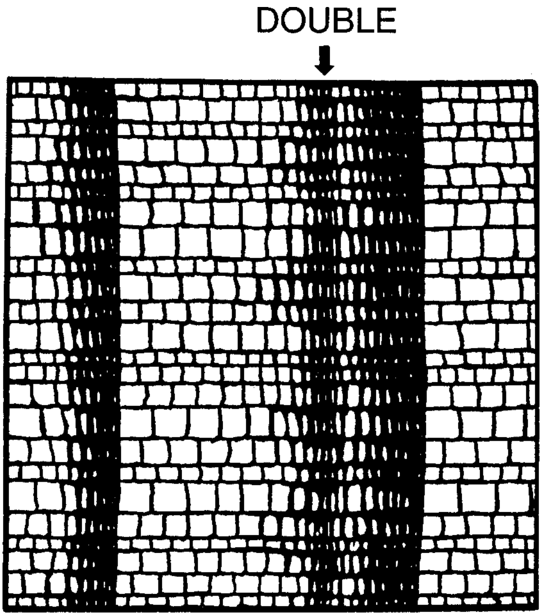

Fig. 3. A schematic view of a "double" or "false" ring, caused by the onset of stressful conditions before the end of the growing season. (Courtesy of the Laboratory of Tree-Ring Research, University of Arizona, Tucson.)

of Arizona (Douglass, 1929; see Nash, 1997a, 1998, 1999, 2000a). This analog technique produces a graphic representation of ring growth, known as a "skeleton plot," in which particularly narrow rings are emphasized and characteristic ring features are noted (Fig. 4). Once a number of skeleton-plotted series are compared, all missing and double rings are identified, and the series have been correctly crossdated, a summary master chronology is developed and used to visually crossdate new specimens (Douglass, 1941). For archaeological purposes, one hopes that older and older specimens will be discovered that allow the tree-ring chronology to be extended further and further back in time (Douglass, 1935). When multiple local master chronologies have been crossdated, they may be combined to produce regional chronologies (Schulman, 1956).

A different situation obtains in the eastern United States, Alaska, Europe, South America, Asia, and other parts of the world where ring growth is usually constrained by complex interactions of temperature, precipitation, and other factors (Schweingruber, 1989, 1993). In these areas, ring-width variation tends to be less pronounced than in the arid Southwest, and the process of extracting climatic information from the ring sequences is more complicated. As a result, ring-width variations are usually measured with great precision, and sophisticated

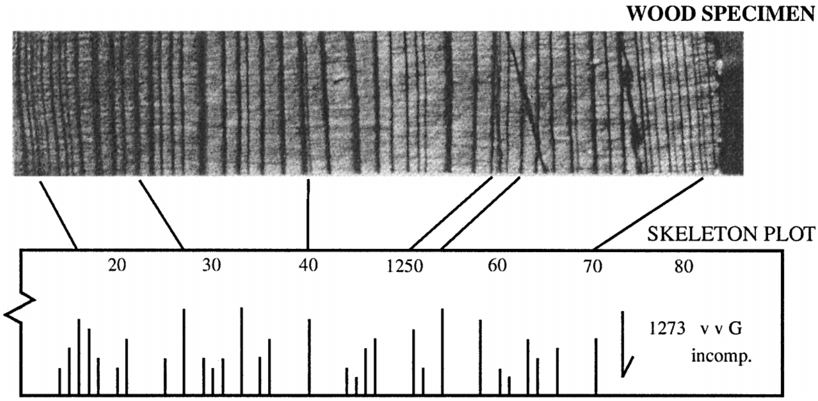

Fig. 4. A schematic view of a skeleton plot, which is a graphic representation of ring-width variability that emphasizes narrow rings and other ring characteristics. The skeleton plot is compared to a regional summary or "master" chronology in order to derive a date for the specimen. (Courtesy of the Laboratory of Tree-Ring Research, University of Arizona, Tucson.)

statistical techniques and computer programs are then used to crossdate the ring-width measurements (Holmes, 1983; see Baillie, 1995). All tree-ring dates, no matter if they are obtained using skeleton plots or ring-width measurements, must be verified by a dendrochronologist who returns to the wood or charcoal specimens to solve particularly recalcitrant crossdating problems. Although it has withstood the test of time and is still commonly used in archaeological dating in the American Southwest, the skeleton plot technique has been criticized by those who do not understand the basic principles of dendrochronology (see Stokes and Smiley, 1996) as being "subjective," simply because it is not quantitative. The terms "quantitative" and "objective" are not synonyms, however, and Douglass long ago pointed out the fallacy of conflating these terms when he pointed out that one does not recognize friends simply by measuring their faces (see Nash, 1999, p. 115)! Pattern recognition is key to the operation, and indeed the scientific aspect of dendrochronology lies not in unnecessary quantification, but in *replication* (Baillie, 1995, pp. 21–27).

Replication in dendrochronology occurs at three empirical and analytical levels. It occurs when independent tree-ring samples from the same geographic area yield the same ring-width pattern because they record the same climate signal, it occurs when independent tree-ring chronologies can be crossdated (for the same reason), and it occurs when dendrochronologists arrive at the same results, independently, because of the efficacy of the crossdating technique. A classic example of replication at all levels occurred when LaMarche and Harlan (1973), of the University of Arizona, independently crossdated a bristlecone pine chronology from the White Mountains of California, which was then used to calibrate the radiocarbon time scale. From the archaeologist's perspective, the analytical utility of tree-ring dates results from the fact that, when crossdated, they have been determined independent of other archaeological data from the site, region, or feature in question (see Hillam, 1987, 1998).

Archaeological Tree-Ring Data: Cutting Dates, Noncutting Dates, and Date Clusters

From a dendrochronological perspective, all crossdated and verified tree-ring dates are created equal. There is no associated statistical uncertainty associated with any crossdated tree-ring date (Jacoby, 2000a); a corollary to this maxim is that tree-ring specimens either crossdate or they do not. Dendrochronologists do not succumb when archaeologists ask for a “likely date” for a specimen (Baillie, 1995), nor do they use independent archaeological data to propose a probable date for an undatable specimen. Once a tree-ring date is determined, however, the interpretation of that date within its archaeological context becomes the archaeologists’ problem and responsibility (Dean, 1978). From that perspective, all tree-ring dates are *not* created equal, and a body of theory has been developed over the last seven decades to guide the interpretation of archaeological tree-ring dates (Bannister, 1962; Dean, 1978; Haury, 1935; Hillam, 1987, 1998; Nash, 1999; Towner *et al.*, 2001). For our purposes, the difference between cutting dates and noncutting dates is important, as is the concept of date clustering.

Cutting dates are assigned to crossdated wood or charcoal specimens that possess evidence that the last ring present on the specimen was the last ring grown by the tree before it died. *Noncutting* dates are assigned to crossdated specimens if there is no evidence indicating that the last ring present on the specimen is the last one grown before the tree died. Note that cutting dates and noncutting dates are not necessarily exclusive: a noncutting date *may* actually record the date of tree death, but there happens to be no discernible, definitive criteria (e.g., bark, beetle galleries, patinated surfaces, etc.) present on the specimen that allow the designation of “cutting date.” Noncutting dates are therefore potentially biased estimates of beam procurement and use events because they underestimate the actual date of death of the tree (Ahlstrom, 1997; Dean, 1978).

The archaeological interpretation of noncutting dates is further complicated because there is no way of knowing exactly how many rings are missing from the outside portion of the specimen. The vagaries of tree growth, site formation processes (see Schiffer, 1987), specimen preservation, and wood use behavior (Dean, 1996b) ensure that only a fraction of tree-ring specimens submitted for analysis date, and, of those that do, most yield noncutting dates because the outer portion of a beam is more likely to be lost due to decay, insect infestation, or anthropogenic removal (Dean *et al.*, 1996). Despite recent efforts to alleviate the interpretive difficulties associated with noncutting dates, they remain the most recalcitrant of tree-ring dates (Nash, 1997b; see below) for archaeological purposes.

Another concept useful for the archeological interpretation of tree-ring dates is that of *date clustering* (Ahlstrom, 1985; Baillie, 1995; Haury, 1935). If a number of tree-ring dates from a given site or provenience cluster in one to three calendar years, one can infer that some archaeologically relevant construction event occurred that year in prehistory and has been dated by the tree rings. For the archaeologist interested in determining an accurate and precise date of construction for a given room or site, the ideal date distribution curve (or histogram) would be a vertical line consisting of *x* number of cutting dates in a given year. Because of beam stockpiling, manipulation, reuse, structure repair, and other site formation processes, actual date distribution curves are usually skewed left, with long tails and occasional date clusters (see Ahlstorm, 1997, p. 343; Ahlstrom and Smiley, 1998, p. 150).

ARCHAEOLOGICAL TREE-RING DATING IN THE NEW WORLD

Applicable Species

In order to be crossdatable and useful in archaeological analyses, tree species must produce annual growth rings that are uniform around the tree stem (i.e., are characterized by "circuit uniformity"), must live for decades and, preferably, centuries, and must have been used extensively by humans either for habitation or fuel. Researchers have found that crossdating exists in dozens, if not hundreds, of tree species around the globe, and new species are added to the list every year (Grissino-Mayer, 1993). In North America, millennial-length chronologies have been developed for two species of bristlecone pine (*Pinus longaeva* in the Great Basin and *Pinus aristata* in the Rocky Mountains), bald cypress (*Taxodium distichum*), coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), eastern cedar (*Juniperus virginiana*), juniper (*Juniperus* sp.), larch (*Larix* sp.), lodgepole pine (*Pinus contorta*), limber pine (*Pinus flexilis*), mountain hemlock (*Tsuga mertensiana*), ponderosa pine (*Pinus ponderosa*), and giant sequoia (*Sequoiadendron giganteum*) (Jacoby, 2000a).

In the southern hemisphere, successful crossdating has been achieved on alerce (*Fitroya cupressoides*) and pehuen (*Araucaria araucana*), also known as "Chilean pine" or the "monkey puzzle tree," specimens in South America, kauri (*Agathis australis*) specimens in New Zealand, clanwilliam cedar (*Widdringtonia cedarbergensis*) specimens in Australia and Tasmania, and huon pine (*Lagarostrobus franklinii*) in Tasmania (Jacoby, 2000a; Norton, 1990). In an exciting development, the second-oldest living tree species in the world was recently discovered in South America (Lara and Villalba, 1993; see also Roig *et al.*, 2001). A 3620-year old alerce specimen suggests there are great opportunities for the continued development and application of millennial-length chronologies in that part of the world.

Chronometry and Chronology

There are four well-established tree-ring laboratories in North America, though only two are currently involved in archaeological dating. The oldest (incorporated 1937) is the Laboratory of Tree-Ring Research at the University of Arizona, where Jeffrey S. Dean and a host of other scholars have focused on archaeological date and chronology production as well as the dendroclimatology of the American Southwest and beyond. The Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University, led by Peter Kuniholm, has for the last three decades focused on date and chronology production in the Old World (and will, therefore, be discussed further below). The Malcolm and Carolyn Wiener Tree-Ring Laboratory at the University of Arkansas, under the leadership of Malcolm Cleaveland and David Stahle, has focused of late on dendroclimatology, but in the late 1970s and early 1980s had some success in dating early historic structures in the American Midwest and Southeast (Stahle, 1979; Stahle and Wolfman, 1985). The Tree-Ring Laboratory at the Lamont–Doherty Earth Observatory of Columbia University focuses on dendroenvironmental applications, though Gordon Jacoby and others have made contributions that archaeologists have found analytically useful over the years. There are many other, smaller tree-ring laboratories at universities across North America, but these tend to be associated with individual scholars rather than institutions and are not discussed further here (see Additional Resources section below).

Because archaeologists in North America are only occasionally interested in chronology and chronometry for their own sake, published papers on archaeological tree-ring dating are surprisingly uncommon in the literature and tend to be concentrated in the American Southwest, although tree-ring dating of archaeological sites has successfully been performed elsewhere in North America (Bell, 1951; Giddings, 1940; Nash, 2000b; Stahle, 1979; Stahle and Wolfman, 1985). Tree-ring dates are often relegated to appendices in the cultural resources management (or “gray”) literature, if they are published at all. Occasional papers do appear however, and a review of some recent contributions is informative and enlightening.

Recently, Dean *et al.* (1996) published 21 new tree-ring dates for pinyon and ponderosa pine charcoal specimens from the Gibbon Springs Site and Whiptail Ruin in the arid Tucson Basin, Arizona. This is a significant development because for years it had been assumed that charcoal or wood found in desert sites would all be from riparian or desert hardwood species and would therefore not be datable. Archaeologists working in such environments thus did not, and typically still do not, submit samples for dating, and a negative feedback loop emerged in which no specimens can be dated because none are submitted. In a similar vein, Nash (1995, 2000b) noted that, despite the fact that Giddings (1940) clearly demonstrated that archaeological tree-ring dating works in Alaska, archaeologists working in the Arctic simply do not submit tree-ring samples for analysis and instead rely on radiocarbon, seriation, stratigraphy, and other dating techniques for their chronometry and chronology development. It is nevertheless clear that productive avenues exist for continued tree-ring dating of archaeological sites in the Arctic, the Great Basin of western North America, northern Mexico and particularly mountainous Chihuahua, and other regions that have received comparatively little dendrochronological attention over the years.

With regard to the historic occupation of New Mexico, Ababneh *et al.* (2000) recently published new tree-ring dates for sites in Palluche Canyon, in the heart of the Navajo homeland. Their analysis suggests, as did Towner's dissertation (Towner, 1997), that pueblito sites in northwestern New Mexico were intermittent, short-term use sites occupied, possibly for defensive purposes, during the first half of the eighteenth century. Towner and Dean (1992) dated samples from the oldest Navajo Pueblito site to revise the dating based on modern dendrochronological analyses. Towner (2000) examined the concordance, and lack thereof, between tree-ring dates and historic documentation for Navajo sites to conclude that the historic documents are less reliable than is commonly assumed. These studies have scarcely scratched the surface in the application of tree-ring dating to historic and protohistoric sites in the Four Corners region.

In a detailed analysis, Ahlstrom (1997) examined patterning and sources of variation in large sets of archaeological tree-ring dates from Black Mesa, Arizona, Mesa Verde, Colorado, and Cedar Mesa, Utah, to make inferences regarding the comparative degree of chronometric and chronological control possible in these regions across space and through time. In general, he found that ninth-century pit structures on the Colorado Plateau are well dated (especially compared to sites in other regions) because the sites were burned when abandoned, preserving the beams as charcoal. In contrast, tenth- and eleventh-century surface sites are often poorly dated because they typically were not burned, and preservation problems lead to a high percentage of noncutting dates, if the specimens date at all. Finally, Ahlstrom (1997) found that thirteenth-century sites in the Four Corners region are well dated because of the unparalleled degree of preservation and the historically intense archaeological interest in the remarkable cliff dwellings of the American Southwest.

Ahlstrom and Smiley (1998) took Ahlstrom's Black Mesa analysis (Ahlstrom, 1997) a step further by including in the analysis the corpus of radiocarbon dates from Black Mesa. They were able to evaluate the interpretive power of both dating techniques under archaeological circumstances that approach the ideal for making chronological inferences. Their contribution provides valuable guidance in the interpretation of chronometric and chronological data of all kinds.

Dendrochronologists and archaeologists in North America and Europe have long attempted to develope methods to estimate cutting dates for specimens that yield only noncutting dates (e.g., Douglass, 1939; Graves, 1991; Hillam *et al.*, 1987; Hughes *et al.*, 1981; Nash, 1997b). Most often, attempts have taken

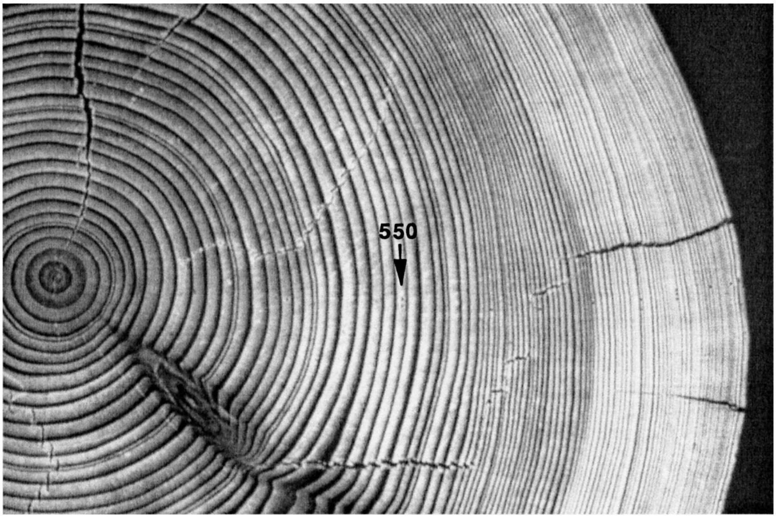

Fig. 5. A dated Douglas-fir specimen. The arrow points to the ring for A.D. 550. Note the difference in color between the darker, inner heartwood and lighter, outer sapwood, and the age-related decrease in ring-width as the tree grows older. (Courtesy of the Laboratory of Tree-Ring Research, University of Arizona, Tucson.)

advantage of the different levels of preservation between heartwood, which is the darker, inner portion of a coniferous tree trunk, and sapwood, which is the lighter, outer portion of the trunk (Fig. 5).

Nash (1997b; see also Nash, 1993) used heartwood and sapwood data from living-tree cores to calculate regression equations that predict the number of sapwood rings based on the number of heartwood rings present. Using case studies from the well-dated protohistoric, historic, and modern site of Walpi Pueblo in Arizona, he concluded that because of the statistical uncertainty associated with estimated cutting dates, they are best considered in the aggregate, in terms of the entire date distribution curve for a site. It is simply too difficult to reliably reconcile the absolute, precise calendar dates provided by crossdated specimens with the statistically uncertain nature of individual estimated cutting dates.

Using a similar technique, Dean and Ravesloot (1993) estimated cutting dates for the massive site of Casas Grandes, in Chihuahua, Mexico. On the basis of uncritical acceptance of 53 noncutting dates, which did not cluster, DiPeso (1974) had inferred an early and major construction phase at Casas Grandes between ca. A.D. 1044 and 1388. This inferred early occupation could not be reconciled with independent archaeological data, particularly the presence of significant amounts of Salado polychrome ceramics. Dean and Ravesloot's estimated cutting dates suggest that, in accordance with independent data, the occupation of Cases Grandes in fact postdated A.D. 1200, building activity was concentrated in the thirteenth and fourteenth centuries, the site was inhabited into the fifteenth century, and repair events occurred as late as A.D. 1470 (Dean and Ravesloot, 1993).

The suite of approximately 70,000 tree-ring dates generated by the Laboratory of Tree-Ring Research at the University of Arizona for the American Southwest remains underutilized from an analytical perspective. Though the pending computerization of archaeological tree-ring dates, site files, and other data sets will build upon previous efforts (e.g., Robinson and Cameron, 1991; Robinson and Towner, 1993) and greatly enhance the number of studies to which tree-ring dating may be applied, the fact remains that a great deal of work still needs to done. Priorities should include (1) the publication of tree-ring dates in other than the gray literature, (2) the continued extension of tree-ring studies into Basin and Range regions of Arizona, New Mexico, and Utah, and (3) renewed tree-ring research in the mountainous portions of Mexico and Alaska.

Prehistoric and Historic Behavior

The study of wood-use behavior has a relatively short pedigree in archaeological tree-ring analysis, but has recently come into its own as a field of inquiry.

Dean (1996b) analyzed a suite of tree-ring dates from Navajo and Anasazi sites to identify two radically different approaches to wood use. The prehistoric, pueblo-dwelling Anasazi used long, straight, heavy Douglas-fir and ponderosa pine timbers in rectilinear dwellings that usually contain dozens, but occasionally hundreds, of beams (Dean and Warren, 1983). The beams required communal labor to harvest and move, and were therefore deemed valuable enough to be stockpiled for periods of 1–5 years and recycled, in some cases for hundreds of years (Ahlstrom *et al.*, 1991). The prehistoric beams were cut with groundstone axes and were therefore harvested when alive, for groundstone axes cannot cut deadwood effectively. Ahlstrom and Smiley (1998) also found that Puebloan wood use is analogous to Cliff Dweller wood use. The historic-period Navajo, in contrast, used pinyon and juniper beams that tended to be shorter, lighter, and highly variable in shape. These beams can be moved by one or a few people, are easy to harvest with metal tools, and, because they are so common on the Colorado Plateau, do not need to be stockpiled and are therefore rarely recycled. Use of dead wood is common as Navajos had access to metal tools that can cut deadwood far more effectively than can stone tools (Dean, 1996b). Ahlstrom and Smiley (1998) note that prehistoric wood-use behavior by pithouse-dwelling Basketmaker populations on Black Mesa is more similar to that of the Navajo than that of the Anasazi, though the prehistoric Basketmakers obviously did not have access to metal tools.

On the basis of an analysis of nearly 1200 tree-ring samples and various documentary sources, Ahlstrom *et al.* (1978, 1991) were able to differentiate no fewer than three wood-use behavior regimens at the long-occupied site of Walpi

Pueblo, on the Hopi Mesas. The first was Hopi and similar to that exhibited by the prehistoric Pueblo. The second was Spanish and included the first use of metal tools. The third was European and included the first use of milled lumber, which arrived with the railroad. This case of modern beam transport can be contrasted with the analysis offered by Betancourt *et al.* (1986), who used crossdated tree-ring sequences at Chaco Canyon and Mount Taylor, New Mexico, to identify prehistoric beam transport across the Chacoan world.

Grissino-Mayer *et al.* (2001) crossdated slash (*Pinus elliottii*) and longleaf (*Pinus palustris*) pine specimens to corroborate historical records that such trees had been intentionally "boxed" to gather sap for the turpentine (e.g., "naval stores") industry in coastal Georgia from the mid-1700s through the 1950s, when the burgeoning pulp and paper industry supplanted traditional technologies.

Kaye and Swetnam (1999) analyzed tree-ring data and historic documents of Mescalero Apache, Euro-American settlement in southwestern New Mexico. The tree-ring data include fire-scar and peel-scar (created when humans remove ponderosa pine bark to get at the edible cambium during periods of resource stress) dates for hundreds of trees and in regional tree-ring chronologies. They found 150 peel-scar dates, none of which date earlier than 1772, from 10 sites. These dates indicate either substantial resource stress in the late eighteenth century, or they serve as a proxy date for the arrival of Mescalero Apache, for there is no documented evidence that Euro-Americans, who had been in the Southwest for two centuries, peeled trees in response to subsistence stress. Studies on culturally modified trees have also been conducted in the Pacific Northwest (Mobley and Eldridge, 1992; Prince, 2001).

Because of the intensive analysis required for behavioral studies of tree-ring data, such studies have essentially been the purview of archaeologists with specialized training in archaeological tree-ring dating, rather than archaeologist consumers of tree-ring dates. However, if such studies continue to provide insights into the vagaries of radiocarbon and other dating techniques (e.g., Ahlstrom and Smiley, 1998), as well as the potential biases or discrepancies inherent in the historic record (e.g., Grissino-Mayer *et al.*, 2001; Kaye and Swetnam, 1999; Towner, 2000), we should look forward to archaeologists who specialize in other topics making use of tree-ring data in their own analyses.

Paleoenvironmental Reconstruction

Though rudimentary environmental inferences from tree-ring dating have long been possible (e.g., narrow rings indicate dry years or cold conditions, wide rings indicate wet years or warmer conditions), modern dendroclimatology came into its own in the 1960s as a result of biological research into tree physiology and growth, the development of new statistical techniques, and the advent of high speed computers capable of processing large amounts of data (Dean *et al.*, 1996;

Fritts, 1976). Although such efforts were initially the purview of archaeologists with training in dendrochronology, recent years have witnessed an explosion of contributions by earth scientists working in conjunction with archaeologists.

Dean and Robinson (1977) provided archaeologists with one of the earliest and most readily accessible dendroclimatic reconstructions of precipitation in the American Southwest. They presented precipitation departures from long-term mean conditions for tree-ring chronologies from across the Southwest in the form of isobars, which archaeologists could overlay on settlement pattern data to make inferences regarding prehistoric population movements, subsistence stress, and the like.

In a now classic empirical paper, Dean *et al.* (1985, see also Dean *et al.*, 1994; Euler *et al.*, 1979) established a body of theory for interpreting how prehistoric populations on the Colorado Plateau may have reacted to environmental shifts recorded in various paleoenvironmental data sets, including dendroclimatic, hydrologic, palynologic, and others. In so doing, the authors differentiated between stable factors, low-frequency processes, and high-frequency processes. Stable factors are those that, from the perspective of individual human experience, effectively do not change. These include general habitat, general climate, geology, and topography. Low-frequency processes include those that have a period greater than one human generation, or about 25 years (other studies use generations of 30 or 50 years). These include climate trends, changes in alluvial groundwater levels, cycles of aggregation and degradation, and slope erosion. High-frequency processes are those that have a period of less than 25 years and include diurnal, seasonal, and annual trends, multiyear fluctuations in precipitation, temperature, frost-free days, drought, stream flow regimes, and changes in floral and faunal productivity. In a similar vein, Larson *et al.* (1996, p. 218) argue that climate's impact on any society is dependent on the magnitude, duration, and frequency of climatic events, the preexisting adaptive strategies of the human population effected, the natural response of important resources to the stress, and the population size and density of the group.

Using sophisticated Geographic Information Systems technology and a large body of tree-ring, soils, and dry-farming crop yield data, Van West (1990, 1994) produced a year-to-year reconstruction of agricultural productivity within a 700 sq mile portion of the Mesa Verde region from A.D. 901 to 1300. On the basis of this research, she argued that the Great Drought (A.D. 1276–1299) is an insufficient explanatory model for thirteenth-century regional abandonment.

Van West and Dean (2000; see also Ahlstrom *et al.*, 1995) examined the environmental characteristics of the Mesa Verde region for the A.D. 900–1300 period in an attempt to determine the reason for its final abandonment in the late 1200s. In the final analysis, they conclude that the abandonment of the central Mesa Verde region, rather than being perceived as a "failure" per se, simply constitutes an adaptive response to a period of diminished precipitation, depressed water tables, stream entrenchment, and high spatial variability in climate. Larson (1996) examined settlement pattern and environmental data to argue that agricultural intensification among the Virgin Anasazi may have been an adaptive response to drought between A.D. 1000 and 1015, but that a similar drought between A.D. 1120 and 1150 may ultimately have led to the abandonment of the region because population levels had increased to a level that was too high to allow continued agricultural intensification to serve as an adaptive strategy (see also Anderson, 2000a).

Using the highly refined archaeological and paleoenvironmental data available for the Long House Valley in northeastern Arizona, Dean *et al.* (2000) used computer simulations to model prehistoric economic behavior and settlement patterns over several centuries. Although still in need of further refinement, their agent-based model was able to reconstruct a great deal of what we know, on the basis of a wide variety of archaeological data, happened in the prehistoric past. Perhaps not surprisingly, the simulation and its predecessors have had difficulty reconstructing the final abandonment of the region, suggesting that this act was at least partially a result of sociocultural factors that are more difficult to include in the model and that may be less precisely recorded in the archaeological record.

Salzer (2000a,b) developed a bristlecone pine chronology (A.D. 663–1997) for the San Francisco Mountains that allowed him to develop the most accurate paleotemperature reconstruction for the American Southwest. He reconstructed annual mean-maximum temperature, a general measure of how warm it becomes during a given year. He used the data to try to explain the chaotic and tumultuous nature of the northern Anasazi archaeological record of the 1200s. The reconstruction indicates that A.D. 1195–1219 was the longest, if not most severe, cold period in the sequence; A.D. 1225–1245 was comparable, but not quite as severe; and that A.D. 1258–1271 was the shortest cold period and of intermediate severity. Although he did not find evidence of a “Little Ice Age” during this period, the turbulence (Lipe, 1995) evident in the archaeological record for the 1200s coincides with a period of low temperature, possibly induced by volcanic activity, and the abandonment of certain areas followed by large-scale aggregation in other parts of the Southwest (Salzer, 2000a, p. 312). Dean (1994) examined tree-ring, geological, and hydrological data from the American Southwest to argue that the Medieval Warm Period (A.D. 900–1300) is primarily a European phenomenon and cannot be seen, in the aggregate, to have affected prehistoric behavior in the Southwest during that period. At the opposite end of the continent, Stahle and Cleaveland (1994; see also Stahle *et al.*, 1988) could not find evidence for either the Medieval Warm Period (ca. A.D. 1000–1300) or the Little Ice Age (ca. A.D. 1600–1750) in baldcypress chronologies in North Carolina, South Carolina, and Georgia.

In the southeastern United States, dendrochronologists David Stahle and Malcolm Cleaveland have been working with archaeologist David Anderson to study the behavioral impact on Mississippian societies of unfavorable climatic conditions (Anderson, 1994; Anderson *et al.*, 1995; Stahle *et al.*, 2000). To do so, they used tree-ring data to reconstruct June Palmer Drought Severity Indices back into prehistory. The Palmer Drought Severity Index integrates precipitation, temperature, soil moisture capacity, and other data into an index that expresses the impact of meteorological drought on crop production. They found, among other things, that a sixteenth-century drought was the most severe and prolonged over much of North America in the last 1500 years (Stahle *et al.*, 2000; see also Stahle *et al.*, 1985a,b). The paleoclimatic data also indicate that drought may have played a role in the failure of a Spanish mission at Santa Elena, in what is now South Carolina, in the 1580s (Anderson, 1994; Anderson *et al.*, 1995) and the disappearance of the Roanoke Colony, off what is now North Carolina (Anderson, 2000b), also in the 1580s.

Blanton (2000) recently examined the bladcypress chronologies created by Stahle and colleagues (Stahle and Cleaveland, 1994; Stahle *et al.*, 1988) in light of the known historic occupation of the Jamestown Colony, on Jamestown Island, in what is now Virginia. Although tree rings could not be used to date the construction or occupation of habitation structures at the site, the 800-year chronologies clearly indicate that the most severe drought to affect the region occurred from 1606 to 1612. English colonists established Jamestown in 1607, at the beginning of the drought. It is entirely possible that resource stress, brought on by the detrimental effects of the drought on food supplies and water quality, led to increased agression between native inhabitants and the colonists. The evidence indicates that during the first decade of occupation, nearly 80% of the colonists lost their lives to famine, typhoid, dysentery, and other afflictions (Blanton, 2000, p. 78). Additional research is necessary to elucidate cause and effect, but the data are intriguing.

Jacoby *et al.* (1999) examined the dendrochronological effects in northwest Alaska of the historically recorded 8 June A.D. 1783 to 7 February 1784 eruption of Laki, in Iceland. Growth in stressed trees in Alaska is typically determined by growing season temperatures, and their reconstruction of ring density over a 400-year period indicates that an unusually cold summer occurred in 1783. Oral histories provided by the Kauwerak people describe “The Time Summertime Did Not Come,” and historical records provided by early settlers and traders indicate substantial resource stress and starvation in the 1780s. Again, additional research is necessary to further examine the relationship between these data sets.

Jacoby (2000b) examined trees near the San Andreas fault in southern California in an attempt to determine the date of the last major earthquake prior to the 1857 event. Crossdating of samples from nine trees indicated severe trauma and cessation or diminished growth sometime between the end of the growing season (e.g., September) of 1812, and the beginning of the growing season (e.g., April) of 1813. Independent examination of historical documents revealed that a major earthquake was felt in San Diego on December 8, 1812. Though such studies are not related to prehistoric archaeology, it is useful and important to empirically examine the concordance, or lack thereof, between tree-ring data and historical records (Towner, 2000).

There have been many exciting developments in archaeologically relevant dendroclimatology in North America. Such studies now encompass far more than precipitation or temperature reconstructions, and archaeologists of many different stripes are beginning to use tree-ring reconstructions to comment on the prehistoric human experience in North America. The clear lesson from such studies in the American Southwest, where the data are most refined, is to avoid environmental determinism. In the words of Van West and Dean (2000, pp. 19–20)

> Modern understandings of the relationship between culture and the environment . . . acknowledge that (their) interactions are complex and non-deterministic; various elements can be dependent, interdependent, facilitating, or neutral, and relationships among the elements can vary as specific historical circumstances change.

Correlation simply does not imply causation. (Dincauze [2000] recently published a comprehensive and informative treatment of the concepts, principles, and practice of environmental archaeology, and she reviews in great detail the many complexities involved in applying paleoenvironmental data in archaeological research.)

The annual and often seasonal level resolution offered by dendroclimatic reconstructions are both a blessing and a curse to archaeologists for, in the absence of historic data, no other data come remotely close to this level of resolution. As a result, it can be argued that tree-ring data are too resolved, even in comparison to the remarkable archaeological record of the American Southwest, to be of use to most archaeologists. Efforts are underway to devise tree-ring chronologies that reconstruct lower-frequency environmental variability that might more easily be compared to changes in the archaeological record (Briffa *et al.*, 1990; Norton *et al.*, 1989; Stahle and Cleaveland, 1994). Much additional research is nevertheless needed to reconcile the analytical difficulties created in the attempted marriage of highly resolved chronometric and climatologic data provide by tree rings and less-resolved archaeological data of prehistoric subsistence, social organization, settlement patterns, ceremonialism, and the like.

ARCHAEOLOGICAL TREE-RING DATING IN THE OLD WORLD

Applicable Species

In temperate Europe, crossdatable species include hardwood species such as pedunculate, or common, oak (*Quercus robur*) and sessile oak (*Quercus petraea*), though some pine species are used as well. In Ireland, some of the longest chronologies devised for Europe have existed for two decades (Baillie, 1982, 1995, 1999). British, French, Polish, Italian, Dutch, German, and Swiss dendrochronologists have made significant contributions using oak as well as Swiss stone pine (*Pinus cembra*), Austrian pine (*Pinus nigra*), and European beech (*Pinus* *sylvatica),* among other (Schweingruber, 1989, 1993, and references cited therein). Further east, in Slovenia, intensive dendrochronological research began in 1993 as researchers sought crossdating in silver fir (*Abies alba*), larch (*Larix decidua*), Norway spruce (*Picea abies*), and Scotch pine (*Pinus sylvestris*). Chronologies for silver fir and larch have been developed for A.D. 1505–1996 and A.D. 1380–1997, respectively (Cufar and Levanic, 1999). These efforts have been hampered by the long history of forest exploitation, for the old, slow growing trees were repeatedly harvested, leaving only the younger, faster growing trees that are less useful to dendrochronology.

Chronology and Chronometry

Dendrochronological research began in Europe in the 1930s when Bruno Huber first attempted to apply the Douglass method of tree-ring dating to various research questions in Germany. Various specialists, including Baillie (1982, 1995) and Schweingruber (1989, 1993), among others, have presented excellent overviews and should be consulted by the interested reader.

Productive dendrochronology programs exist all over the Old World, although, as in the New World, not all are engaged in archaeological dating. Archaeological dating programs exist in the Laboratory of Wood Anatomy and Dendrochronology at Lund University in Sweden, the Oxford Dendrochronology Laboratory, which has close ties to the Research Laboratory for Archaeology and the History of Art at Oxford University, and at the Interdisciplinary Institution for Archaeology in Vienna, Austria. The Ancient Monuments Laboratory at Sheffield University in England publishes dozens of archaeological tree-ring studies each year, although not all of these describe successful dating operations. (Publications that provide dates use the phrase “Tree-Ring Dating” in the title, those that do not use “Tree-Ring Analysis” in the title. These contributions are too numerous to list here, but see, for example, Arnold *et al.* (2001), Bridge (2001); Worthington and Miles (2001).)

Dendrochronologists at Queen’s University in Belfast, Northern Ireland, led by Michael Baillie, have developed 11,000-year-long chronologies for Ireland (Baillie and Pilcher, 1987) and made significant contributions to the understanding of prehistoric and historic occupations in northern Europe over the last three decades. Dendrochronologists in Germany also have developed Holocene-length chronologies (Becker, 1993). Tree-ring specialists at the National Museum of Denmark, led by Niels Bonde and Thomas Bartholin, focus on Danish applications, including the dating of Viking ships. As noted above, Peter Kuniholm and colleagues at Cornell University have made significant contributions to the dendrochronology of the Aegean and Near East (Kuniholm, 1995; Kuniholm and Striker, 1983, 1987). Given the abundance of relevant publications, and my limited expertise in European dendrochronology, this review examines but a selection of the many interesting studies of the last few years.

Because the historic record can reach back 4500 years in the Old World, tree-ring dating can be applied to a host of research questions ranging from art historical analysis, architectural analysis, underwater archaeology, resource economics, as well as prehistoric archaeology and volcanology. Significant advances have recently been made in extending the length of chronologies, such that chronologies spanning the entire Holocene are available in Ireland and Germany, and nearly so in the Aegean. New developments are occurring rapidly in Asia as well.

Bridge and Dobbs (1996) identified a repair episode on the warship Mary Rose in 1536, some 27 years after its original construction in 1509. Tercier *et al.* (1996) used crossdating to identify possible areas of ownership, or at least territorial control, in the architectural use of trees in Switzerland. They noted rebuilding episodes in periods of 8–32 years, suggesting that rebuilding was a social activity possibly correlated with the life span of the head of a household. Billamboz (1996) used crossdating, date distributions, and beam attributes (somewhat awkwardly referred to as “dendrotypology”) from studies of pile dwellings at the Neolithic site of Ehrenstein in southwestern Germany to postulate cycles of forest exploitation. Hillam and Groves (1996) took dendrochronological advantage when disaster struck Windsor Castle. By crossdating structural elements exposed by the catastrophic fire of 1992 they identified a previously undocumented building phase that coincides with the reign of either Edward IV or Henry VII.

Hoffsummer (1996) used tree-ring dating to date 180 roofs in Belgium and northern France and to develop a history of roofing technology in the area. Using specimens collected in churches and cathedrals dating from A.D. 1015 to 1500, and from churches, cathedrals, and vernacular buildings after 1500, he was able to detect a diffusion of roof building technology from thirteenth-century Chichester Cathedral in England to fourteenth- and fifteenth-century structures in the Meuse Basin of southeast Belgium. Baillie (1995, 1999) has made an interesting venture into the realm of speculative epidemiology via tree-ring analysis by suggesting that a gap in the tree-ring record, and therefore the building construction record, in the middle fourteenth-century may be blamed on the Black Death of A.D. 1347–1350, when people may have been more concerned with survival than they were with new home construction.

In Asia, recent efforts (Schmidt *et al.*, 1999) have developed an archaeologically useful tree-ring chronology in Nepal, going back to A.D. 1324, and a large number of timbers from houses, monasteries, and other sites have been dated as a result. At barrow sites in Russia, preliminary indications (Marsadolov, 1996) are that archaeological samples may one day be dated, but right now only undated chronologies exist. In South Africa, pioneering attempts to discover crossdating have not been successful because of myriad and apparently idiosyncratic locally absent rings in a number of species (February, 2000). Guibal (1996) was not able to date archaeological sites and shipwrecks in the French Mediterranean because of poor preservation, the scarcity of large and datable beams, deforestation beginning as early as 2800 B.C., and the fact that stone was often used as construction material in lieu of wood. Kuniholm (2000) faced a similar situation with Roman period sites—because stone was the preferred building material in many areas, a tree-ring record can scarcely be found, much less dated.

One of the great conundrums in the history of archaeological tree-ring dating deserves further review for the surprising implications it has for the history of science and the importance of examining unstated assumptions in one's research (Baillie, 1995, see chapt. 3; Baillie *et al.*, 1985). In the 1960s, European dendrochronologists began to analyze tree rings from fifteenth-, sixteenth-, and seventeenth-century oak panel paintings in an attempt to provide art historians with dates after which each painting must have been created. In so doing, they hoped to assist the art historians in the identification of forgeries. The reasoning is simple: if the tree-ring date for a supposed Rembrandt painting falls 5, 10, 15, or more years after the date of Rembrandt's death, the painting must be a forgery.

In the late 1970s, dendrochronologists faced an enigma: they had a crossdated oak chronology from panel specimens in the Netherlands that dated A.D. 1109–1637. In England, they had an oak chronology from panel specimens that extended from A.D. 1385 to the present. The oak chronologies crossdated with each other, but they did not against other panels in either England or the Netherlands. The English oak chronology did, however, crossdate against a chronology found further away in southern Germany.

Explanations for the failure to crossdate these chronologies with local trees focused on three potential sources of ring-width variability: one biological, one historical, and one economic. It was possible that the two oak panel chronologies could not be crossdated with local oaks in England or the Netherlands because the oaks from which the panels were created somehow responded differently to the same climate regime. This biological hypothesis was rejected because the two species of oak were known to hybridize and should therefore exhibit the same climate response. It was possible that early historic deforestation in England and the Netherlands somehow created a bias in the tree-ring record, but which only affected the oaks from which the panels were extracted. This historical hypothesis was rejected because significant deforestation had occurred elsewhere in Europe and had not, so far as was known, severely impacted local variability in ring-width series. Finally, it was deemed possible that one of the oak panel chronologies was constructed from trees that were actually foreign to England and the Netherlands, but the source of which had simply not yet been found. This third, economic hypothesis was rejected because researchers saw no *a priori* reason for large-scale trade in oak timbers or panels prior to the early seventeenth century. Subsequent analysis of historic documentation revealed that there was indeed an extensive oak trade across Europe throughout history. It turns out that the oak panels were produced from trees harvested in Poland, in the Baltic region, near Gdansk (Baillie, 1995).

On the basis of further dendrochronological and historical research, the general outlines of over 1000 years of oak timber trade in northwestern Europe have now become clear. From the seventh to ninth centuries, oak moved from central to northwestern Europe. During the eleventh and twelfth centuries, the tree-ring data indicate a strong eastward trade from Ireland to Denmark. Dendrochronological analyses of the recently raised shipwreck of Skuldelev 2 in Denmark indicate that the ship was either made in Ireland or was built in Denmark of Irish oak (Baillie, 1999). Given that it can take more than 4000 logs to produce one ship, the construction and maintenance of a fleet such as those later maintained by the Dutch, Spanish, or Portuguese would have required a substantial source of, and investment in, good wood. From the thirteenth through seventeenth centuries, the primary trade was westward from the Baltic, near Gdansk, to England, with especially strong connections to Scotland from the fourteenth through sixteenth centuries. The end of the oak trade now appears to have occurred toward the end of the Thirty Years War (1618–1648), which disrupted shipping and trade relations all over Europe (Baillie, 1994, 1995; Wazny, 1992).

Baillie (1999) recently pursued the sociological and economic implications of the modern oak trade into the realm of conspicuous consumption. Dendrochronological analysis indicates that lower status housing in parts of Ireland was composed of lower quality domestic oak, and that higher status housing was constructed of higher quality oak imported from either Scandinavia or North America. Although the source of the latter has not yet been found, it would indeed be exceedingly interesting if a New World source for these timbers were discovered. Lavier and Lambert (1996) recently broadened the analysis of art historical objects to include, in addition to paintings, the analysis of sculpture, retables, furniture, manuscript covers, and musical instruments. They were able to date some 40 caskets in France and succeeded in deriving a date of A.D. 786 for a medieval book cover.

After nearly three decades of research, Kuniholm (1995) has more than 6000 years of tree-ring chronologies (some as yet undated) covering much, though not all, of the Neolithic going back to about 7500 B.C., for an area bounded by the Turkish/Georgian border on the east, Lebanon to the south, all of Turkey, Cyprus, Greece, west to the instep of the Italian boot, and including parts of Bulgaria and Yugoslavia. Kuniholm (2000) recently published a date compilation for over 50 well-dated Ottoman buildings and sites from the twelfth through ninteenth centuries in Turkey. The sites were dated using an oak chronology that extends back to A.D. 360, a pine chronology that extends back to A.D. 743, and a shorter juniper chronology that dates back to A.D. 1037. His research fortuitously benefited from earthquakes in Macedonia in 1978 and 1979 that exposed architectural elements that could not otherwise be sampled (Kuniholm and Striker, 1983).

The distinctive feature of tree-ring chronometry in the Old World in general and Europe in particular is the ability to establish the veracity of tree-ring dates against the historic record, and vice versa. Clearly, the myriad applications of tree-ring dating in historical, architectural, and artistic studies should continue, for they make a valuable and independent contribution to a diverse data set bearing on recent occupations of Europe and the Mediterranean. Hopefully, undated tree-ring chronologies will soon be tied to the dated sequences and additional long chronologies will be developed so that archaeologists will be better situated to understand Neolithic occupations across the Old World.

Paleoenvironmental Reconstruction

Paleoenvironmental reconstruction from tree rings has nearly as long a pedigree in the Old World as in the New (see papers, and references cited therein, in Dean *et al.*, 1996; Hughes *et al.*, 1980). Dendrochronologists in the Climatic Research Unit at the University of East Anglia in Norwich, England, led by Keith Briffa, have made significant contributions to climate reconstruction in northern Eurasia, as has the Dendroclimatology Laboratory at Stockholm University. The Wood Biology and Tree Ring Research Group in the University of Agriculture, Forestry, and Renewable Natural Resources in Vienna, Austria, has contributed studies on climatic impacts on tree growth, led by Rupert Wimmer. Fritz Schweingruber and others lead a number of dendrochronologists based at the Swiss Federal Institute for Forest, Snow, and Landscape Research in Birmensdorf. The sheer volume of such contributions makes them difficult to categorize and summarize, even for an author who has more than passing familiarity with the subject matter. Many of these contributions have not, by definition, been directly related to archaeological research, but interested readers may find paleoenvironmental reconstructions for many parts of temperate Europe and Asia with a minimal amount of research (see Additional Resources section below). In this section, I focus on recent multidisciplinary work on dating volcanic eruptions, not because I believe that such events have deterministically impacted human existence and behavior, but because the data from a wide variety of sources indicates that such events may, on occasion, have had discernible worldwide effects that may be investigated and tested archaeologically.

In order to date large volcanic eruptions and examine their impact on worldwide environments and populations, data from tree rings, ice cores, historical records, and other sources are analyzed for coincident, or slightly lagged, instances in which frost rings are produced, tree growth is suppressed, ice core acidity levels peak because of the emission of large quantities of sulfuric acid, and historical records indicate significant stress on human populations or subsistence resources (Baillie, 1995, 1996).

Baillie (1995, see chapts. 5, 6, and 7) describes in detail the efforts to disentangle the ice-core and tree-ring data for a number of eruptions, including the eruption of Santorini (Thera) in 1628 and 1627 B.C., as well as events at 1159 B.C., 208 B.C., and A.D. 536 (see also Baillie and Munro, 1988; LaMarche and Hirschboeck, 1984). Isotopic and historic evidence exists for the Tambora eruption of A.D. 1815 and the Krakatoa eruption of A.D. 1883 (Loader *et al.*, 1999). An event at 2345 B.C.

associated with a possible comet impact has been identified (Baillie, 1999) as the possible source of the myth of Noah's Ark.

Another major event recorded in worldwide tree rings and other media occurred in A.D. 536. The A.D. 536 event, possibly from the eruption of Rabaul, in New Britain (Loader *et al.*, 1999), or a cosmic impact (Baillie, 1999), has in particular received a great deal of attention of late (D'Arrigo *et al.*, 2001; papers in Gunn, 2000). An anomalous event is recorded in ice cores and tree rings between A.D. 536 and 540. Historic records indicate famine from Ireland to China. Astronomical data indicate anomalous eclipses in Europe in A.D. 538 and 540 and the failure of seeing the star Canopis in China in 536 (Baillie, 1995; see papers in Gunn, 2000).

Although instances of clear cause and effect are difficult to pinpoint, compelling circumstantial evidence points to widespread impacts of certain eruptions on prehistoric cultures. Using these data, testable and highly refined hypotheses may be developed to guide further research.

ADDITIONAL RESOURCES

A number of resources exist with which the interested reader may pursue his or her own interests. The Tree-Ring Society maintains a website that communicates basic information about this professional organization (http://www.treeringsociety.org/). Henri Grissino-Mayer of the University of Tennessee maintains an excellent website (http://web.utk.edu/∼grissino/) that contains overviews of dendrochronology, dendroclimatology, and their applications, links to tree-ring laboratories and individual dendrochronologists around the world, as well as searchable bibliographies, downloadable software, and other resources that are valuable to the novice and expert alike. For the expert, the International Tree-Ring Database (www.ngdc.noaa.gov/paleo/treering.html), maintained by the National Oceanic and Atmospheric Administration's Paleoclimatology Program, curates an updated list of downloadable tree-ring chronologies from all over the world, although these are almost exclusively constructed for climate reconstruction and not archaeological dating.

Given the increasingly international flavor of dendrochronology, Kaennel and Schweingruber (1995, 1996) recently published a multilingual glossary for dendrochronology, which has proven to be an exceedingly valuable resource for scholarly communication across borders. Grissino-Mayer (1993) produced an updated list of species used in tree-ring research. Brown (1996) recently completed a database of the oldest trees for each species. The recent reincarnation of the journal *Tree-Ring Bulletin* as *Tree-Ring Research* indicates that the multidisciplinary professional dendrochronology community again seeks a common forum in which to communicate progress (see for example Grissino-Mayer *et al.*, 2001; Hughes *et al.*, 2001; Towner *et al.*, 2001).

CONCLUSION

This overview has focused on archaeologically and anthropologically related tree-ring dating in the New and, to a lesser degree, Old Worlds, and therefore cannot do justice to other significant aspects of dendrochronology, particularly paleoenvironmental research, in those areas. Since its development over seven decades ago, however, dendrochronology has contributed more to archaeology than mere chronology control. In areas such as the American Southwest and western Europe, where dendroarchaeology has a long history (Baillie, 1995; Nash, 1997a, 1999, 2000a; see also McGraw, 2000, 2001), the long-established fundamental principles and techniques of tree-ring dating are being applied to increasingly sophisticated questions about prehistoric occupations, relationships between human populations and natural resources, and the veracity of historical documentation. In areas such as the southeastern United States, Eastern Europe, Africa, South America, Tasmania, and elsewhere, where dendrochronology was once thought impossible, exciting new developments are extending the reach of accurate and precise archaeological dating to new areas and time periods. The meeting program of the 2001 EuroDendro Conference, held in Slovenia in June, illustrates the diversity of applications currently enjoyed by tree-ring dating. Papers were presented on the European oak timber trade, the dating of Roman churches and Latvian buildings, paintings by artist Henri Bles, and musical instruments, as well as the development of master chronologies in Lithuania, Estonia, Scotland, and Fennoscandia. The recent discovery of a 3600-year-old Alerce specimen in Chile shows promise for the development of long chronologies in the southern hemisphere. In short, archaeological tree-ring dating as we enter the twenty-first century is alive, well, and vigorous. Archaeologists will appreciate continuing efforts to extend the limits of tree-ring dating beyond current chronologies and regions. What is perhaps most needed, however, is continuing collaboration between archaeologists and tree-ring scientists to broaden the application of dendrochronology to new archaeological questions, and to continue examining the critical nature of the relationship between the highly precise chronometric and climatological data and those aspects of human behavior that are recorded in the archaeological record.

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