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Relevant Website

http://www.gg.rhul.ac.uk – Royal Holloway: Department of Geography.

Dendroarchaeology *see* **Plant Macrofossil Methods and Studies**: Dendroarchaeology

DENDROCHRONOLOGY

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Dendrochronology

Dendrochronology is the science that deals with the dating and study of the annual growth layers, or tree rings, in woody trees and shrubs. In temperate climates, these layers of wood (tree rings) contain seasonal cell structures (earlywood and latewood) that signify one annual growth ring. When all the trees at a site are affected by a common environmental factor, such as climate, crossdating provides an accurate chronological record that can be used to date events or describe variations in environmental conditions. Due to the annual resolution possible throughout an entire tree-ring record, dendrochronological analyses provide both reliable and ubiquitous archives for paleoenvironmental reconstruction.

Origins and History

Although observations of tree-ring structures and related phenomena have a lengthy history, dendrochronology as a scientific discipline emerged relatively recently. As early as the fifteenth century, Leonardo da Vinci noted the annual nature of tree-rings, recognizing a relationship between tree ring widths and precipitation (Stallings, 1937). The first recorded application of dendrochronology occurred in 1737 when Du Hamel and De Buffon noted a prominent frost damaged tree ring in recently felled trees that was later recorded in both Sweden and Germany (Studhalter, 1955, 1956). By the mid-1800s, the ecological foundations of dendrochronology were established following Theodore Hartig's studies of wood structures and annual tree-ring development (Schweingruber, 1988). By the end of the nineteenth century, Hartig's son, Robert, had published numerous papers on the anatomy and ecology of tree-rings, and had used tree-rings to date hail, frost, and insect damage in trees (Schweingruber, 1988).

Astronomer Andrew Ellicott Douglass pioneered the science of dendrochronology in North America. In 1904, he began examining the annual rings of Ponderosa pine trees in the southwestern United States as a potential source for preinstrumental climate records. He soon established that narrow tree rings were formed in very dry years over large geographical areas, thereby confirming that the crossdating of tree-ring patterns between sites could be used as a chronological tool to identify the exact calendar year a ring was produced (Douglas, 1909). By 1914, Douglass had developed a 500-year crossdated pine chronology and established a positive correlation between ring width and precipitation of the preceding winter (Douglass, 1914). Douglass subsequently devoted the next 15 years to developing long tree-ring chronologies to date wood samples from prehistoric sites of the American southwest. His successful crossdating of a 585-year floating (undated) archeological tree-ring sequence provided precise dates of construction for numerous previously undated pueblo sites, bringing the science of dendrochronology to age as a dating tool (Dean, 1997).

Prior to pioneering the subfields of dendroclimatology and dendrohydrology, Edmund Schulman began working with Douglass to develop better methods of tree-ring analysis (Schulman, 1945). In his quest for improving the length and sensitivity of tree-ring records, Schulman also discovered the oldest living trees in the world, the over 4,000-year-old bristlecone pines of the California White Mountains (Schulman, 1954). This discovery was key to calibrating atmospheric ^{14}C records and set the foundation for precision radiocarbon dating methods (LaMarche and Harlan, 1973).

The basic premise of radiocarbon dating relies on the fixation of an unstable atmospheric carbon isotope (carbon-14) by organisms (e.g., trees) in the biosphere. As long as plants and animals are living and continue to take up air in their biophysical processes, their tissues absorb carbon-14. Once the organism dies, its intake of carbon atoms ceases and the amount of carbon-14 within their tissue begins to decrease logarithmically at a fixed rate, which can then be used to determine the time since death (Libby *et al.*, 1949). It was soon realized, however, that raw radiocarbon measurements were not equivalent to calendar dates, as the level of atmospheric carbon-14 has not been constant with time. Fortunately, long-lived trees, like the bristlecone pines studied by Sherman (1954), retain an annual measure of the amount of carbon-14 present in the atmosphere. By crossdating the tree-ring records from both living and dead trees, and measuring the amount of carbon-14 present in each tree ring, researchers have developed annually resolved time-series of radiocarbon concentrations, or radiocarbon calibration curves. The raw radiocarbon date of any sample within this timeframe can then be converted to a calendar date using the calibration curves (Damon *et al.*, 1974). These tree-ring based calibrations have successfully increased the accuracy of radiocarbon dating and presently provide annually-resolved carbon-14 records for the last 12,000 years (Friedrich *et al.*, 2005).

After the Second World War, German botanist Bruno Huber established an ecological approach to dendrochronology in Europe. His discovery that the year-to-year variation in tree-rings was not as pronounced in temperate tree species, as it was in those of semiarid zones, led to the development of a more quantitative approach to dendrochronology. Huber developed the statistical test of similarity, the Gleichlaeufigkeit (Huber, 1943; Eckstein and Pilcher, 1990) that remains an integral component of statistical crossdating in European laboratories.

In the early 1960s, Hal Fritts established the basic physiology of radial tree growth by employing a dendrograph (Haasis, 1933) to measure the daily growth of tree-rings. As detailed in his seminal publication *Tree Rings and Climate* (1976), Fritts was able to describe many of the complex connections between tree-rings and climate, and used these insights to provide annually-resolved climate reconstructions for eastern and western North America (Fritts, 1991). During the same time period, Polge (1966) applied X-ray densitometry to the study of tree rings and illustrated how latewood density provided higher resolution dendroclimatic insights than was possible from an analysis of the total annual ring-width increment (Lenz *et al.*, 1976).

In the last 50 years, dendrochronology has evolved from a discipline primarily applied to the dating of monuments and archaeological pueblos, to one with a variety of applied applications including studies of: the history and effects of pollution (Schweingruber, 1988); geobotanical dating (Winchester and Harrison, 2000); earthquakes (Jacoby *et al.*, 1997); snow avalanches (Smith *et al.*, 1994); glacier movement (Luckman and Villalba, 2001); volcanoes (Jones *et al.*, 1995); river flooding (St George and Nielson, 2003); and insect life cycles (Swetnam and Lynch, 1993). In addition to the continued application of the techniques first pioneered by Douglass, the introduction of new analytical techniques (i.e., X-radiography, X-ray densitometry, neutron activation analysis) are providing insights into climate-induced morphological and chemical changes within tree-rings and wood cells, and are being used to described trace-element and isotopes signatures (Kuniholm, 2001).

Biological Foundation of Dendrochronology

Tree-ring formation

Tree-ring dating is possible due to the physiological behavior of trees growing in locations with seasonal climates. In temperate climates, this annual growth appears as ‘rings’ that vary in width in response to fluctuating environmental variables (Fritts, 1976). Although there are differences in the anatomical structure of tree rings between angiosperms (deciduous) and gymnosperms (coniferous), both tree types are commonly used in dendrochronology.

Radial growth in trees is achieved by the division of vascular cambium cells that, in seasonal climates, are active for only part of the year. During winter, the cambium is dormant and cell production stops until the warmer and/or wetter days of spring reactivate cambium activity (Fritts, 1976). The xylem cells formed at the beginning of the season tend to be large and thinned-walled, and are commonly referred to as springwood or earlywood. As the growing season progresses and conditions become less favorable (e.g., hotter and drier), cambial activity slows and the xylem being produced has smaller cells with thicker walls, and is referred to as summer or latewood (Fritts, 1976). It is this marked difference between earlywood and latewood cells that make it possible to discern the annual growth rings (Figs. 1 and 2).

Although a single tree ring is normally formed every growing season, in some years a tree may fail to develop an annual ring (i.e., a missing ring) or the ring may be locally absent when viewed in cross-section. False rings (intra-annual growth bands) are sometimes produced if seasonal growing conditions temporarily deteriorate (Schulman, 1938; Fritts, 1976). Missing, locally absent, and false rings can usually be detected by cross-dating trees from the same plot or region. However, false rings are usually easily detectible, as the transition from one cell type to another is gradual, while the resumption of earlywood production after winter dormancy produces a distinct cell boundary.

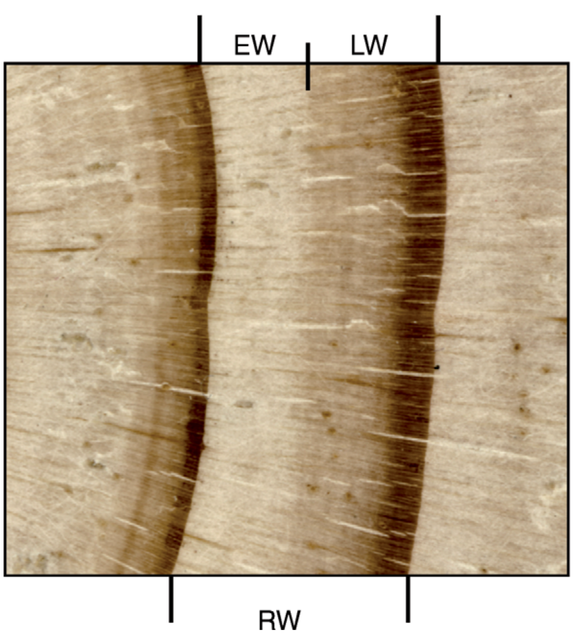

Figure 1 Cross-sectional view of tree rings scanned from a mountain hemlock (*Tsuga mertensiana*) tree. Highlighted are the annual ring-width (RW), latewood (LW), and earlywood (EW). © D. Lewis 2006.

Figure 2 A cross-section from a young sub-Alpine fir (*Abies lasiocarpa*) illustrating the annual concentric ring pattern around the stem of tree. © D. Lewis 2006.

Principles of Dendrochronology

Although different tree species and individual treesexhibit distinct growth characteristics, dendrochronological analysis of common patterns within their annual growth rings allows for comparative study. Seven widely accepted principles govern the application of dendrochronology. While some of these principles are specific to dendrochronology, others have been borrowed and modified from other disciplines.

The Uniformitarian Principle

The principle of uniformitarianism was originally proposed by James Hutton in 1785. Applied to dendrochronology, it states that the physical and biological processes that link contemporary environmental processes to current variations in radial tree growth existed in the past. This does not mean that past conditions were the same as present ones, but rather that the tree growth was influenced in the past in the same manner as in the present (Fritts, 1976). Hence, by understanding present climate tree-ring growth relationships, dendrochronologists are able to reconstruct paleoenvironmental records from tree-ring records. For example, Figure 3 shows a reconstructed glacier mass balance record that was developed by calibrating historical tree-ring width data with glacier mass balance records. Based on the principle that growth-response conditions must have been similar in the past, a lengthy tree-ring width record was statistically developed as a proxy (or substitute) for actual mass balance anomalies prior to the historical record.

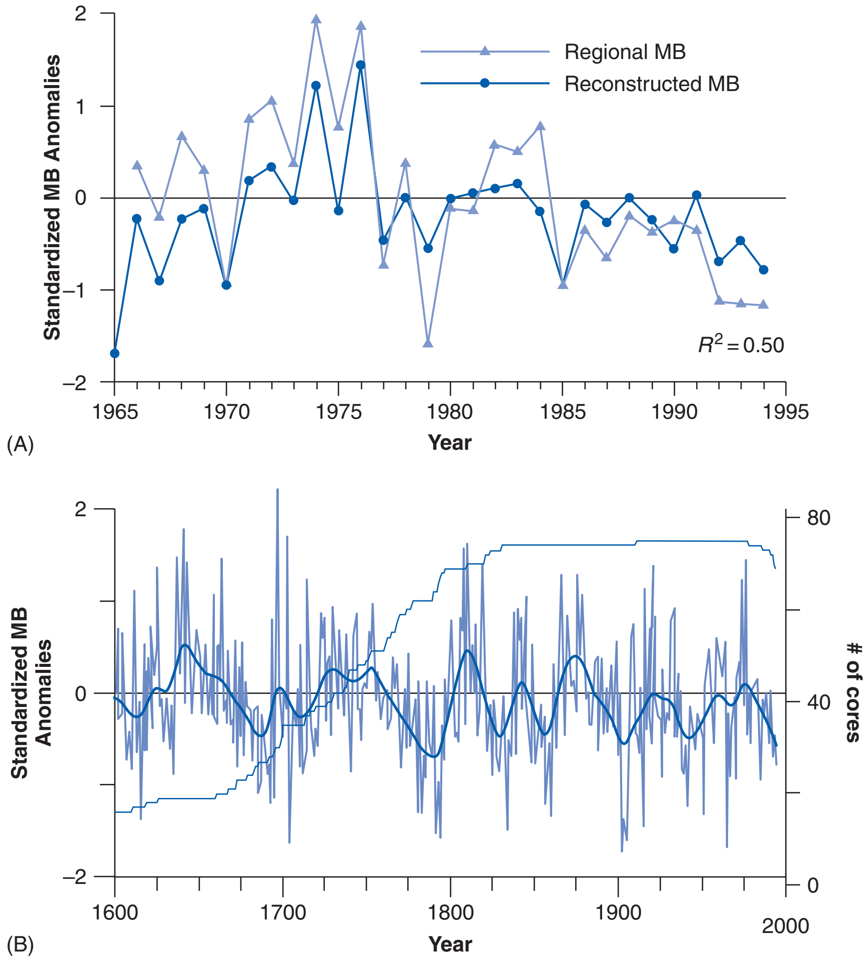

Figure 3 Reconstructed standardized mass balance anomalies for the period 1966 to 1994. The upper graph is the validation against the instrumental mass balance record. The lower graph (B) is the mass balance anomaly reconstruction back to 1600 AD. The thin gray line is the annual values and the thick black line is a 25-year spline. © D. Lewis 2006.

The Principle of Limiting Factors

This principle states that tree-ring growth cannot proceed faster than permitted by the most limiting factor (Fritts, 1976). For instance, in arid and semi-arid regions, a lack of precipitation often limits tree growth and the annual radial increment is a direct function of the amount of precipitation. Other limiting factors include air temperature and non-climatic parameters such as soil condition (e.g. well drained soil). This principle is important to dendrochronology because tree rings can be crossdated only if one or more of the environmental factors become significantly limiting, persist sufficiently long enough, and act over a wide enough geographical area to cause widespread ring width or density variation.

The Principle of Aggregate Tree Growth

This principle states that the individual tree-ring growth series of a tree can be broken down into an aggregate of environmental factors, both human and natural, that affect the patterns of tree-ring growth over time. A simplified linear model of a tree ring from Cook (1987) is given below:

$$R_t = A_t + C_t + D1_t + D2_t + E_t$$

In this example, the observed tree-ring width (R) in any one year (subscript $_t$) is a factor of: (A), the age-related growth trend due to normal physiological aging processes; (C) the climate related signal during that year; (D1) the pulse of a localized disturbance factor within the forest stand (e.g., blowdown, endogenous disturbance); (D2) the occurrence of a standwise disturbance factor (exogenous disturbance, e.g., fire, insect outbreak), and; (E) the unexplained year-to-year variability not accounted for by these other processes (Cook, 1987). Therefore, to maximize the desired component (signal), the other factors (noise) should be minimized. For example, to maximize the climate signal, age-related growth trends must be removed, and trees and sites selected to minimize the possibility of internal and external ecological processes affecting tree growth.

The Principle of Ecological Amplitude

This principle states that tree growth is particularly sensitive to environmental factors at the latitudinal, longitudinal, and elevation limits of the distributional range of the species (Fritts, 1976). For example, the growth of trees found growing at their altitudinal limit in mountainous settings is frequently discovered to be restricted by summer air temperatures, a relationship that has been used in some instances to develop millennial-long temperature reconstructions (Luckman and Wilson, 2005).

The Principle of Site Selection

Dendrochronologists recognize that the most useful locations for environmental reconstruction can often be identified based upon site characteristics. For example, trees found growing on bare rocky outcrops are often moisture-sensitive and their tree-ring records contain an historical record of drought conditions. Conversely, trees found growing in mesic (wet) sites usually contain complacent tree-ring records, as their annual ring growth is unlikely to be limited by a lack of moisture (precipitation) (Fig. 4).

The Principle of Crossdating

Probably the most important principle in dendrochronology, crossdating ensures that individual tree rings are assigned their exact year of formation. This is accomplished by identifying recognizable patterns of wide and narrow rings within a living tree-ring chronology. These tree-ring patterns develop in response to the sensitivity of trees to limiting factors or site condition changes. Crossdating of ring-width patterns in living trees allows for the identification of comparable patterns in undated wood samples; thereby providing a means to develop tree-ring chronologies that extended back in time beyond the age of living trees or to date an event. For instance, the date when a tree was killed by an advancing glacier can be determined by matching the tree-ring patterns of a glacially-sheared stump with those found within a chronology spanning the same period of time (Fig. 5).

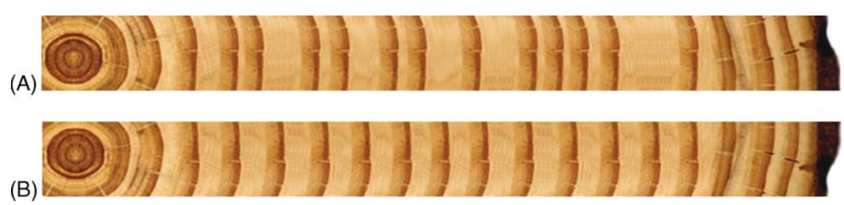

Figure 4 Illustration of effects of the Principles of Ecological Amplitude and Site Selection. Shown is the radial growth response of trees to limiting environmental factors under different site conditions. The top ring-width pattern (A) is from a tree found growing near its ecological limit and as a result of being is temperature and moisture stressed, it produces variable ring-widths sensitive. The sample below (B), is from a tree near the center of ecological range and not limited by environmental factors. As a result, the tree is not stressed and is producing complacent tree rings with little variability. © Arctic, Antarctic & Alpine Research 2004, V36, p. 602.

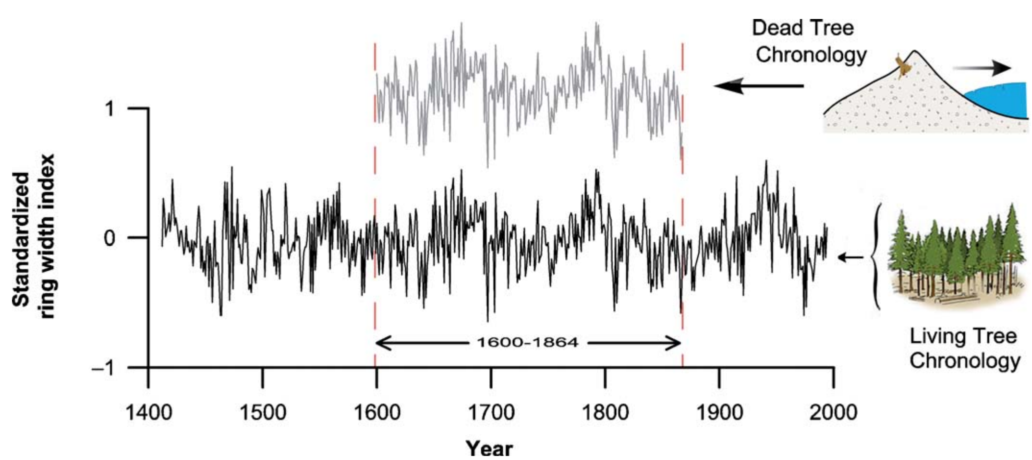

Figure 5 Illustration of how a calendar date for the growth rings of undated wood samples can be established by crossdating with a dated living chronology. By anchoring floating chronologies to the living chronology, it is possible to determine when a sample was killed.

The Principle of Replication

This principle states that an environmental signal of interest can be maximized, and the amount of 'noise' minimized by sampling more than one stem radius per tree, and more than one tree per site (Fritts, 1976). Examining and crossdating multiple samples from multiple trees, avoids the possibility that all collected samples may be missing a ring or could include a false ring. Obtaining more than one sample per tree reduces the amount of 'intra-tree variability', the amount of nondesirable environmental signal peculiar to a given tree. Obtaining numerous trees from one site, and perhaps several sites in a region, ensures that the amount of 'noise' (environmental factors not being studied, such as air pollution) is minimized (Cook, 1987).

Application of Dendrochronology

Tree-ring dating typically begins with the measurement of tree-ring widths or a density parameter, followed by the development of a master tree-ring chronology. The primary objective in developing tree-ring chronologies is to develop stationary time-series that are directly comparable and appropriate for statistical analysis (Fritts, 1976). Chronology development follows a three-step procedure:

(1) *Crossdating*: is used to check for measurement errors and false or missing rings. Although skeleton plots of tree-ring series are useful for visually identifying dating or measurement problems (Stokes and Smiley, 1963), the application of quality checking software programs provides a statistical measure of quality control (Holmes, 1983).

(2) *Standardization*: Although ring-width increments are assumed to change in response to climate variability, they also vary in size with tree age, stem height above the ground surface, in response to site-specific characteristics, and productivity (Fritts, 1976). For the purpose of climate reconstruction, it is essential to determine if the changes in ring width are associated with aging or disturbance factors, and to then remove these influences from the chronology. This correction is known as standardization, and the transformed values are referred to as ring-width indices (Fritts, 1976). Each set of tree-ring measurements requires a different standardization, depending on the statistical and morphological properties of the ring-width series (Cook and Kairiukstis, 1990).

(3) *Master chronology development*: The transformed time-series are combined into a single dimensionless ring-width index, or site chronology, that reflects the extrinsic (environmental) constraints on growth (Cook and Holmes, 1986). Crossdating provides the means to assign an absolute date to each ring in a tree-ring series of unknown age by matching the undated ring-width patterns to those of a known dated series (Fig. 5). If the entire ring sequence is present in the outermost perimeter of the undated sample (earlywood and latewood tissue), it is assumed that the sample was killed sometime between the end of one year's growth period and the beginning of another. Precise dating is possible when a sample has bark, as this infers that the last year of growth is present (Baillie, 1982).

Summary

Dendrochronology has proved to be an invaluable tool for dating events and for providing robust annually-resolved paleoenvironmental insights. The ongoing development of long tree-ring chronologies offers opportunities to develop paleoenvironmental reconstructions at local to hemispheric scales. The recent focus on developing tools and techniques suitable for discerning the climatic signal inherent in sub-annual cellular structures has the potential to provide reliable dating applications and studies of environmental variables that act on seasonal timescales.

See also: **Introduction**: Societal Relevance of Quaternary Research; History of Dating Methods. **Glacial Landforms, Tree Rings**: Dendrogeomorphology. **Plant Macrofossil Methods and Studies**: Dendroarchaeology.

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DENDROCLIMATOLOGY

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Tree-ring series provide the most widely distributed and easily accessible archive of annually resolved proxy climate data. In regions with well-defined seasonal growth, the annual growth rings of trees provide both chronological control and a continuous time series of proxy environmental variables. The year-to-year variability of the physical (e.g., width and density) and chemical properties of these annual rings provides potential proxies for the environmental factors that influence tree growth. Dendroclimatology can be defined simply as 'the science that uses tree-rings to study present climate and reconstruct past climate' (Grissino-Meyer, n.d.), and during the past 30 years it has become a major tool in the reconstruction of climates of the past millennium in many areas of the world (Hughes, 2002).