Reading between the Lines

Dendrochronologists find that the past is still present in tree rings

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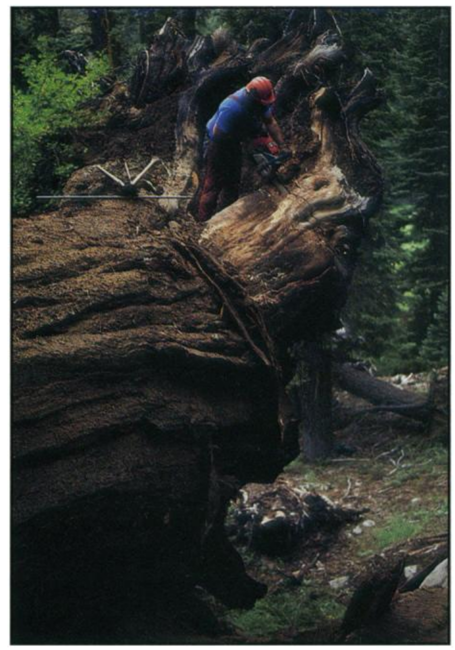
In the early decades of the twentieth century, the astronomer Andrew Douglass noted that trees growing in a particular area, which are exposed to the same sequence of wet and dry growing seasons, typically share the same pattern of variation in the width of their annual growth rings. This observation allowed Douglass to be the first to precisely date the ancient Anasazi ruins of the Southwest, by matching ring sequences in living trees with those found in ancient wooden beams and charcoal fragments. Thus the science of dendrochronology, or tree-ring dating, was born.

Working in close collaboration with a number of archaeologists and other scientists, Douglass went on to found the world's first center for dendrochronological analysis, the Laboratory of Tree-Ring Research (LTRR) at the University of Arizona. Today the lab is still going strong and is just one of dozens of facilities around the world dedicated to the analysis of tree rings not just as a dating tool but as a window into past environments. Since Douglass's day, the construction of thousands of tree-ring chronologies from both the Northern and Southern Hemispheres has provided striking evidence that climatic patterns recorded in the relatively recent past, since the advent and widespread deployment of weather monitoring instruments, are often far from what is "normal" in a broader historical context. Along with other indicators of past climatic and ecological variability—including ice and sediment cores and annual growth bands in corals—tree-ring data now provide vital information for scientists trying to assess the magnitude and significance of global warming and other environmental changes taking place today.

More than just indicators of past temperature and rainfall patterns, tree rings provide a historical perspective on some of the fundamental processes that shape biological communities and ecosystems. "Tree-ring data are vitally important because they provide a temporal scale to studies that need to establish what environmental conditions were like in the past," says Henri Grissino-Mayer, a dendrochronologist at Valdosta State University in Georgia (University of Tennessee as of 1 July 2000). "These reference conditions are becoming increasingly important as we try to restore ecosystems disturbed by human activities." Tree rings can provide information on such things as the structure and composition of past forests and the size and frequency of wildfires and other disturbances before human intervention.

Paleoecologist and new LTRR director Thomas Swetnam says that historical studies based on tree rings have helped bring about a shift in the field of ecology, from an emphasis on stability and balance to one focused on disturbance and nonequilibrium processes. "The idea that you don't have to necessarily be there to set up a monitoring device and take measurements, that it's possible to use a natural archive like tree rings to reconstruct history, is something that for a long time was not fully appreciated in ecology," Swetnam says. "Today we see that ecosystems are dynamic, they change all the time across all spatial and temporal scales. Tree rings have helped us to see the great changeability of the ecological landscape."



Dendrochronologist Thomas Swetnam, director of the Laboratory of Tree-Ring Research (LTRR) at the University of Arizona, is seen here sawing a giant sequoia log to collect a fire scar specimen. Photo: Chris Baisan, LTRR (courtesy of T. Swetnam).

Although the southwestern United States remains an active center of tree-ring studies, dendrochronology today is international in scope. Chronologies and climate reconstructions now exist for much of the temperate Northern Hemisphere, and a growing number of labs are conducting studies in the Southern Hemisphere and even the tropics. Chronologies are also extending farther and farther back in time. Continuous, annually resolved ring series in excess of 5000 years now exist from several regions of the world, including parts of Europe, the western United States, and New Zealand. The National Oceanic and Atmospheric Administration's International Tree-Ring Data Bank, which Grissino-Mayer helps administer, contains over 3000 tree-ring chronologies from over 1500 sites worldwide.

The field has matured analytically as well. New tools are making it possible to extract more information from the size, physical structure, and chemical composition of tree rings than ever before. "At each point when we develop a sharper tool with better resolution, we see new structures," says former LTRR director and paleoclimatologist Malcolm Hughes. And as this ever more detailed information is gathered and assembled into networks spanning ever larger geographic areas, new and previously unsuspected patterns reflecting ecosystem response to climatic variability become visible.

Trees as data collectors

A good deal of the art of applying dendrochronology to ecological and climatological questions is in knowing what and where to sample. "Site selection is the key to dendroclimatology," says Gordon Jacoby, cofounder of the Tree Ring Lab at Columbia University's Lamont-Doherty Earth Observatory (LDEO), in Palisades, New York. "One must go to [sites] where the limiting factor to growth is known." For example, if a record of past precipitation is desired, researchers will choose trees growing on exposed rocky slopes where the only moisture comes from rainfall. And signals of past temperature variation are best recorded in situations in which temperature more strongly affects growth, as is usually the case for trees living near the upper elevational or latitudinal limit of their range.

Collecting multiple wood samples at multiple sites allows researchers to apply Douglass's principle of matching ring patterns, known as cross-dating. The great value of tree-ring chronologies, Swetnam notes, lies in their absolute precision. Cross-dating ensures that any idiosyncrasies in the ring patterns of particular trees will be recognized as such; chronologies are based on the shared, year-to-year variation in growth that emerges across multiple trees and sites. "When you have cross-dated material, you know you have accurate dates," Swetnam says. "It's not a plus or minus some number of years. I know with total certainty that this ring is from the year 1694, because I've matched the pattern with our regional composite."

Cross-dating also lets dendrochronologists build histories longer than the lifespan of any living tree. A ring sequence corresponding to a particular block of time—say, the years 1540–1550—laid down early in the life of a tree still alive today might be matched by one found toward the perimeter of an ancient stump. A link is thus established between one ring series, ending in the present, and another ending in the sixteenth century and perhaps extending back into the first millennium. Through a number of such links, a continuous chronology can be established dating back thousands of years.

Although cross-dating can be accomplished through fairly simple, visual pattern-matching techniques, new image-processing equipment and software are making the process less labor intensive. Computerized microscopes are used to take the precise ring measurements needed for climatic reconstructions. And although ring width remains the fundamental variable in most dendrochronological analyses, researchers now commonly supplement this information with measures of ring wood density obtained through a technique called X-ray densitometry. Density measurements can help reveal the separate effects of precipitation and temperature and can often show seasonal growth responses within annual bands.

Through even newer techniques, such as microdensitometry and stable isotope analysis, tree-ring studies are now progressing to the cellular and even the molecular levels. "The changes in technology in recent years are making it possible for us to get down to actual cell dimensions much more economically," Hughes says. These measurements in turn are making it possible to test and calibrate detailed physiological models of tree-ring growth. Researchers, including LTRR's Steven Leavitt, are developing techniques of isotopic analysis that may make it possible to determine where on the planet the rainwater that stimulated a particular cell's growth came from. In the Southwest, for example, such analyses might reveal changes through time in the incidence of storm patterns originating over the Pacific Ocean and the Gulf of Mexico. If techniques for coaxing this kind of information out of centuries-old tree rings can be perfected, researchers will have a powerful new tool for exploring spatial and temporal variation in seasonal climatic patterns.

Cycles of disturbance

One of the primary applications of dendrochronology to historical ecology has been in reconstructing how the size and frequency of fires have shaped forest ecosystems. Fires that do not kill a tree usually leave a scar, which is recorded in the tree's annual growth ring. By carefully examining the tree rings, researchers can determine the year and often even the season in which the fire occurred. One of the most spectacular examples of this approach was carried out by Swetnam and colleagues working in the giant sequoia groves of California, where detailed fire histories spanning over 3000 years were reconstructed from fire-scarred rings.

Craig Allen, a research ecologist

with the US Geological Survey, has collaborated with Swetnam in studying the history and effects of fire in the Jemez Mountains of northern New Mexico. Allen's team has put together over 4000 fire dates from over 550 trees, logs, and stumps. "The Jemez is one of the better-sampled landscapes of its size anywhere," Allen says. "There are very few areas that have as much fire history."

The Jemez data form part of a larger tree-ring network that Swetnam and numerous coworkers have compiled from mountain ranges throughout the Southwest. Fire scars indicate that, historically, blazes were most frequent in the dry spring and early summer, before the arrival of the late-summer monsoon rains. Although fires were very frequent, most burned only along the ground, clearing away debris and tree seedlings. The regular occurrence of these low-intensity blazes resulted in mostly open, parklike forests. Fire behavior began to change dramatically in the late 1800s, when large numbers of cattle and sheep were introduced into southwestern forests. As grasses were reduced by grazing, ground fires ceased to spread across the landscape. Over time, larger and larger patches of forest went unburned over longer and longer intervals.

This trend of reduced fire activity continued when fire suppression became the norm early in the twentieth century. With the natural fire regime interrupted, the complexion of the forests changed. Open areas disappeared and the density of young trees skyrocketed. Fires that escaped control often became enormous, tree-consuming crown fires rather than the cooler understory burns that were the historical norm. Cross sections of ponderosa pine collected in New Mexico and Arizona illustrate this change dramatically. "You can see these three or four hundred-year-long time sequences with fires burning once or twice a decade right up to around 1900—and then suddenly they stop," Swetnam says. "It's a striking change."

Work by Grissino-Mayer has shown that in historically ungrazed forest pockets situated in the middle of lava badlands in central New Mexico, the regime of frequent low-intensity fires lasted long into the twentieth century. Swetnam and collaborators have also analyzed wood samples taken from remote regions of the Sierra Madre mountains of northern Mexico, where neither fire suppression nor grazing has ever been significant. In these areas, tree rings reveal ongoing patterns of fire activity and forest structure like those that disappeared a century ago in much of the southwestern United States.

The tree-ring network created by Swetnam and his coworkers also revealed that in particular years—often separated by a decade or more—fire activity became synchronized and widespread throughout the Southwest. By comparing fire-scar records with independent tree-ring reconstructions of precipitation patterns, the researchers have shown that the episodic occurrence of these "regional fire years" is associated with El Niño and La Niña events. El Niño years bring heavy rainfall to the region, whereas La Niña years—which often follow on the heels of El Niños—are dry. Years of intense regional fire activity often occur at the end of an El Niño–La Niña cycle, when excess plant growth resulting from one or more unusually wet years becomes a blanket of dry fuel across southwestern mountain ranges.

Swetnam has also used tree rings to study the frequency and effects of other ecological disturbances. In the western United States, for example, major outbreaks of spruce budworm occur every few decades, defoliating trees for periods of 5–15 years over wide areas. Swetnam has been able to reconstruct the history of these insect outbreaks from tree rings. Defoliated trees often survive, but their growth is greatly reduced during the period of infestation, resulting in very narrow annual rings. Because not all tree species are vulnerable to spruce budworm attack, the separate effects of insects and climate on tree growth can be distinguished by comparing records from different kinds of trees. Although spruce budworm outbreaks may occur only a few times per century, for reasons that are not entirely understood, Swetnam has shown that these events have a significant and long-lasting influence on forest structure. "This has been a wonderful source of information on the timing and dynamics of a very mysterious ecological phenomenon," Swetnam says.

A change in the weather

Tree rings not only record abrupt disturbances like fires and insect outbreaks; they also capture more gradual shifts in environmental conditions. Tree-ring records give climatologists a vastly expanded time frame in which to study both natural variability and directional change in rainfall and temperature patterns. "The instrumental, observed record of climate variability is very short," Hughes notes. "There are few parts of the world where it is longer than 90 or 100 years. And yet we know there are important phenomena that we would only get two or three realizations of over a 90-year period." Thus, an understanding of climate based solely on the twentieth-century record may be as misleading as an analysis of stock market variability based solely on performance in the 1990s.

David Stahle, director of the Tree-

Web sites of interest

Henri D. Grissino-Mayer's Ultimate Tree-Ring Web Pages:
tree.ltrr.arizona.edu/~grissino/henri.htm

Laboratory of Tree-Ring Research:
tree.ltrr.arizona.edu

Tree-Ring Laboratory of the Lamont-Doherty Earth Observatory:
www.ldeo.columbia.edu/trl

After 1900, forest fires were less frequent and were more likely to escape control and become enormous, tree-consuming crown fires, such as the one that swept through this ponderosa pine forest at Bandelier National Monument, near Los Alamos, New Mexico, on 26 April 1996 (left). The change in fire pattern resulted from alterations in forest structure caused by the introduction of cattle and sheep grazing in southwestern forests in the late 1800s and by a fire-suppression policy that started early in the twentieth century. Tree-ring researchers can detect changes in fire pattern and frequency by examining fire scars in the annual growth rings visible in cross sections of trees. This cross section from a ponderosa pine (right) shows evidence of the more frequent, low-intensity blazes that predominated up to around 1900. Photos: Craig Allen, US Geological Survey, Bandelier, New Mexico (left), and Chris Baisan, Laboratory of Tree-Ring Research, University of Arizona (right; both photos courtesy of T. Swetnam).

Ring Laboratory at the University of Arkansas, has been working with a team of researchers from around the world to uncover the pre–twentieth century history of El Niño and La Niña cycles from tree rings. The effort has centered on several regions, including South Africa, Mexico, and the southern United States, whose climates are strongly affected by the El Niño phenomenon. "During El Niño events, you tend to get big fat tree rings in the Sierra Madre Mountains of Mexico," Stahle says. In fact, he says, in recent decades atmospheric pressure gradients over the equatorial Pacific, which determine the strength of El Niño or La Niña events, have been highly correlated with ring-width patterns in the Mexican trees. The work is still proceeding, and Stahle says that more data are needed, particularly from outside North America, to definitively reconstruct centuries-long time series of El Niño–La Niña events.

In the United States, enough tree-ring chronologies now exist from different regions to allow examination of past precipitation patterns on a continental scale. In a paper published last year in the *Journal of Climate* (12: 1145–1162), a team led by Edward Cook, of LDEO, presented a continent-wide reconstruction of summer droughts since 1700, based on 450 tree-ring chronologies. Droughts at local to regional scales appear on a regular basis, and over long spans of time more widespread and severe droughts, such as the Dust Bowl drought of the 1930s, are also part of the normal cycle of variation. Stahle, who coauthored the study, says that tree-ring records from the western and southeastern United States indicate that the worst drought of the past thousand years occurred in the sixteenth century, when a 40-year long dry period affected much of North America.

One of the longest climate reconstructions in the Southwest, spanning over 2000 years, comes from Grissino-Mayer's work in New Mexico. He notes that although a prolonged drought did strike the region in the 1950s, overall the region has been wetter than normal since 1800—a fact that few people in this arid region realize and one that may have serious implications for the future. "We know that rainfall has fluctuated in the past to well below average conditions," he says. "When this happens again, what will happen to the large populations of humans now living in the Southwest, which have been supported by the above-average rainfall of the last 200 years?"

Reconstructions of past climates are also invaluable to researchers trying to determine whether recently observed changes in global temperatures signify a departure from normal climatic variation. Recent studies of conifers growing in the boreal treeline forests of Mongolia and Alaska by Jacoby, Rosanne D'Arrigo, and others at LDEO have provided a record of unusual warming in recent decades, relative to the past 500 years. These findings have helped to complete a network of tree-ring data that spans most of the far north and that provides strong evidence of an unprecedented twentieth-century shift toward warmer temperatures. LDEO researchers have also created some of the longest temperature reconstructions from the Southern Hemisphere. Like conifers in the far north, Huon pines from Tasmania and New Zealand have responded to recent warm temperatures that are highly unusual in a historical context.

But puzzles remain because some studies have detected growth responses in trees that cannot be fully accounted for by a rise in temperature. "Because dendroclimatologists have very closely examined the relationship between climate and the annual radial increment of trees in many places on

Dendrochronologists use cross-dating—that is, matching ring patterns among several trees—to ensure the accuracy of dates assigned to individual tree rings. In these cross-dated core samples from Douglas fir trees growing in El Malpais National Monument, in New Mexico, the large ring visible in each core sample is from 1816, which is known as the "Year without a Summer." This year was exceptionally cool because of the large amount of dust in the atmosphere from the 1815 eruption of Tambora, a volcano in Indonesia. The unusually cool weather reduced water evaporation and increased the amount of ground water available for plant growth. The equivalent sets of very narrow rings that formed after 1816 also aid in the cross-dating of these samples. Photo: H. Grissino-Mayer.

the earth, we have been able to notice some changes in those relationships in the past few decades," Hughes says.

In a paper published in *Nature* last year (400: 149–151), Hughes and several Russian collaborators proposed a new explanation for growth anomalies observed in the boreal forests of Siberia. They suggested that some difficult-to-interpret patterns in the recent tree-ring record may be attributable to changes in the length of the growing season brought about by variation in winter snowfall. In northern forests, seasonal tree growth can begin only after snows melt and the ground starts to thaw. The authors employed a simulation model to calculate tree-ring growth based on the complex dynamics of light intensity, temperature, precipitation, snowmelt, and soil thawing. Chronologies generated using the model were very similar to those taken from trees at several sites in the Siberian subarctic.

Hughes says that the recent studies in Siberia exemplify a growing interest in using networks of tree-ring and climate data in conjunction with physiological models to better understand and predict the seasonal growth responses of forests. Such approaches may ultimately yield greatly improved estimates of how forest productivity may be responding to increasing global temperatures and atmospheric CO_2 levels.

Currently, the seasonal "greening" response of terrestrial vegetation is measured by sensors aboard satellites, and some of these data suggest that in recent years the onset of spring growth may be taking place earlier across much of the far north. Hughes says that efforts are now under way to weave together tree-ring and remote sensing data. If researchers can extract from tree rings the same kinds of information now provided by satellites, it will become possible to reconstruct annual cycles of forest growth for time periods predating the use of remote sensing technology. "People get all excited about changes they see taking place over a decade," Hughes says. "But did the same thing happen in the 1870s or the 1430s? We don't know for sure if we can actually answer that yet, but a number of us are looking at it very closely."

New frontiers

Such new approaches exemplify how dendrochronology is continuing to expand, both geographically and technologically. Stahle says that gathering the data needed to fully understand the history of El Niño is part of an even larger endeavor: to build a network of tree-ring data for the tropics comparable to the existing data for temperate regions of the Northern Hemisphere. "The real frontier of tree-ring research is in the tropics," he says. "If we can build up a tree-ring network for many tropical regions, the payoffs—for our understanding of climate and the ecology of tropical forests—would be enormous."

Although tropical forests are the global centers of plant and tree diversity, they have long been considered out of bounds for dendrochronology. In temperate regions, growth rings are a manifestation of trees' adaptation to the seasonal cycle of favorable and unfavorable growing conditions. By contrast, most tropical tree species grow year-round and do not produce annual rings. But, Stahle says, although ring-producing trees are rare in the tropics, they are not entirely absent. He and a number of colleagues are explor-

This cross section is from a longleaf pine tree at Lake Louise, the Valdosta State University research area in southern Georgia. The variability in the latewood, or dark bands of wood, in this cross section, which was collected by Henri Grissino-Mayer and a colleague, shows the extreme sensitivity of the ring patterns of this species to climate. Photo: Jeffrey H. Tepper, Valdosta State University (courtesy of H. Grissino-Mayer).

ing ways of bringing tree-ring analysis to tropical latitudes. One approach is to search for outlying populations of temperate zone species at high elevations in the tropics. Stahle's group is using such an approach to build a network of data from Douglas fir growing in mountainous regions of southern Mexico.

Stahle believes that much more effort should also be put into searching out those rare tropical tree species that produce visible rings. In Kenya and Zimbabwe, he and coworkers have identified several such species and are using them to establish some of the first tree-ring chronologies from equatorial Africa. Jacoby and others at LDEO are conducting similar pioneering work in tropical regions of Southeast Asia, focusing on species of teak and pine.

With so much information now available, it is becoming possible to develop increasingly detailed computer models simulating ring growth. One of the most ambitious of such efforts is the one undertaken by Harold Fritts, of LTRR, and Alexander Shashkin, of the Russian Academy of Science in Krasnoayrsk, Russia. Under development for the past 10 years, the researchers' model simulates how a tree's basic metabolic processes, as well as its allocation of water and glucose, respond to climatic variables. Unlike existing statistical models, which are based on correlations between mean climatic conditions and measurements of tree growth, Fritts and Shashkin's model is intended to capture the actual mechanisms of stem growth at the cellular level. It breaks down the formation of annual rings into a series of daily steps, revealing exactly how trees record environmental information in the microscopic structure of their rings.

Specifically, the model simulates daily changes in the width, cell number, cell size, and cell wall thickness of conifer tree rings. These outputs are generated from a complex array of parameters describing climatic and environmental conditions for the particular geographic location to which the model is being applied and the size and condition of a single simulated tree. Equations describe the processes by which these variables govern daily changes in tree water balance, photosynthesis, carbon allocation, crown growth, and cambial activity. Predictions are then checked against actual cell measurements for trees growing in the study area; discrepancies between predicted and actual tree responses are used to further fine-tune the model.

"What Hal Fritts is trying to do is simply amazing," Grissino-Mayer says. "He's taking immense amounts of environmental data, throwing them into a computer model, and actually producing a tree ring. The implications of this are enormous." Fritts says the model will give dendrochronologists a detailed physiological understanding of the relationships between cause—environmental variation—and effect—variation in annual growth rings. Such an understanding may have many applications, particularly in situations in which scientists want to predict how vegetation may respond to anticipated environmental changes for which no parallel exists in the recent historical record of climatic variability.

The work by Fritts and Shashkin represents a particularly striking example of the versatility and integrative power of dendrochronology. As Douglass foresaw decades ago, this seemingly specialized discipline gives scientists a remarkably effective tool for uncovering complex connections—between past and future, between physical and biological systems, and across levels of biological organization, from cells to ecosystems. Today, the astronomer's invention has become one of the most powerful devices available to scientists seeking a broad-picture perspective on the earth's climate and ecology. ❑

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