Fundamentals of Tree-Ring Research

By James H. Speer

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Cover Image: This cross section is a *Pinus occidentalis* tree from the Dominican Republic and is one of the most difficult pieces of wood that I have ever tried to date. This piece comes form a site at above 3,000 meters elevation, but still has missing rings, false rings, and pinching rings around the circumference of the sample. You can see on the cross section, my many pencil marks that indicate the border of rings as I try to follow them around the section.

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Proloque

I envisioned writing this book since I was an undergraduate student at the University of Arizona in the Laboratory of Tree Ring Research, when in my introductory dendrochronology class (taught by Tom Swetnam), we used a photo copy of a book written by Hal Fritts that was no longer in print. That book was the famous "Tree Ring and Climate" but during the 1990s, the only way to acquire a new copy of the book was from a photo copy directly from the author. Thankfully, Blackburn Press later reprinted the book in its entirety in 2001, and that book is now again available to new students in dendrochronology. Another book that was often suggested for the novice dendrochronologist was "An Introduction to Tree-Ring Dating" Marvin Stokes and Terah Smiley. The first book was written at a high level with the explicit focus of dendroclimatology while the second book was a basic introduction that specifically used a dendroarchaeological project to explain the techniques of dendrochronology. I have written this book as a basic introduction to the breadth of dendrochronology including some of the principles and physiological background that one needs to conduct dendrochronology. The second half of the book has individual chapters dedicated to each of the sub-disciplines of dendrochronology, providing a basic bibliography for one to start dendrochronological research in any of the applications within the field.

I further saw a need for this book in teaching and organizing the North American Dendroecological Fieldweek (NADEF) for the past nine years along with teaching my own dendrochronology class at the university level for the past seven years. I found that the students consistently asked the same questions about the field and I hope that this book answers those questions. In teaching at NADEF, I realized that every laboratory has its own perspective on the field, although the Tucson Lab has wide-reaching influence because so many people spend some time at that laboratory for aspects of their training in the field. My own training in dendrochronology came from four years at the Laboratory of Tree-Ring Research and therefore my perspective is from the Tucson Lab in Arizona. I have contacted researchers in other countries to try to ensure the inclusion of the best literature from around the world, but admittedly my perspective is based on my own research in North America.

I hope that you find this book useful as a reference and as a primary starting point for work in dendrochronology. It is the result of four years of dedicated reading and writing along with the input from 30 other dendrochronologists through reviews of different stages of the book.

Chapter 1: Introduction

Dendrochronology is one of the most important environmental recording techniques for a variety of natural environmental processes and a monitor for human caused changes to the environment such as pollution and contamination. The word dendrochronology has its roots in Greek: "dendro" means tree and "chronology" means the study of time. Dendrochronology examines events through time that are recorded in the tree-ring structure or can be dated by tree rings. Because the tree becomes the instrument for environmental monitoring, it provides a long-term bioindicator that extends for the lifetime of the tree. Dendrochronology can be applied to very old trees to provide long-term records of past temperature, rainfall, fire, insect outbreaks, landslides, hurricanes, and ice storms to name only a few applications. Wood from dead trees can also be used to extend the chronology of tree rings further back in time. Trees record any environmental factor that directly or indirectly limits a process that affects the growth of ring structures from one season to the next making them a useful monitor for a variety of events.

Some Interesting Applications of Dendrochronology

The discipline of dendrochronology is used to mark time or record environmental variability in the structure of the wood from trees growing in seasonal climates, such as in the mid-latitudes, high latitudes, and some tropical trees growing in environments with a pronounced wet or dry season. Because many different environmental variables can affect tree growth, different records can be gained from a variety of tree species on a site and on a variety of sites in a region. Dendrochronologists have been able to develop interesting records that contribute too many areas of modern culture, from forensic science to boundary disputes. For example, tree rings were used as forensic evidence in a murder case by dating the age of a root that grew over a buried corpse (Thomas Harlan personal communication). Sellards *et al.* (1923) used tree rings to settle a boundary dispute between the states of Oklahoma and Texas along the Red River. A carving on an aspen (*Populus tremuloides*) tree stem supposedly made by Ted Bundy (the infamous serial killer) was dated to 1976, a time he was reported to be in that region, thus causing investigators to intensify their search for Ted Bundy's victims in this area (Thomas Swetnam personal communication). This was an unusual use of dendrochronology because the carving was only in the bark of the tree and not in the wood. Aspens produce rings in the bark (although not as continuously as in the wood) which were counted to establish the date.

Tree rings have been used to help elucidate strange atmospheric events such as the Tunguska Event that occurred on June 30^{th}, 1908 (Vaganov *et al.* 2004). One of the main hypotheses of what caused this event that flattened 80 million trees over 2,150 square kilometers in Siberia is the arrival of a large meteoroid that disintegrated in the atmosphere from 5-10 kilometers above the surface of the Earth. This is the largest impact event in the written history of the Earth. Vaganov *et al.* (2004) examined tree rings at the time of the impact and found that the cells growing during the end of 1908 were deformed. They could conclude that this was likely caused by a forceful impact on the trees and suggested an upward adjustment of previous estimates to the amount of force that was exerted on the trees from this event.

One of the more remarkable stories in dendrochronology comes from attempts to date the Stradivari violin called the Messiah which has a label date of 1716 (Figure 1.1). The Messiah violin is considered one of Antonio Stradivari's crowning achievements. It is a well-preserved

Figure 1. 1 The Messiah Violin. Any object that is made of wood and has enough rings in a sensitive series can potentially be dated using tree rings. In an unusual example, the Stradivarius Messiah Violin was dated using dendrochronology (photo from Topham and McCormick 2001). instrument that has a distinct red hue to its finish. This instrument was valued between 10 and

20 million dollars if it could be authenticated as the true "Messiah" violin, but if it was made by a copyist in the 1800s, it would be worth far less. This instrument is housed in the Ashmolean Museum in Oxford, England. Initial tree-ring dating on the Messiah suggested that the instrument was the original Stradivari (Topham and McCormick 1997, 1998, 2001), but others (including one dendrochronologist) claimed the violin was made after Stradivari died in 1737 (Pollens 1999, 2001). To settle the controversy, Dr. Henri Grissino-Mayer of the University of Tennessee was asked to assemble a team of experts and examine the rings a second time in an attempt to date the violin.

It should be noted that dendrochronology cannot conclusively demonstrate that the instrument was made by Stradivari. Dendrochronology, however, can be used to disprove the possibility of it being a Stradivari instrument by finding growth rings in the wood of the instrument that post-date Stradivari's death in 1737. The "Messiah" violin was made from a spruce tree and had 120 rings showing on the top of the instrument. Grissino-Mayer *et al.* (2002, 2003, 2004) worked at dating this violin against European reference tree-ring chronologies and against chronologies developed from other known Stradivari instruments. They demonstrated that the last rings in the instrument dated to A.D. 1687, which was consistent with two other instruments made by Stradivari: the "Archinto" (dating to 1686) and the "Kux/Castelbarco" violas (dating to 1684).

Some Basic Principles and Definitions in Dendrochronology

Many proxy records (alternate sources of information from natural phenomena) of climate and the environment exist, such as pollen, ice cores, lake varves (annually layered sediment), coral layers, and speleothems (calcium carbonate dripstone from caves)(Bradley 1999), but dendrochronology provides the most reliable dating with the highest accuracy and precision of any of these paleorecords. The practice of **crossdating** (matching the pattern of wide and narrow rings to demonstrate dating between trees), which was developed by A.E. Douglass in the early 1900s (Douglass 1909, 1917, 1920, 1921, 1929, 1941), is now being used for some of the other proxy records that form regular (sometimes annual) increments, such as ice cores, corals, rings in clam shells, and otoliths (the bony structure in the ears of fish) as a check on the dating of those records (Black *et al.* 2005).

The science of dendrochronology has a few basic principles and concepts that have been repeatedly demonstrated by scientific evidence from multiple disciplines and experimentally supported by dendrochronological research. These principles are the subject of Chapter 2, but I summarize some of them here because it is hard to discuss dendrochronology without the use of some of these terms. The main principle of **crossdating** suggests that variation in ring width is driven by limited environmental factors needed for growth; matching these narrow rings provides the quality control required by dendrochronologists, allowing the assertion of annual resolution and being able to provide exact calendar years for every tree ring in a sample. This principle is strengthened by the concept of **replication** which states that reliable dates must be supported by enough samples to assure the probability of being in error is sufficiently minute. For example, for most sites in the southwestern United States, 20 overlapping tree records (**sample depth**) are usually sufficient for a reliable **chronology** (a site-level representation of tree growth). Good chronologies have been developed with as few as 10 trees sampled on sites with a consistent site-level chronology and many chronologies have been developed with more than 100 tree samples. By sampling two cores from each tree, statistics can be used to calculate the amount of year-to-year agreement within trees as well as between trees. Two cores per tree also enable the researcher to start the crossdating process within a tree and to better represent overall tree growth. If the researcher can take a cross section from a tree, then they have the opportunity to examine as many radii as they want around the section. This sampling protocol of 20 trees with two cores per tree results in 40 cores represented in a site-level chronology; a **site** is defined as a spatially proximal group of trees with similar environmental conditions such as slope, aspect, and climate.

Tree-ring width responds to a similar set of environmental factors that limit tree growth. This is the well-known biological principle of **limiting factors**. Because ring width is influenced by anything that limits tree growth, the dendrochronologist must consider what problem is to be addressed, then find the particular sites and trees that provide the necessary information. This procedure is one of the most important principles called **site selection**. Dendrochronologists label tree-ring chronologies **sensitive** when their ring-width patterns varied markedly from year-to-year, while chronologies that had similar amounts of growth every year are called **complacent** series. For climate studies, sensitive trees are targeted because their ring variation is likely to better reflect climate than complacent trees. Climate is essentially the primary limiting factor that imparts the year-to-year variability that makes crossdating possible. The history of dendrochronology in Chapter 3 introduces the pioneers in the field that were the first to recognize and apply many of these basic principles.

Subfields of Dendrochronology

Because tree-ring width can vary with anything that affects tree growth, annual records of many natural phenomena can be developed. The term *dendrochronology* refers to the science of dating tree rings and studying their structure to interpret information about environmental and historical events and processes (*sensu* Kaennel and Schweingruber 1995). Many subfields within dendrochronology have been developed and subsequently named by keeping the base of the word "dendro" and adding a secondary prefix to describe the specific field being studied. For example, *dendroclimatology* uses the variation in tree-ring structure and width to infer information about past climate, while *dendroarchaeology* uses the date of the outside tree ring from a beam to study the timing and process of archaeological construction. (see Table 1.1 for a brief synopsis of the many subfields of dendrochronology, which are discussed in greater detail in Chapters 7-11).

Limitations of Dendrochronology

As with all research, dendrochronology has certain limitations that must be acknowledged (Table 1.2). Annual tree rings (Figure 1.2) can form in any forest that has one yearly growth period followed by a dormant period, but some locations, such as many tropical areas, do not have the seasonality to allow the formation of annual rings. Crossdating must be used to verify the dates of every ring in a sample. This technique is time consuming, takes special skills, and requires much patience to learn and apply properly.

The development of wood through cambial activity that forms xylem and phloem in the trees is a very complex process which has been the topic of an entire book (Larson 1994). Tree physiologists have not been able to explain the exact biochemical processes that occur from

Table 1. 1 Subfield of dendrochronology. Many of the subfields also have subheadings (written in bold) that more specifically describe the discipline. Dendrochronologists will often identify themselves as practitioners of one or more of these subfields.

Subfield	Description
Dendroarchaeology See Chapter 7	Tree-ring samples from beams and posts in archaeological dwellings are dated to provide construction dates for the dwellings. The position of these beams in the dwelling can be used to study the timing of construction and expansion of dwellings and to start to understand human behavior in these cultures. Correlation with regional master chronologies can also help to **dendro-provenance** archaeological and historical wood object.
Dendroclimatology See Chapter 8	Samples from trees can provide short- or long-term records of past climatic variability for the life-time of the trees. Most often temperature, precipitation, and drought indices are reconstructed, although anything that affects the processes of tree growth such as number of cloudy days, relative humidity, or wind strength can be reconstructed as well if they have limited growth. Information from dendroclimatology has provided important information about past climate change and help us understand what the future climate might be like. This subfield also includes **Dendrohydrology** which is the reconstruction of water level or streamflow, although this is often sperated out as its own subdiscipline.
Dendroecology See Chapter 9	Because trees are an important functional feature of many ecosystems, they can be used as a natural record of ecological processes, such as tree-line movement, successional processes through the establishment and death of trees, fire occurrence (**Dendropyrochronology**), insect outbreaks (**Dendroentomology**), synchronous fruiting (masting) in trees (**Dendromastecology**), or movement of invasive tree species.
Dendrogeomorphology See Chapter 10	The vertical structure of a tree enables it to gather the most light while standing up straight so that land movement can be reconstructed by the tilting of a tree and the resultant reaction wood (thicker growth rings produced to straighten the stem of a tree). Also tree death or establishment can be used to date geologic phenomena such as landslides, mudflows, seismic activity along faults (**Dendroseismology**), glacial activity (**Dendroglaciology**), or volcanic events (**Dendrovolcanology**).
Dendrochemistry See Chapter 11	Trees absorb chemicals along with the water that they absorb from soil and the gases that they take in from the atmosphere. These chemicals are deposited in the wood in the trees' stem, roots, and branches and can be used as a record of contamination, nutrient availability, and pollution. **Stable isotopes** can also be measured in wood structure to reconstruct past temperature, humidity, and the source of water or growing conditions of the trees.

Table 1. 2 List of the general limitations to dendrochronology along with solutions to those limitations.

Limitation	**Solution**
Young trees	Finding old trees in unique sites, buried wood, or archaeological samples to extend a chronology.
Calibration datasets	Conduct studies close to available climate or ecological datasets or establish monitoring stations for future calibration data sets in remote areas. Regionalized climate data are also being used to examine broad scale climate response in areas without local climate stations.
Lack of ring formation in the tropics	Looking for a chemical or stable isotopic signal in tropical woods. Examine wood anatomy of many species to find some with annual ring formation.
Lack of a physiological understanding of how tree rings form	More wood anatomy, tree physiology, and biochemical studies need to be conducted to better understand the growth of tree rings.

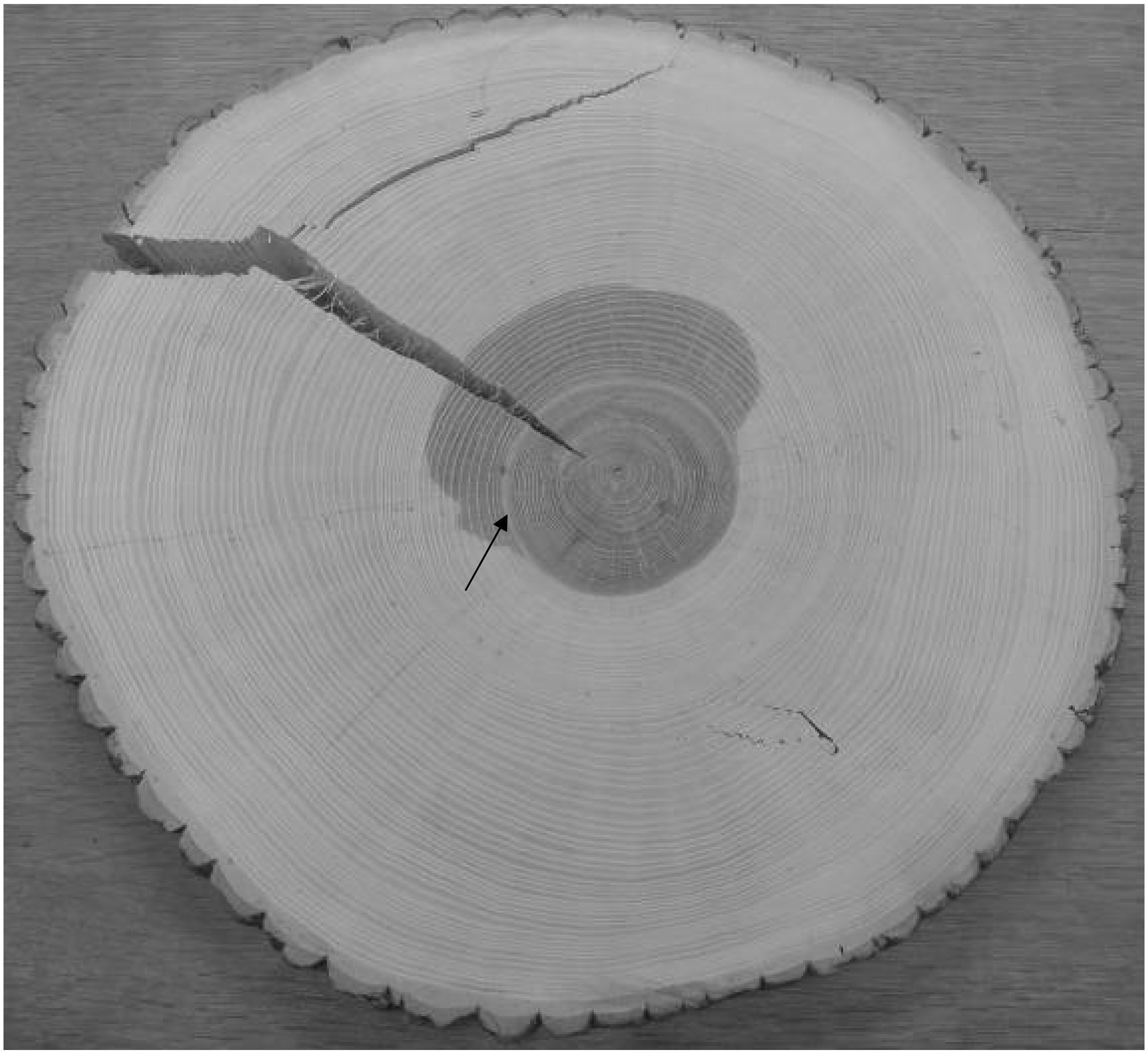


Figure 1. 2 A cross section of an ash (*Fraxinus* sp.) tree. Note the dark colored heartwood near the center of the tree and the suppressed rings in the 1930s and the 1950s (at arrow). The split in the top left section of the wood is a natural break in the wood due to the cross section drying out after it was sampled (photo by Jim Speer).

photosynthesis to the formation of tree rings. Some physiologists have argued that because we do not completely understand the mechanisms that occur from the assimilation of abiotic elements from the environment to the formation of the tree ring, we should not be conducting dendrochronological studies. However, countless analyses of the correlation between tree growth and environment variables have demonstrated consistent predictable results demonstrating that despite our lack of understanding of the exact mechanisms, we know that tree growth does reflect environmental variables. Over 100 years of productive research in dendrochronology supports its validity and importance in environmental reconstruction.

The development of well-dated tree-ring chronologies for the reconstruction of environmental variables is restricted by the location of sensitive tree-ring series (Fritts 1976). Trees are not ubiquitous on the landscape and even when they are present, dendrochronologists must choose specific sites that are likely to record the environmental variable that they wish to study. Furthermore, many reconstructions depend upon calibration and verification datasets such as modern temperature and precipitation records to create a statistical model to reconstruct past climatic variations (Stahle *et al.* 1998a). These constraints geographically limit dendrochronology to areas where the trees produce datable annual rings and where local paired climate or ecological data exist for calibration of the trees' response. This calibration data enable a scientifically meaningful reconstruction and independent verification data allows the researcher to determine the validity of the reconstructions. Still, tree-ring data can be useful even when calibration data is not available. For example, the variability of rings in petrified wood demonstrates variability in climate millions of years ago, and long-term growth suppressions and releases in tree rings can demonstrate stand dynamics processes.

We can use trees to interpret past environmental phenomena, but trees are biological entities that are driven by their own physiology and biochemistry that creates filters on the climatic or ecological processes that they record in their annual rings. Trees, therefore, are not strict monitors of the environment and these biological factors must be taken into consideration when interpreting tree-ring data.

In comparison with many other proxy data, dendrochronology provides a relatively short record with only three tree-ring chronologies in the world that extend back 10,000 years or longer. These are developed from bristlecone pine (*Pinus longaeva*) in California (Ferguson *et al.* 1985), oak (*Quercus* sp.) in Ireland (Pilcher *et al.* 1984), and oak in Germany (Becker 1993, Friedrich *et al.* 2004). Dendrochronological records for any particular area are further constrained by the need for well-preserved wood samples that represent a range of time scales. For example, most wood in the eastern United States will decay on the forest floor in 20 to 50 years, while wood found on a lava flow in the western United States may last for a thousand years without much decay of the heartwood (Grissino-Mayer 1995). Very little wood can survive decay for longer than hundreds or thousands of years thus limiting the length of our tree-ring records. Some researchers have begun to use subfossil (buried but not permineralized) wood that may extend their chronologies back 15,000 years or more (Roig *et al.* 2001, Guyette and Stambaugh 2003). Petrified wood also provides a possible source of information on climatic variability from millions of years in the past as long as the rings are well preserved (Chaloner and Creber 1973, Falcon-Lang 1999) although it is important to not over-interpret the climate information that can be gleaned from fossilized wood (Falcon-Lang 2005).

Objective

The objective of this book is to introduce the fundamental principles, concepts, and methods of dendrochronology and provide the basic instruction, theoretical framework, and biological and ecological background for the practitioner of tree-ring research. While portions of this information are presented elsewhere (Stokes and Smiley 1968 [reprinted as Stokes and Smiley 1996], Fritts 1976 [reprinted as Fritts 2001], Phipps 1985, Schweingruber 1996), I hope to compile this knowledge into a single basic user manual and easy reference book that covers the breadth of the field. Whether you are a graduate student incorporating tree-ring chronologies into your thesis or dissertation, a professional land manager who is looking for environmental information, or a layperson who has heard about dendrochronology and wants to learn more, I attempt to provide a practical resource that will provide you a strong start in the field of dendrochronology.

No previous volume provides a comprehensive history of dendrochronology that incorporates old world and new world pioneers in dendrochronology. I strive to provide a more complete history of dendrochronology in chapter three that draws from European, American, Russian, and Asian dendrochronologists up to the 1950s. An understanding of wood anatomy is becoming more important in dendrochronology as we push the geographical bounds of past research and start to study tree species growing in moist environments such as the Eastern Deciduous Forest or the Tropics. I attempt to provide a quick primer on the aspects of wood growth and structure that underlie the study of tree rings in chapter four. The core of this book is the field and laboratory methods that are incorporated in chapters five and six. I try to provide a basic founding in field practices and provide some greater depth in working with the programs and statistics that are important to dendrochronology. I hope to provide a broad overview and a useful starting point for all of the major subfields in dendrochronology in chapters 7-11. Each chapter describes some specialized methods in each subfield and provides a bibliography as a starting point for research into each area. Finally, chapter twelve describes what I see as some frontiers in dendrochronology where researchers are gaining the most ground. Dendrochronology is still a young science and there are many exciting frontiers yet to be explored.

Summary

I have heard many discussions about the status of dendrochronology. People ask if it is a discipline, a tool, or an application. I respond that the answer depends upon who is doing the research and how they approach their work. I, among others, see dendrochronology as a thriving discipline with its own governing body of principles, theoretical advancements, and areas of important contributions to society. Others may simply use it as a tool to obtain dates or longer-term records of past phenomena. Other researchers may work mainly on advancing theory in different fields but call on the techniques of dendrochronology to advance their understanding within their discipline. Through my experience teaching dendrochronology classes in the university setting and coordinating and teaching the North American Dendroecological Fieldweek (NADEF), I have found that that a basic set of knowledge exists that is new to and important for the starting practitioner of dendrochronology.

The graphics that are collected in this book are the ones that visually represent the state of knowledge and the theoretical basis of this firmly established field. The text is meant to present the principles and methods that you will need to work through basic research projects in dendrochronology on your own. This book is not intended as the final word in dendrochronology and any practitioner of these methods should delve deeply into the primary literature and other resource books available in the field. I strive to cite most of the pertinent literature throughout the text and to lead the reader to useful internet resources that are available in dendrochronology. I hope that you will find this book useful, whatever your intended application.

Chapter 2: Some Basic Principles and Concepts in Dendrochronology

Introduction

Dendrochronologists follow some basic principles and concepts that describe sampling protocols, model our concepts of how environmental factors are incorporated in tree growth, and form our basic procedures of how to date tree rings and build chronologies. We also make some basic assumptions about the natural world in the way that we conduct research. In this chapter, I will discuss some of the assumptions, guiding principles, and core concepts in the field of dendrochronology.

Some basic terminology associated with dendrochronology will be introduced first. The **signal to noise ratio** is an important measure of the amount of desired information recorded in the chronology versus the amount of unwanted information and random variation also included in the tree-ring record. The noise can come from environmental factors not of interest to the researcher. For example, growth releases due to mortality of neighboring trees (processes involved in gap dynamics) are considered noise to a dendroclimatologist, whereas they are the signal of interest for the dendroecologists interested in reconstructing forest succession.

Calibration is the process of comparing a known record of some environmental variable to the tree-ring chronology for the purpose of determining tree growth response to that variable. We use meteorological data (for example monthly temperature, precipitation, or Palmer Drought Severity Index) as a calibration data set for climate reconstruction. Similarly, we use a record of past fruiting of trees as a calibration data set for mast reconstruction (synchronous fruiting in trees) or the historical records of insect populations to identify the growth pattern associated with insect outbreaks. Part of this independent data can be withheld from the original model and used to verify the reconstruction. This step is important to determine how accurate reconstructions may be.

Principle of Uniformitarianism

The Principle of Uniformitarianism is a basic assumption of geology and most other natural sciences. It can be succinctly stated as:

The present is the key to the past.

This means that the processes occurring today are the same processes that occurred in the past. The classic example states that by collecting the sediment washing down a stream over a certain time period one could extrapolate how long it will take the entire mountain to erode away, because the Principle of Uniformitarianism assumes that the processes that determine the rate of erosion remain the same through time. This basic assumption enables estimates of the rate of change in natural systems. Dendrochronologists use the Principle of Uniformitarianism when we reconstruct past climate. Researchers realize that the climate is changing through time and that this change (e.g. the availability of CO_2) may alter how a tree responds to climate, but this is the best estimate that can be provided until further information is added to the model.

Dendrochronologists use calibration data sets such as meteorological data, historical records of insect outbreaks, or masting to build mathematical models of how trees respond to these environmental factors. Once this model is developed (usually with regression analysis) it provides an understanding of how the trees respond to the variable of interest. The model can then be inverted to reconstruct that variable into the past for the lifetime of the trees. For this reconstruction to be possible, dendrochronologists have to assume that the processes affecting the tree's response to these environmental factors have not changed from the calibration time period to the period of reconstruction. This is a common assumption made in the natural sciences, but it has some drawbacks of which the researcher should be aware.

The trees' response to the environment does vary with age. Seedlings are more sensitive to environmental factors and are more likely to perish because of limitations in moisture availability or temperature extremes. Young trees often go through a period of juvenile growth during which they produce larger than average growth rings. Dendrochronologists should be aware of and control for these tree responses as they build chronologies and reconstruct environmental factors over the lifetime of the trees.

Humans have changed the environment, which may change how a tree will respond to climate variations. We live in a world of elevated CO_2 in the atmosphere; prior to the industrial revolution the normal level of CO_2 was 280 ppm while the current level is close to 380 ppm. This amount of CO_2 in the atmosphere is outside the natural range of variability recorded over the past 100,000 years by ice cores. Most of the calibration climate data has been recorded during a time of elevated CO_2 and tree response to variability in temperature and precipitation may be moderated by the amount of CO_2 in the atmosphere. This may affect our climate calibrations and the resulting climate reconstructions.

There are some ways to reduce the risk of violating the assumptions of the Uniformitarianism Principle. For example, tree-ring series can be truncated to remove juvenile growth. This shortens the resultant chronology and reduces sample depth further back in time, but it results in more reliable reconstructions. Series can also be detrended by fitting curves such as a negative exponential or a cubic smoothing spline (described later) to the ring-width measurements to remove trends through time. But none of these treatments deals with the calibration problem of living in a time of an altered climate. We know that our assumption that present processes have not changed through time is not always correct, but Uniformitarianism is a productive starting point in the analysis of past climates and environmental variability. The researcher must be aware of these assumptions and work to overcome such limitations to understand the natural world.

Principle of Crossdating

The principle of crossdating is the basic tenet of dendrochronology. It is the main tool by which the exact year of growth of every annual ring is determined. Without crossdating, a simple ring count is likely to produce error due to locally absent or false rings. Crossdating is imperative when ring-width measurements are compared to annual phenomena such as meteorological data. Without exact annual dating of the tree rings, accurate calibration is impossible because the chronology will be misdated by one or more years. For example, the temperature data from 1973 may be erroneously compared to the annual ring grown in 1972 or 1974, and the result is a degraded or non-existent climate signal.

The history of the concept of crossdating is relatively long. The French naturalists Duhamel and Bufon first used crossdating to identify the 1709 frost ring in a series of samples collected in 1737. Twining rediscovered the process in 1827 and Babbage spoke about it in great length in 1838. But it was not until 1904, when Douglass laid out the basic methodology of skeleton plotting and the refined technique of the memorization method that crossdating was really tested and documented.

Crossdating matches the pattern of wide and narrow rings in a tree to determine the location of real ring boundaries based on anatomical wood structure, providing a check of the actual date of a specimen (Figure 2.1). In this sense, a tree core is like a bar code with varying widths of lines representing each year. The patterns from one tree can be matched with those of other trees to determine if all of the rings are represented on a sample. This technique shows where rings are missing from a sample or where a tree might have formed two or more rings in one year. Crossdating results in accurate dates for every single ring in the tree-ring record.

There are many ways to date tree rings, but the most repeatable and tested techniques are those originally developed by Douglass. The method of **skeleton plotting** assigns each year of growth to a vertical line on a piece of graph paper (usually graph paper with five lines per centimeter is used). The length of the line represents the importance of the ring to the signal of the chronology. Narrow rings are more important for recording limiting environmental factors, so

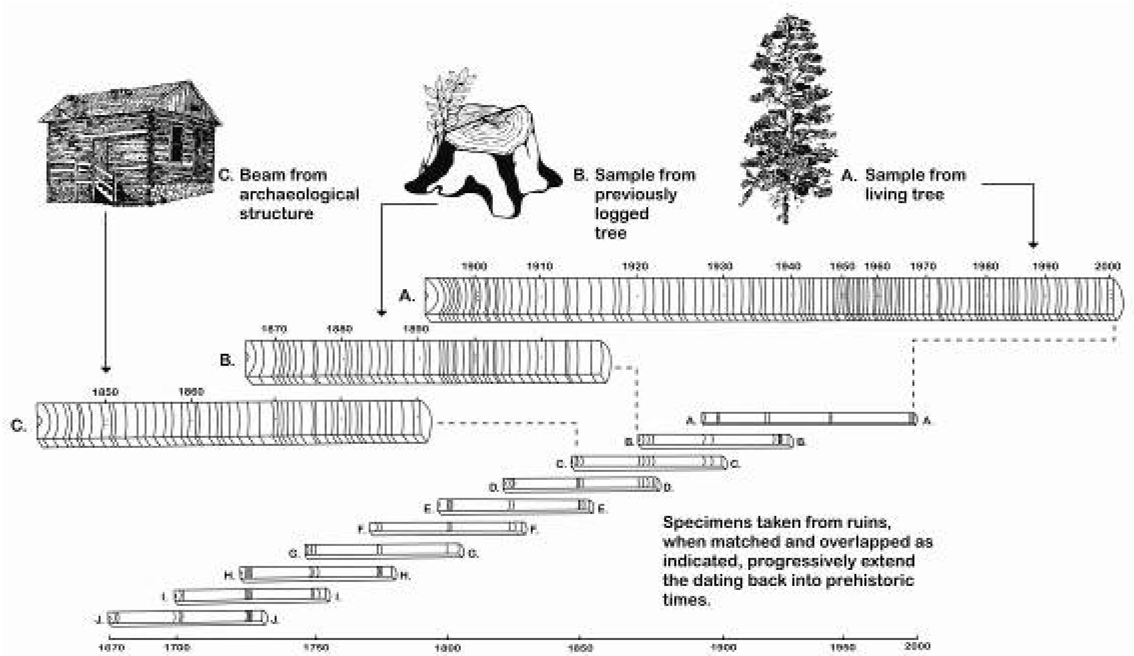
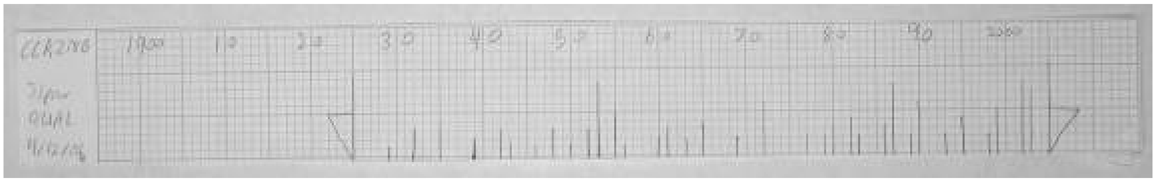
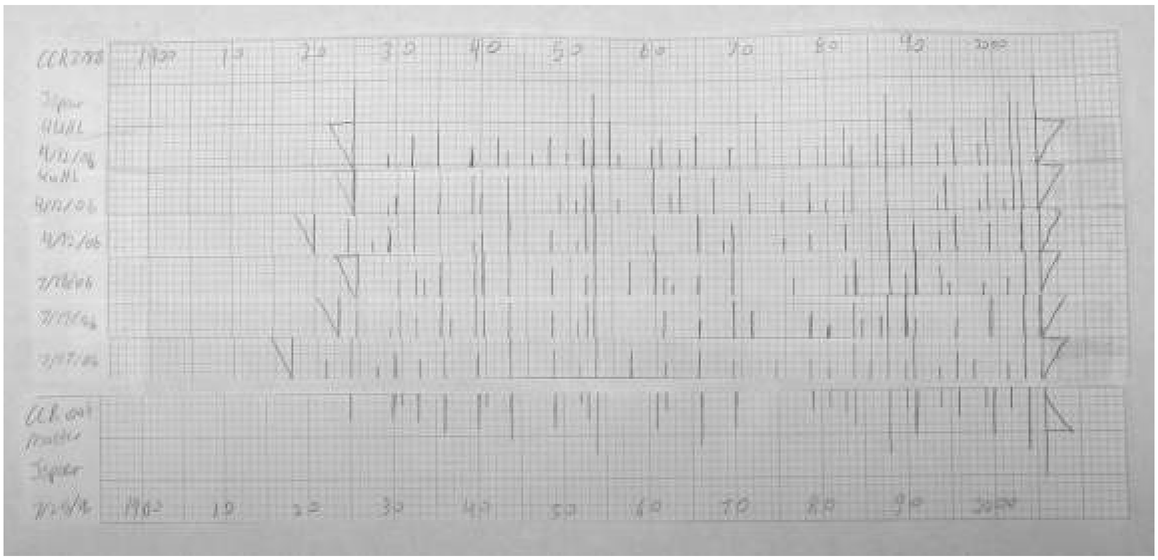


Figure 2. 1 Crossdating. Crossdating is the basic principle of dendrochronology and provides the annual resolution of the dated rings (modified from Stallings 1949).

more attention is usually given to the rings that are below average in width. Therefore, the more narrow a ring, the longer the line marked on the skeleton plot (Figure 2.2). Because of the age-related growth trend, which will be discussed below, and the individual variability of growth in the tree through time, the dendrochronologist uses a process of mental standardization in which the relative width of the ring is determined by comparing the ring of interest to three rings on either side. Only seven rings are compared at a time and the narrowest rings are noted on the skeleton plot. This mental standardization keeps long-term trends or short-term suppressions from dominating the signal in the chronology. The skeleton plot allows for a range of line lengths from zero indicating an average or larger than average ring width to 10 which is usually reserved for a ring found to be absent through crossdating. The sample about to be dated should be visually scanned to determine the size of the smallest and largest rings across the entire cross section to set the overall scale of the skeleton plot. The smallest rings in the sample will have a line length of nine boxes and the entire range from 1-9 should be used for all samples. The resultant plots illustrate the interannual ring- width variability within the wood sample whether the wood is complacent with very similar ring widths or sensitive containing much variability in ring width. Many beginning dendrochronologists have a difficult time with this apparently arbitrary determination of the length of the line on the skeleton plot, but after some practice, most researchers and students will produce very similar skeleton plots. The process can be duplicated by a computer program, showing that it is not a purely subjective process (Cropper 1979). However, dating should always be performed visually and can be second checked with various computer methods. Skeleton plotting allows two different trees growing at vastly different rates to be compared to determine if all of the rings are represented (see Chapter 5 for specific details in marking the wood and making a skeleton plot). A **master chronology** (a



A



B

Figure 2. 2 A) Photograph of a single skeleton plot showing the beginning and end arrows that represent the inner most date and bark dates respectively. Notice on the left side, the sample ID, Dendrochronologists name, species, and date are recorded. B) Once multiple skeleton plots are completed on a site, they can be taped together with scotch tape and a master chronology can be drawn from them. For a ring to be represented on the master chronology it has to appear on 50 percent of the plots then the length of the lines are averaged together (usually only counting the trees that represent that ring). The master chronology is drawn upside down from a regular plot so that it is easy to check the date of subsequent plots against it. You can see in the stack of skeleton pots, the rings that are represented on most of the samples. These are the rings that become marker rings on the master chronology.

record of ring widths representing the stand level signal) can also be developed from the individual tree skeleton plots. This is usually done by lining up the skeleton plots so that they share the same time axis along the bottom and any ring that is consistenly marked on half of the samples in a given year will be averaged onto the master skeleton plot. Dead wood can then be dated against this master chronology. One clear advantage of skeleton plotting over the list method is that samples with unkown outside dates can be dated using skeleton plots.

The **list method** is a technique used to develop the chronology of marker rings without the added steps of plotting them on graph paper (Yamaguchi 1991). It should be noted that the skeleton plot provides more data and a clear graphic representation of the samples, making the dating of difficult samples more probable. Also, the list method can only date complete samples from living trees as the outer ring provides the starting point for the list. The list method, therefore, is not of any use in dating archaeological samples or fire scars from dead wood. The list method is a faster procedure and can be more efficiently used in wood with a clear pattern of rings. When developing the list, the researcher starts at an anchor in time, which is the outside of the sample with the known coring date. Care should be taken to develop the master list only from good quality cores in which the samples are complete and the tree was living. Note the date of each small ring on a piece of paper while counting back from the bark of the tree so that a list of marker rings is generated (Figure 2.3). Those rings that are consistently noted between samples will be the reliable marker rings that can be used to date other cores.

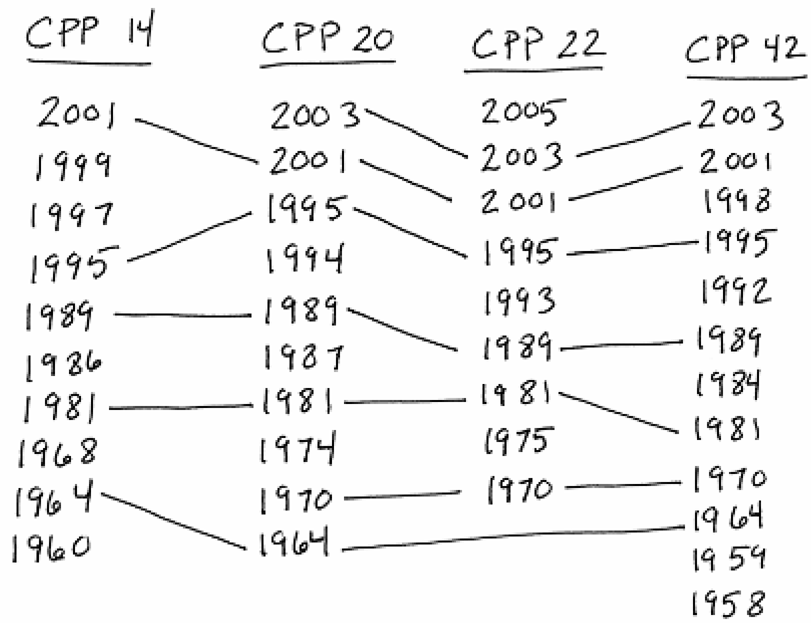


Figure 2. 3 A picture of marker rings recorded using the list method. Five rings (2001, 1995, 1989, 1981, and 1964) all appear as important marker rings that occur between all of the samples that are recording growth at the time. Note that the marker rings from sample CCP22 stop at 1970 because this tree does not extend earlier than this time. One can list the inside ring date in a box at the beginning of the list to indicate when the sample started recording.

The **memorization method** is generally used once the master chronology is known for a set of samples (Douglass 1941). The master chronology may have been produced from skeleton plots, the list method, or a published chronology. The marker rings in the chronology are memorized (sometimes with a written aid) and the tree rings are counted back from the bark to the inside of the core. Each time a narrow ring is encountered it is mentally checked with the list of previously derived marker rings. If the small ring is a marker ring and should be small, then continue dating the sample. If the ring is not a marker ring, it is usually best to count to other marker rings to check the dates across a couple marker rings. The chronology of marker rings would be consistently off from the master in the case of a missing or false ring. If the whole chronology appears to be shifted forward in time by one year, then the wood representing the period in time where that pattern started to diverge from the master should be examined to identify the missing ring.

Principle of Limiting Factors

The Princple of Limiting Factors states that the most limiting factor will control the growth of the organism. This is based on Liebig's Law of the Minimum which is a simplification of the actual physiological response of a tree to environmental forcing, but it can be used as a first approximation of the environmental factor that is most likely to be recorded in a given tree-ring chronology (Figure 2.4). For example, trees growing in the semi-arid environment of southern Arizona are normally limited by the amount of rainfall each year and actually stop growth in the middle of the summer when the soil moisture is depleted and very little rain falls to sustain the trees. But those same trees will start to grow again when the monsoon rains come in late summer and replenish the water. Trees growing at high elevation tend to be limited by

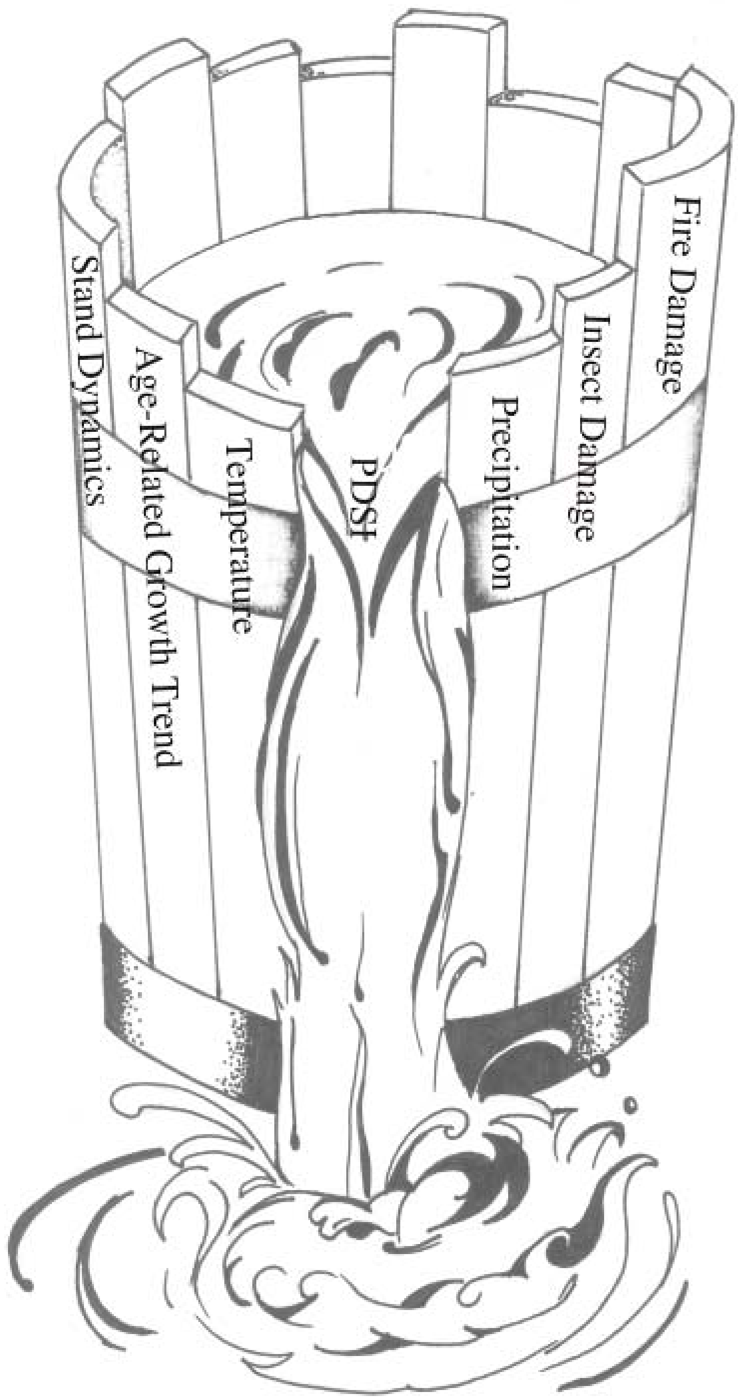


Figure 2. 4 Limiting Factors. Liebig's Law of the Minimum states that whatever factor is most limiting to growth will control the rate of growth for that organism. In this case, the slat labeled PDSI (Palmer Drought Severity Index) would be the most limiting factor for plant growth, therefore availability of moisture to the plant will control the ring width. It should be noted that this limiting factor may change through time.

temperature, whereas defoliated trees are limited by the reduction in their photosynthetic potential. Tree growth can also be limited because of a lack of access to nutrients in the soil. Gardeners often experience the benefits of fertilizing plants with nitrogen to increase growth. A limiting factor will dominate the growth for each year and will be the main variable recorded in ring width creating a series of rings that vary in width from one year to the next (Figure 2.5). It is possible, however, that this limiting factor will change through a plant's life making reconstructions of environmental factors more tenuous. When one variable was limiting but then occurs in abundance, another limiting factor is likely to control growth. Also, trees may be limited by multiple factors at one time, complicating the physiological response of the tree.

Principle of the Aggregate Tree Growth Model

The principle of Aggregate Tree Growth suggests that trees record everything that effects their growth and provides a conceptual model for how to envision these effects, ultimately providing a tool to tease apart the disparate effects of the environment on tree growth. Trees can be severely limited by one factor, but most likely, they are recording multiple factors that limit their growth. The Aggregate Tree Growth Model (Equation I; Cook 1985, Cook 1992) is used to conceptualize this response and to try to understand the different variables that can affect tree growth.

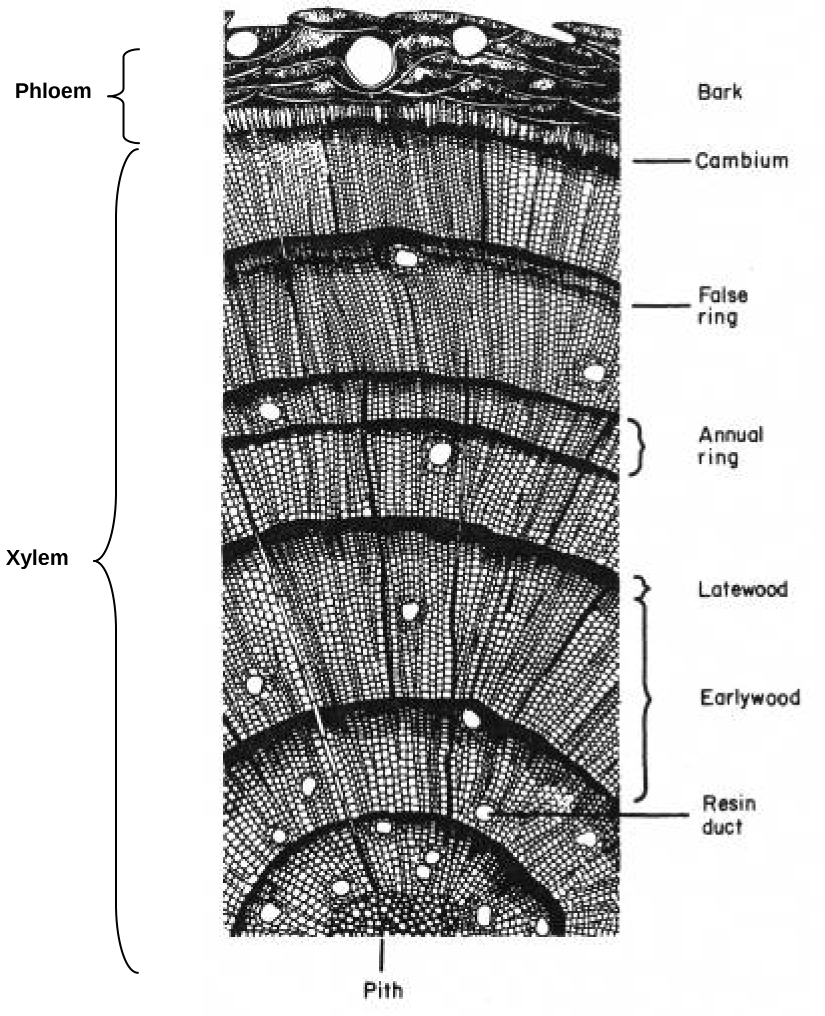


Figure 2. 5 Pine crosssection. Conifer trees in temperate areas produce one ring per year. These rings can be broken into the earlywood portion (open cells with thin cell walls) and the latewood portion (cells with thick cell walls and a smaller lumen). Other features that are present are the pith, resin ducts, cambium, and the bark. The variation in ring width is generally driven by climate and results in the pattern of wide and narrow rings that we use to cross date the wood samples. Sometimes a false ring may be present, as in this sample, where the tree growth slows because of a reduction in the limiting factor for growth of the tree, such as drought. When that environmental factor limiting growth returns (e.g. when it rains), the tree resumes growth and the cells grade back to earlywood structure with thinner cell walls (from Fritts 1976).

$$R_t = f(G_t, C_t, D1_t, D2_t, E_t) \qquad [I]$$

Where:

R_t is ring width at year t.

G_t is the age (or size)-related growth trend.

C_t is climate at year t.

$D1_t$ is the endogenous disturbance within the stand.

$D2_t$ is the exogenous disturbance from outside the stand.

E_t is the error term incorporating all of the signal that is not controlled for by the above variables.

This conceptual model demonstrates that ring width for each year is dependent upon a complex array of variables that contribute to growth. Trees have an intrinsic age-related growth trend, respond to current climate conditions as well as reflect the previous year's climate, and are affected by disturbances from within and outside of the stand. The age-related (also known as size-related) growth trend results from a tree putting the same volume of wood on an ever increasing cylinder. When a radius of the tree is examined, ring-width often decreases in size with age of the tree. In an open-grown pine tree, this trend can be modeled with a negative exponential curve, while the ring-width pattern from trees grown in a dense forest may be dominated by competitive effects from neighboring trees more than this age-related growth trend. Finally, some variability always remains that cannot be explained which is incorporated in the model by the error term. Recent research has begun to explore the information that is contained in the error term by looking at new variables such as biological constraints to growth (see Speer 2001 for an example with mast reconstruction). Calling this the error term is not the most accurate wording as it incorporates all things not explicitly identified in the model not just errors in measurement.

The Aggregate Tree Growth model demonstrates the complexity incorporated in each year's growth, but it can also be used as a tool to explore the different layers of response. The age-related growth trend can be removed from the chronology through basic standardization techniques which will be discussed later. The climate data can be removed by running a regression analysis between ring widths and the climate variables to which the tree responds. The residuals from that analysis (the variability not accounted for by the regression model) can be analyzed to determine what environmental factors are present beneath the age-related growth trend and climate variables that have been removed, assuming the appropriate calibration data set is available to build such a model.

Concept of Autocorrelation

All biological organisms are subject to autocorrelation because of the continuity and unidirectional flow of the progression of time and the development of growth (Figure 2.6). The needles of conifers produced in one year because of a favorable climate are maintained on a tree the following years, adding to the photosynthetic potential of that tree (Figure 2.7; LaMarche 1974, LaMarche and Stockton 1974). Therefore, previous year's climate affects current year's growth. This is the most obvious example of autocorrelation, but any biological organism produces cells, proteins, and sugars which can be used in subsequent years, creating autocorrelation in the response of that organism to environmental variables. Autocorrelation can

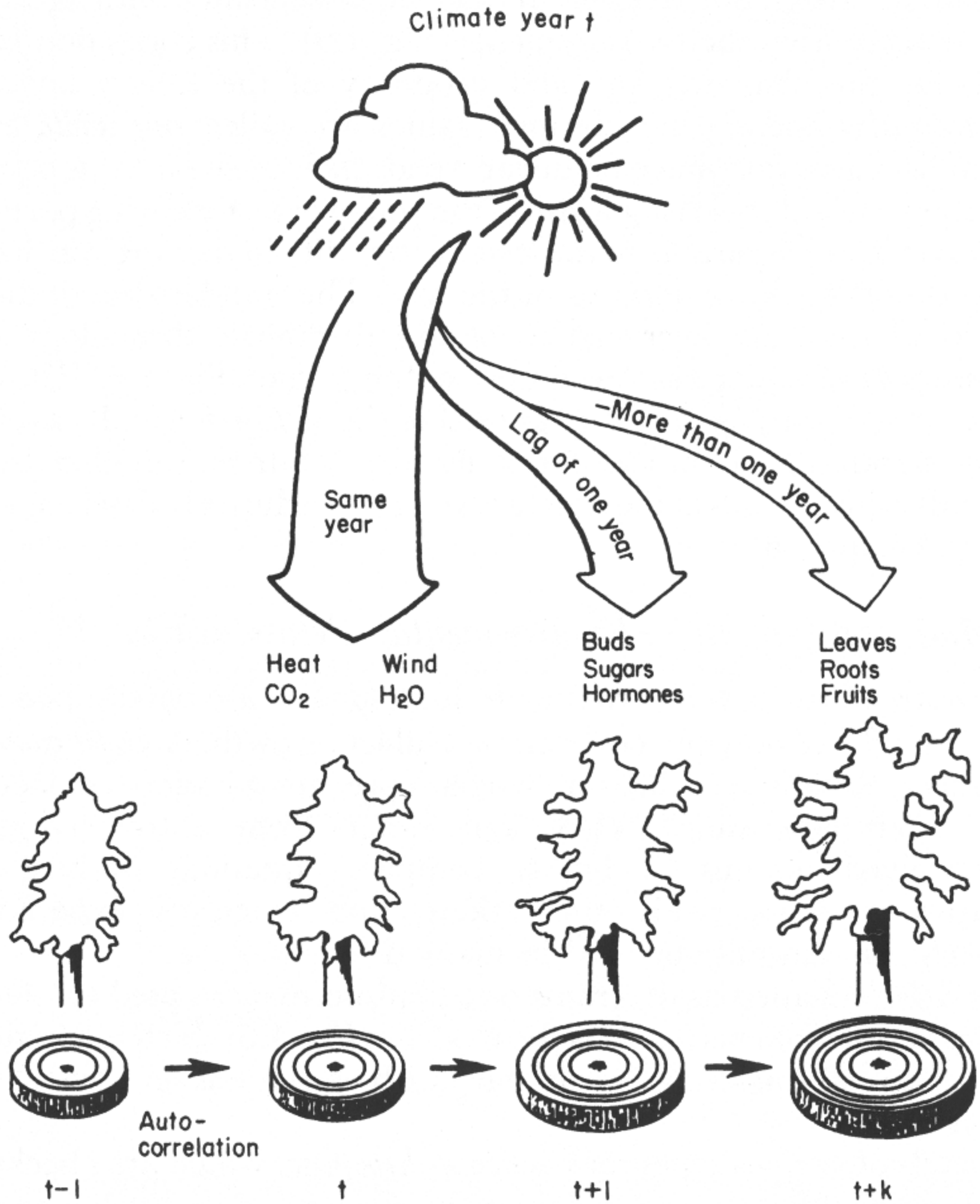


Figure 2.6 Autocorrelation. Tree growth often times includes autocorrelation which is the statistical characteristic that the current year's growth is affected by the previous year's growth. Autocorrelation can be driven by the biological activities of the tree in that the current year's climate will affect the heat, rainfall, and CO2 levels for this year's growth but it also effects the following years growth through development of new buds, sugars, and hormones. Finally the climate from that same year will affect growth even further in the future by the development of leaves, roots, and fruits.

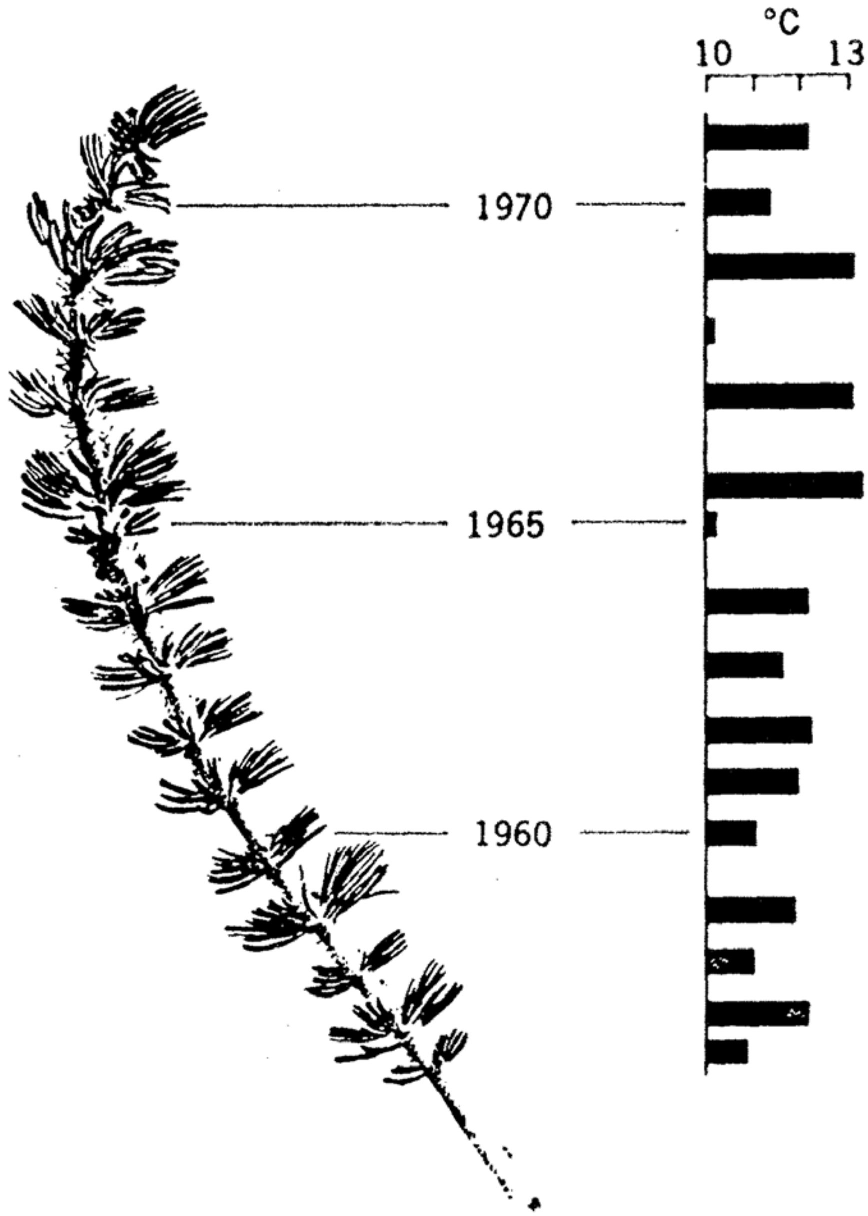


Figure 2. 7 Needle retention in bristlecone pine at upper treeline related to summer temperature (from LaMarche and Stockton 1974). Bristlecone pine trees retain their needles for many years, in this case 16 years, resulting in good growing conditions in the past affecting current year's photosynthetic potential.

become a problem because most statistical analysis (such as regression analysis) assumes that the data is not autocorrelated because it can artificially increase correlation statistics. Fortunately, this component can be described and removed by determining the variance of the current year's growth that is explained by the previous year's growth. This one-year lag is described by a first order autoregressive model. The correlation to growth two years prior is described by a second order autoregressive model, and this continues back in time until no significant autoregressive signal can be detected.

Concept of the Ecological Amplitude

Ecological amplitude is the pattern of vegetation on the landscape which is controlled by the range of climate variables to which a species responds (Lomolino *et al.* 2006). The microclimate of a site is also modified by topography, slope, and aspect which affects the local distribution of species. Based on this idea, a tree species should be less stressed at the center of its range and more stressed near the margins of the range where the climate might be harsher for that species. Therefore, for climate related research it is often better to sample a species near the edge of its range to find trees that are more likely to record the climate variable of interest. These ecotones, or edge regions, are also the areas where change is more likely to occur in the face of a changing climate, making ecotones important sample sites. For example, black gum (*Nyssa sylvatica*) is at the northern limit of its range distribution in New Hampshire (Figure 2.8) so samples taken from this species at this location are likely to be more sensitive to temperature if that is the limiting climatic factor at the northern edge of its ecological amplitude. Samples taken from just north of the Everglades in Florida, at the southern end of black gum's ecological amplitude, are not likely

Figure 2. 8 Distribution of black gum. The shaded area represents the range of black gum (from Little 1971). (http://esp.cr.usgs.gov/data/atlas/little/nysssylv.pdf).

to be limited by lower temperatures but may be limited by competition with other species or by an excess of precipitation and soil moisture.

Principle of Site Selection

Given that trees will record all of the variables that affect their growth, dendrochronologists use the concept of site selection to maximize the signal recorded in the trees they sample. Sites should be located where the trees are most likely to be stressed by the variable that the researcher is interested in reconstructing (Figure 2.9). For example, if a precipitation reconstruction is needed then trees located in an arid environment should be sampled. Trees that are growing on the edge of their ecological amplitude, such as the extreme lower elevation of species in a semi-arid environment or the southern boundary of the species in North America are more likely to record drought events. A temperature signal is likely to be recorded at high elevation or high latitude where low temperatures during the growing season can limit growth. Similarly, historical documentation of insect outbreaks or fire history is used to guide initial sampling of trees to demonstrate the tree-ring response to these phenomena.

Trees that are growing at the center of their ecological amplitude with favorable climate year round are likely to produce complacent growth in which each ring is a similar width. If a tree is complacent, it does not record much environmental variability that could be used for crossdating. The tree is likely to be a poor environmental recorder; however it may be limited by its biological ability to grow, which could be genetic or could be driven by other physiological factors that might be of interest to a dendrochronologist, such as masting. The opposite of complacent growth is sensitive growth, where the tree demonstrates considerable variability in

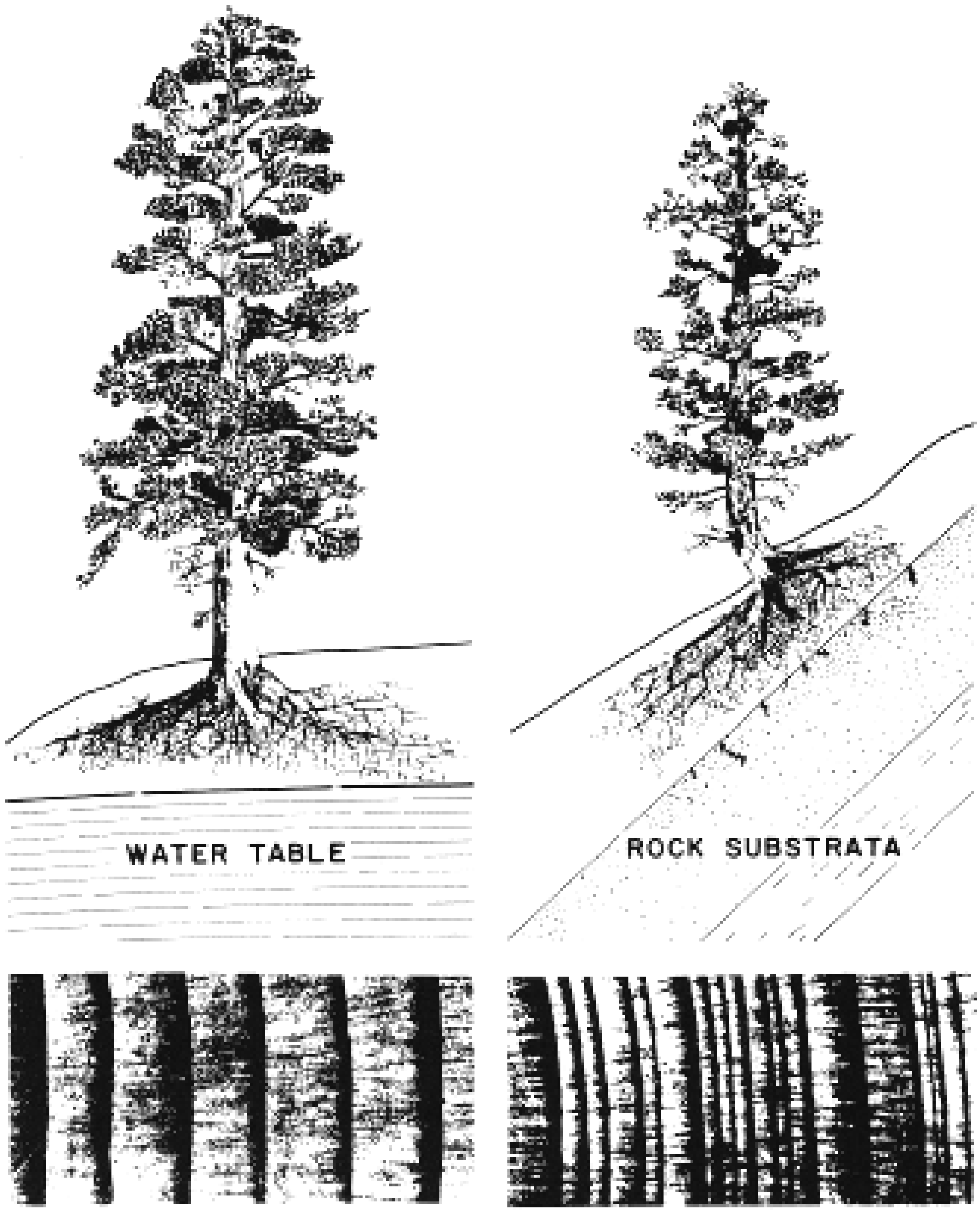


Figure 2. 9 Site selection. Specific sites are chosen from which trees are likely to record the variable that we are interested in reconstructing. A tree with the same size rings is considered to have a complacent ring-width series (tree on the left) and a tree with a lot of variability in growth is considered to have a sensitive tree-ring series (tree on the right) (from Stokes and Smiley 1968).

year to year growth and is thus recording some environmental variable (Figure 2.9). All of these factors must be taken into consideration when choosing a site to sample for a given research project.

Principle of Replication

Replication is the use of multiple samples to develop an accurate stand-level chronology or the use of many samples back in time to provide good sample depth throughout the chronology. This principle was recognized by many of the early researchers in the field such as Twining (1833) and Babbage (1838). By taking multiple samples on a site and matching the ring width pattern between these trees, valid crossdating for the stand can be demonstrated. Averaging the growth between two cores from one tree and between 20 trees on a site can remove individual tree variability and yield a stand-level signal. Averaging across many samples enables dendrochronologists to change the spatial scale over which a study is conducted; essentially stepping up from the individual tree to the stand and even regional level (Figure 2.10). Replication provides the basis for crossdating and contributes to the robustness of environmental reconstructions. The appropriate sample depth can be determined by using the expressed population signal (EPS) statistic described in chapter 6.

Concept of Standardization

Standardization removes age-related growth trends and other long-term variability that can be considered noise by fitting curves to trends in ring series (Figure 2.11). Note that the long-term trend could be the signal that climatologists are interested in when they examine long-term

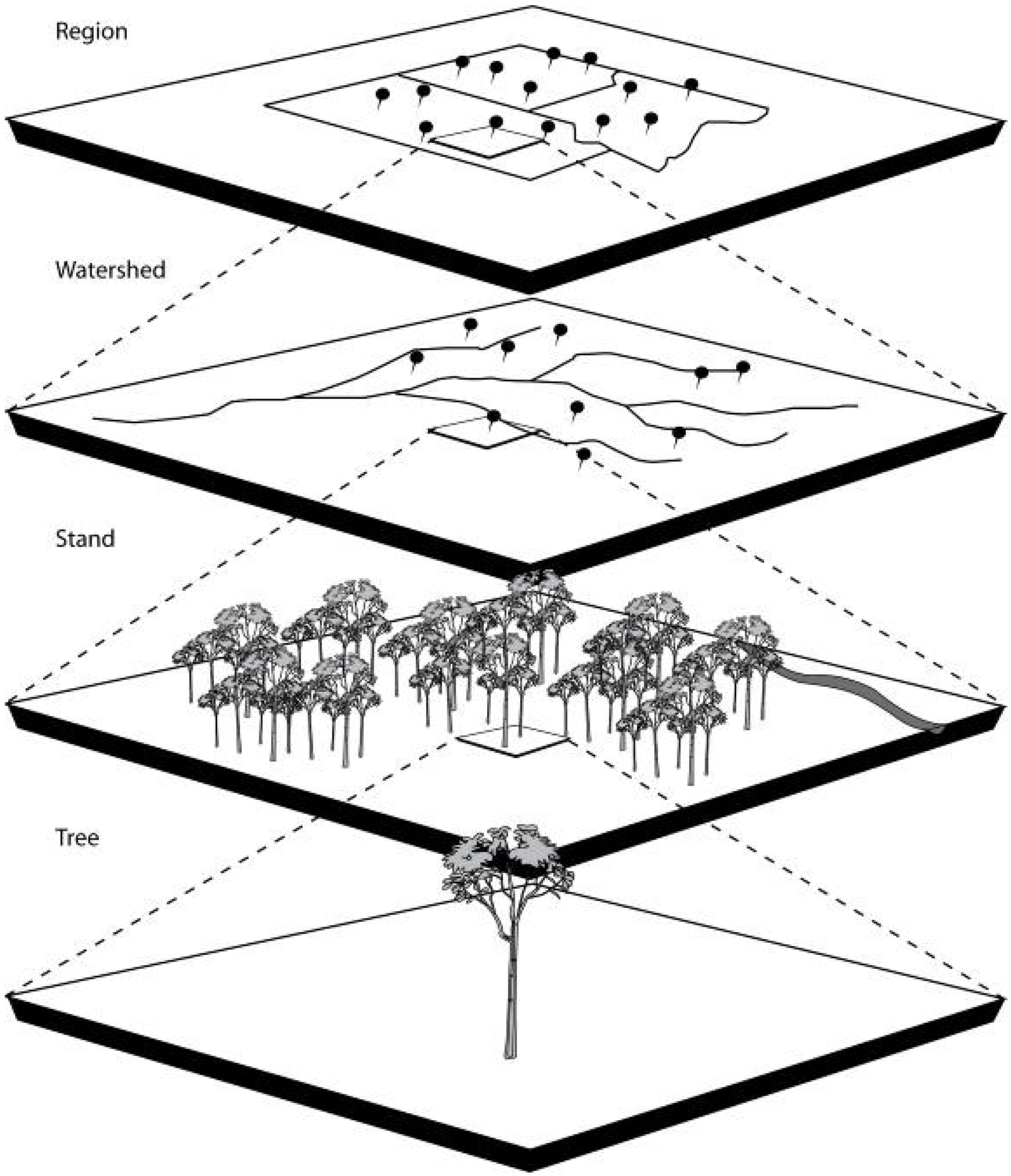


Figure 2. 10 Sampling scale. By taking replicate samples, we can average out individual tree variability and change our analysis level to higher spatial scales (such as the stand, watershed, or regional levels) (modified by Bharath Ganesh-Babu from Swetnam and Baisan 1996).

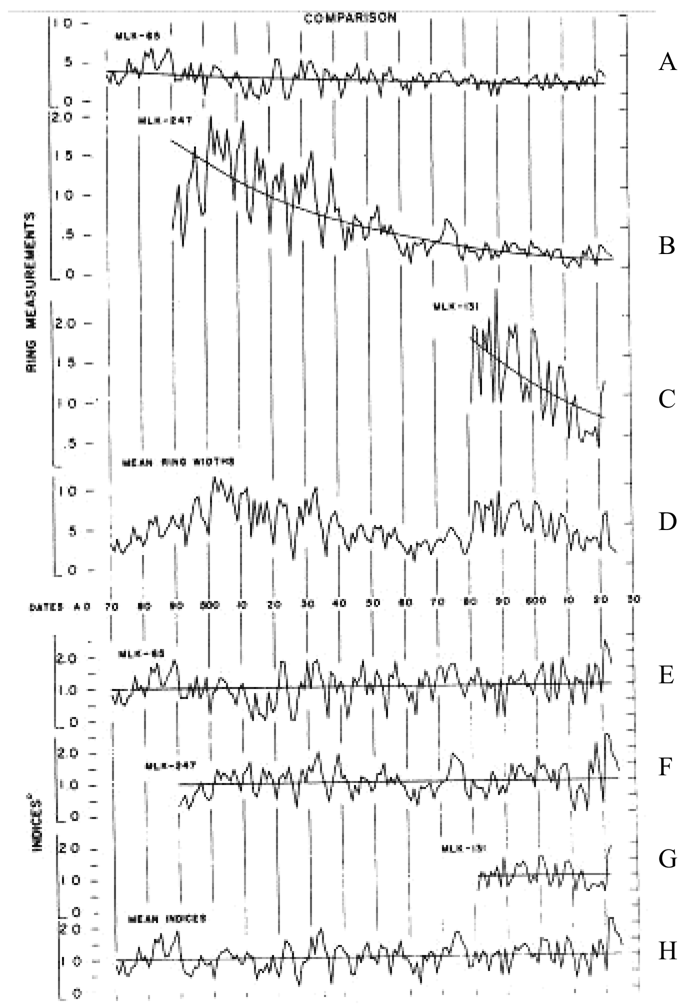


Figure 2. 11 Standardization. The juvenile growth effect results in a higher level of growth when a tree is young. If cores from three trees (A through C) are averaged together without regard for this age-related growth trend, the resultant chronology (D) will mainly record when these younger trees are incorporated into the chronology. If, however, the series are standardized with a negative exponential curve and index chronologies are generated by dividing the measured ring width by the model curve fit value, then these index chronologies (E through G) can be averaged together to generate a master chronology that maintains its interannual variability and enhances the stand level signal (H; modified from Fritts 1976).

changes in climate, but it is noise to an ecologist that is studying shorter-term variability in forest dynamics. This process also removes differences in growth rates between samples and produces a series mean equal to 1.0. The most conservative technique of standardization is the negative exponential curve that is common in the growth of many trees and is geometrically mandated by adding the same volume of wood on the surface of an ever increasing cylinder. The negative exponential curve is deterministic meaning that it follows a model of tree growth. Other standardization techniques are empirical, meaning they are chosen through experimentation to find the best fit to a series of data. A cubic smoothing spline is an example of an empirical model that uses a flexible curve that is allowed to adjust at a regular interval (Cook 1985; Figure 2.12). When using these forms of standardization, the researcher should be cognizant of the signal that is being removed from the record. A 40-year cubic smoothing spline, for example, removes 50 percent of the variance at 40 years, leaves 99 percent of the variance at 12.67 years, and removes 99 percent of the variance at 126.17 years so that very little century length signal is left in the resultant chronology (see table 2.1 for data on other splines). Splines are a more organic fit to the data than straight line or exponential fits, but they do remove different amounts of variance at different temporal scales.

Standardization is a powerful technique that can be used to minimize noise in a chronology and increase the signal of interest, but it is also a complex issue and probably one of the more controversial steps in dendrochronological analysis. New techniques are being developed for the standardization of tree-ring series and will be further discussed in chapter 6.

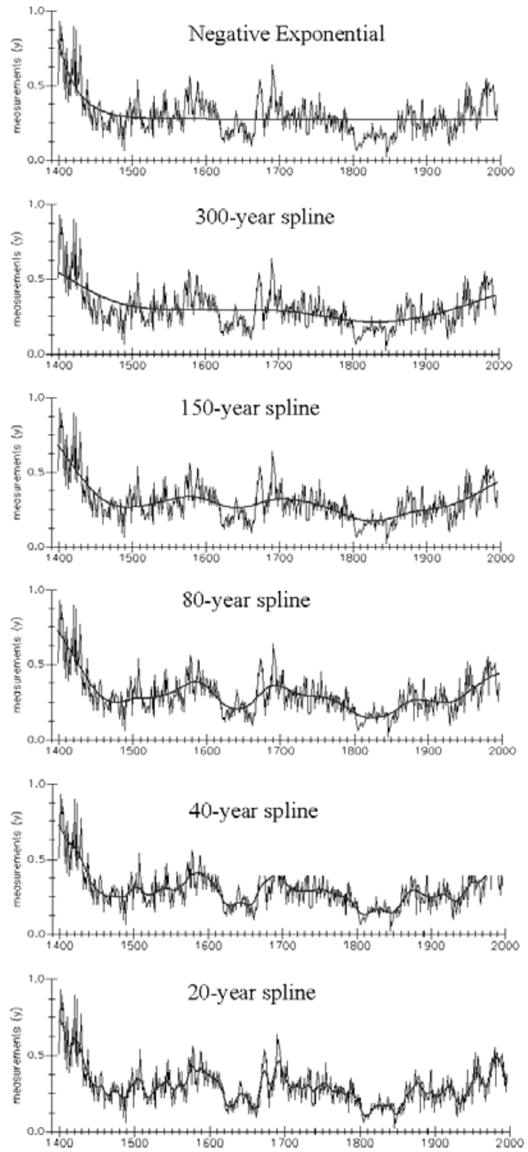


Figure 2. 12 Standardization with a negative exponential curve and cubic smoothing splines. Each curve represents the same set of ring width measurements back to A.D. 1500. A negative exponential curve is fit to the ring widths followed by a series of shorter cubic smoothing splines (300, 150, 80, 40, and 20 years) and the resultant curve fit is shown as the smooth black line. You can see that shorter and shorter wavelengths are removed from the master chronology.

Table 2. 1 The frequency of the variance that remains using different cubic smoothing splines.

Spline Length	Leaves 99 percent of Variance at	Leaves 50 percent of Variances at	Leaves 1 percent of the Variance at
20	6.24 years	20 years	63.09 years
40	12.67 years	40 years	125.17 years
60	19.01 years	60 years	189.26 years
80	25.35 years	80 years	252.35 years
100	31.69 years	100 years	315.43 years
150	47.53 years	150 years	473.15 years
200	63.37 years	200 years	630.87 years
300	95.06 years	300 years	946.20 years
400	126.75 years	400 years	1261.73 years
500	158.44 years	500 years	1577.17 years

Summary

The principles and concepts described in this chapter help dendrochronologists to work through the process of developing valid dendrochronological reconstructions. Some studies are starting to show that our perception of concepts such as ecological amplitude and what we expect a site should be recording are not necessarily as we suppose (Tardif *et al.* 2006, Speer unpublished data). The patterns that we observe on the landscape are more complex than some of the basic models presented in this chapter, but these principles help to guide our sampling and chronology development and are a good first approximation of the factors that drive our sampling methods. The next chapter explores the history of dendrochronology and discusses the people who developed many of these principles.

Chapter 3: History of Dendrochronology

Introduction and the Early Years

Dendrochronology is a young discipline in the realm of the sciences with many new frontiers left to be investigated. The first Laboratory of Tree Ring Research was founded at the University of Arizona in 1937 by A.E. Douglass. The subfield of dendroecology became a major area of research only in the 1970s and today new research is being conducted using stable isotopes from tree rings to examine trees' physiological responses to climate change. Despite these recent beginnings, the idea that trees produce annual rings had been suggested since the time of Theophrastus in 322 B.C. (Studhalter 1956).

In this chapter, I will describe the development of the field and many of the basic concepts that we still use today (Table 3.1). In the 1400s and 1500s, some famous naturalists recognized the annual character of tree rings and started to look to the environment for causes of variation in ring growth. In the late 1400s, **Leonardo da Vinci** (Figure 3.1) described annual ring formation and suggested that the growth of tree rings is related to weather (Stallings 1937, Sarton 1954, Corona 1986). "…the rings in the branches of trees that have been cut off show the number of its years, and which were damper or drier according to the greater or lesser thickness of these rings." (Kemp and Walker 2001; translation of Leonardo da Vinci's *Treatise on Painting*).

From 1580 to 1581, **Michel de Montaigne** traveled through Germany, Switzerland, and Italy and kept a diary of his journey. While in Italy, he reported on a conversation that he had with an unnamed carpenter who noted the annual nature of tree rings.

Table 3. 1 The early dendrochronologists sorted by the dates that they used tree rings.

Scientist	Location	Year	Contribution	Reference
Theophrastus	Greece	322 B.C.	Noted that trees put on new growth every year	Schweingruber 1996
Leonardo da Vinci	Italy	1452-1519 1482-1498	Noted the relationship between climate and tree growth Wrote the Trattato della Pittura mentioning tree rings	Sarton 1954
Michel de Montaigne	Italy	1581	The idea of counting tree rings to attain tree age was related to Montaigne by an unnamed carpenter	Sarton 1954
Duhamel and George Louis Leclerc de Buffon	France	1737	Counted rings to determine the date of a conspicuous frost ring	Webb 1986 Dean 1978
Carl Linnaeus	Sweden	1707-1778	Counted rings to determine the age of trees	Webb 1986 Online Article
A.C. Twinning	Connecticut	1827	Used crossdating and noted the common signal across a site.	Dean 1978
Theodor Hartig	Germany	1837	Set up the ecological basis for dendrochronology in Germany.	Schweingruber 1996
Charles Babbage	England	1838	Noted the concepts of competition, complacency, replication, reaction wood in trees, the concept of parent trees, climate reconstruction, and specific tree-ring patterns from storms and floods.	Babbage 1838 Heizer 1954 Zeuner 1958
Jacob Kuechler	Texas	1859	Used modern principles of site selection by choosing trees on low ridges with good drainage and he used tables to note ring characteristics demonstrating an early example of crossdating	Dean 1978
Robert Hartig	Germany	1867	Used tree rings to date events of hail, frost, insect damage, and examined trees that were killed by pollution	Schweingruber 1996
A.L. Child	Nebraska	1871	Compared tree growth in red maple to meteorological data for spring and summer	Webb 1986
A. Stoeckhardt	Western Europe	1871	Examined forest damage from air pollution.	Eckstein and Pilcher 1990
Jacobus C. Kapteyn	Denmark	1880-1881	Examined the relationship between tree growth in oaks and rainfall	Webb 1986
F. Shvedov	Ukraine	1892	Examined black locust trees for a dendroclimatic analysis that he used for prediction.	Kairiukstis and Shiyatov 1990
B.E. Fernow	New England	1897	Wrote a paper on determining the age of blazing on trees by counting the tree rings	Webb 1986
A.E. Douglass	Arizona	1904	Developed crossdating as a tool and was persistent in developing chronologies and training future dendrochronologists	Webb 1983 Nash 1999
Bruno Huber	Germany	1940	Spent considerable amount of time dating wood samples and worked on new statistical techniques to quantify the strength of dating of different specimens	Schweingruber 1996

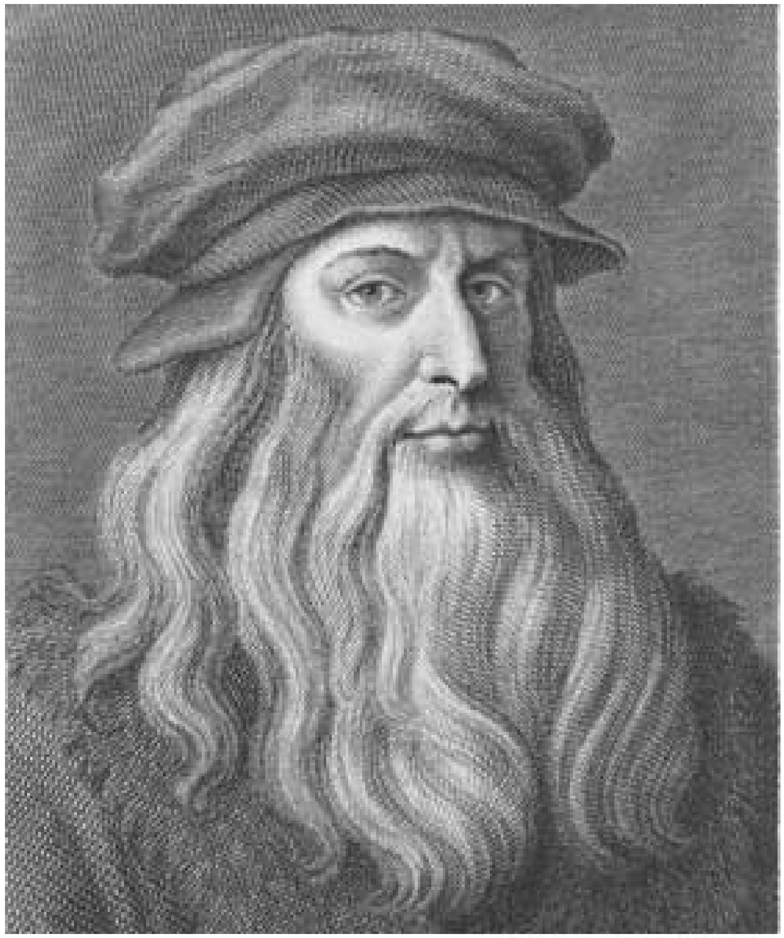


Figure 3. 1 Leonardo da Vinci (1452-1519) mentioned that trees put on annual rings and respond to local climatic conditions in the Trattato della Pittura (Treatise on Painting), which he worked on from 1482 to 1498 in Milan at the court of Ludovico Sforza (from the Library of Congress).

> The artist, a clever man, famous for his ability to make mathematical instruments, taught me that every tree has inside as many circles and turns (*cerchi e giri*) as it has years. He caused me to see it in many kinds of wood which he had in his shop, for he is a carpenter. The part of the wood turned to the North is the straightest, and the circles there are closer together than in the other parts. Therefore when a piece of timber is brought to him he is able, he claims, to tell the age of the tree and its situation (the orientation of the section), (translation of the original Italian text by Sarton 1954).

The 1700s and the 1709 Frost Ring

Many other early scientists had recognized tree-ring growth and used tests to demonstrate that trees produce rings annually. French naturalists **Henri Louis Duhamel du Monceau** and **George Louis Leclerc de Buffon** discovered in 1737 that a conspicuous frost-damaged ring occurred 29 years in from the bark of several newly felled trees in France recording the 1709 marker ring. The winter of 1709 was significant in dendrochronology because of its frequent use as a marker ring by early dendrochronologists across Europe. **Carl Linneaus** noted the 1709 frost ring when he examined wood samples in Sweden (Linnaeus 1745, 1751). Two other scientists also noted this frost ring in other countries demonstrating how important this type of marker ring is in dating tree rings. Duhamel went on to conduct early experiments in pinning trees (the process of creating a small wound in the tree that can later be sampled to examine growth since the wounding) and used aluminum foil as an early type of dendrometer band around the tree to examine the annual growth of trees in 1751 and 1758 (Studhalter 1956).

In 1785, **Friedrich August Ludwig von Burgsdorf** examined tree growth over a blaze marking a trail that was cut into a tree in 1767. He found 18 rings had formed since the blaze was cut, thus demonstrating annual growth in this oak (*Quercus* sp.) tree in Germany. Burgsdorf also noted the 1709 frost ring in beech (*Fagus* sp.) and other trees in Germany (Studhalter 1956). **Alphonse de Candolle**, a Swiss botanist, discovered the 1709 frost ring when examining juniper (*Juniperus* sp.) tree rings in France in 1839-1840. Candolle went further by suggesting a number of early methods that could be used to crossdate rings, although much of his work dealt with average ring widths over a period of time rather than maintaining the annual resolution of the rings (Studhalter 1956).

The 1800s: Tree Rings Become Common Knowledge

De Witt Clinton in 1811 (while he was mayor of New York City and the year before an unsuccessful run at the U.S. presidency) counted tree rings from trees growing on the earthen mounds near Canandaigua in New York State. He estimated that the trees had about 1,000 rings, and concluded that the mounds were created by prehistoric Native Americans and not by early Europeans. This was the first recorded archaeological use of tree rings although Clinton did not exactly date the wood to obtain more reliable bounding dates on the structures and his ring count of 1,000 rings seems greatly exaggerated considering the tree species in this area he was able to test if the structure was made prior to or after European colonization (Zeuner 1958).

Alexander Catlin Twining (Figure 3.2) used *replicated* samples in 1827 from many trees harvested for the building of a wharf in New Haven, Connecticut. This early account is unique because it conducts dating across multiple samples and relates the growth to climate.

Figure 3. 2 Alexander Catlin Twining (1801-1884) noted the application of using tree rings to examine climate in 1827. Photo from http://www.rootsweb.com/~ctnhvbio/Twining_Alexander.html.

> In the year 1827, a large lot of hemlock timber was cut from the north eastern slope of East Rock, near New Haven, for the purpose of forming a foundation for the wharf which bounds the basin of the Farmington Canal on the East. While inspecting and measuring that timber, at the time of its delivery, I took particular notice of the successive layers, each of which constitutes a year's growth of the tree; and which, in that kind of wood, are very distinct. These layers were of various breadth, indicating a growth five or six times as full in some years as in others, preceding or following. Thus every tree had preserved a record of the seasons, for the whole period of its growth, whether thirty years or two hundred, -and what is worthy of observation, *every tree told the same story.* Thus, if you began at the outer layer of the two trees, one young and the other old, and counted back twenty years, if the young tree indicated, by a full layer, a growing season for that kind of timber, the other tree indicated the same (Twining 1833: 391-392; The italics are in the original text).

Twinning goes on to foreshadow the use of tree rings to reconstruct climate beyond modern records. He also suggests that different genera will have a different climate response.

> It would be interesting … to compare the sections of one kind of tree with that of another kind from the same locality, - or to compare sections of the same kind of tree from different parts of the county. Such a comparison would elicit a mass of facts, both with respect to the progress of the seasons, and their relation to the growth of timber, and might prove, hereafter, the means of carrying back our knowledge of the seasons, through a period coeval with the age of the oldest forest trees, and in regions of the country where

> scientific observation has never yet penetrated, nor a civilized population dwelt (Twining 1833: 393).

Charles Babbage (Figure 3.3) in England wrote at length about the application of tree rings in determining the age of geological strata in his 1838 paper "On the Age of Strata, as Inferred from Rings of Trees Embedded in Them" (Heizer 1954). He discusses, with examples, the concept of crossdating (the process of matching ring widths to obtain exact dates of annual growth) and goes further to mention that distinctly small rings are due to climatic variability. Babbage (1838) also discusses competition, complacency, replication, reaction wood in trees, the concept of parent trees, climate reconstruction, and specific tree-ring patterns from storms and floods. He also formulates a research agenda using stem analysis to understand the growth throughout an entire tree and suggests that tree-ring patterns found in the roots should be the same as those found in the canopy.

In the following quote, Babbage talks about the climate response of trees and their ability to record climate through time. "These preeminent effects are obvious to our senses; but every shower that falls, every change of temperature that occurs, and every wind that blows, leaves on the vegetable world the traces of its passage; slight, indeed, and imperceptible, perhaps, to us, but not the less permanently recorded in the depths of those woody fabrics" (Babbage 1838: 258).

Babbage described the principle of crossdating with an example of the trees' response to climate.

> If we were to select a number of trees of about the same size, we should probably find many of them to have been contemporaries. This fact would be rendered probable if we

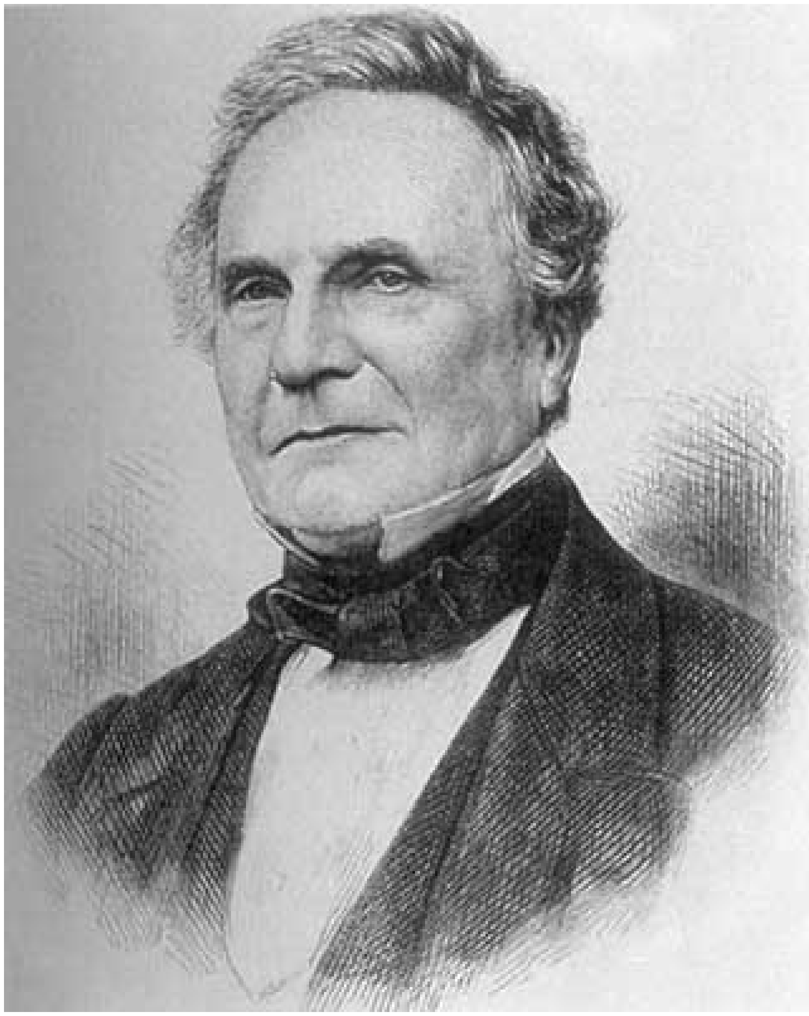


Figure 3. 3 Charles Babbage (1791-1871) wrote an article in 1838 about the potential for dendrochronology applied to buried wood in the Ninth Bridgewater Treatise, although his tree ring comments were restricted to “Note M: On the Age of Strata, as Inferred from the Rings of Trees Embedded in Them” (image from http://encyclopedia.laborlawtalk.com/Charles_Babbage .)

> observed, as we doubtless should do, on examining the annual rings, that some of them conspicuous for their size occurred at the same distances of years in several trees.… The nature of the season, whether hot or cold, wet or dry, might be conjectured with some degree of probability, from the class of tree under consideration (Babbage 1838: 258-259).

The concept of the effect of local ecology on tree-ring response were also noted by Babbage. "Some [trees] might have been protected by adjacent large trees, sufficiently near to shelter them from the ruder gales, but not close enough to obstruct the light and air by which they were nourished. Such a tree might have a series of large and rather uniform rings; during the period of its protections by its neighbour; and these might be followed by the destruction of its protector" (Babbage 1838: 260).

One of the more important principles in dendrochronology is the concept of replication which Babbage also realized could be used to examine broad scale climate patterns. "But the effect of all these local and peculiar circumstances would disappear, if a sufficient number of sections could be procured from fossil trees, spread over considerable extent of country" (Babbage 1838: 260-261).

From 1837 to 1877, **Theodor Hartig** taught botany at the University of Braunschweig in Germany where he laid the ecological groundwork for later dendrochronological research in Germany done by Robert Hartig (his son) and Bruno Huber (Schweingruber 1988, Schweingruber 1996). Theodor Hartig started a tradition of ecological examination in Germany that included the use of tree rings. Much of the present day dendroecological research in Europe has grown from this foundation.

Jacob Kuechler, a German immigrant to the U.S. with an interest in weather, used crossdating to examine three post oak (*Quercus stellata)* trees from Texas in 1859. Kuechler's (1859) own publication is in German, but an editorial by Cleveland Abbe (1893) relates an investigation made by Kuechler and reported on by Colonel William W. Haupt. Kuechler used modern principles such as site selection by choosing trees on low ridges with good drainage as well as tables to note ring characteristics, demonstrating an early example of crossdating (Stallings 1937, Glock 1941).

Many of the early researchers mentioned above noted the climatic application of tree rings. Other researchers in the late 1800s noted additional applications that could be studied using tree rings. In 1866, the German botanist **Julius Ratzeburg** was probably the first to document an insect outbreak due to the effect of defoliation by a caterpillar on tree rings (Ratzeburg 1866). He was able to assign absolute dates to the outbreak events by examining tree rings (Studhalter 1956). In 1882, **Franklin Hough** also discussed the possibility of dating insect outbreaks from damage the insects caused to trees (Studhalter 1956). Some of the first work in examining forest damage from air pollution was conducted by **Adolph Stoeckhardt** in Western Europe (Stoeckhardt 1871). This early investigation provided the lead for current researchers to examine and quantify the effects of air pollution (Eckstein and Pilcher 1990). **Elias Lewis** (1873) would frequently count the number of rings on fallen trees or stumps to determine the local growth rate of a species and then use that number to estimate the age of living trees based on their diameter and this age/diameter relationship. This was an early use of tree rings to estimate age structure in a forest stand although today we realize that diameter is not always a good predictor of age (Studhalter 1956).

John Muir, the famous American naturalist, noted the annual nature of tree rings and that they could be used for geomorphic reconstructions, specifically determining the age of glacier-carved structures in the Sierra Nevada Mountains of California. He also expressed interest in having the time to study such phenomena with tree rings in his writing *My First Summer in the Sierra* which were from his journals written during his first visit to the Sierra Nevada in 1869.

> Have been sketching a silver fir that stands on a granite ridge a few hundred yards to the eastward of camp – a fine tree with a particular snow-storm story to tell. It is about one hundred feet high, growing on bare rock, thrusting its roots into a weathered joint less than an inch wide, and bulging out to form a base to bear its weight. The storm came from the north while it was young and broke it down nearly to the ground, as is shown by the old, dead, weather-beaten top leaning out from the living trunk built up from a new shoot below the break. The annual rings of the trunk that have overgrown the dead sapling tell the year of the storm. Wonderful that a side branch forming a portion of one of the level collars that encircle the trunk of this species (*Abies magnifica*) should bend upward, grow erect, and take the place of the lost axis to form a new tree. (Muir 1911 compiled in Cronon 1997: 235-236).
>
> Young pines, mostly the two-leaved and white-barked, are already springing up in these cleared gaps [avalanche tracks in the Sierra Nevada of California]. It would be interesting to ascertain the age of these saplings, for thus we should gain a fair

> approximation to the year that the great avalanches occurred. Perhaps most or all of them occurred the same winter. How glad I should be if free to pursue such studies! (Muir 1911 compiled in Cronon 1997: 280).

The recognition of the formation of annual rings in trees, their record of the climate and insect outbreaks, and their dependence upon microsite differences was common knowledge to foresters in the 1880s as evidenced by repeated discussion of annual rings in a forestry textbook called *The Elements of Forestry* by **Franklin Hough** (1882).

> In cross sections made years afterwards, the record of the seasons for a long period may be determined, at least in effect, by the width of the rings of annual growth. We sometimes find, at recurring intervals, a narrow ring, perhaps in every third year, that may have been caused by the loss of leaves from worms that appear at that interval, and that have thus left their record when every other proof of their presence has perished. We have seen sections of trees in the museums of Schools of Forestry, in which these proofs were recorded through a century or more of time, and the years could be definitely fixed by counting inward from the year when the tree was felled (Hough 1882: 70).

Hough (1882) goes on to discuss the calculation of basal area increment for the purpose of quantifying the amount of growth in each year. He also discusses the microsite variations that affect tree-ring growth. “The rate of growth in wood differs very greatly, according to the soil, elevation, aspect, climate, humidity, temperature, prevailing winds, and other causes” (Hough 1882; 75). The growth rings of multiple species are also shown in many figures throughout the text. From this textbook, it must be concluded that knowledge of the annual growth rings of trees and their response to the environment was common knowledge at this time. Hough (1882), however, describes counting rings for this record (a practice still common in forestry today) rather than the process of crossdating.

In 1881 **Arthur Freiherr von Seckendorff-Gudent** collected tree samples from 6,410 Austrian black pine (*Pinus nigra*) throughout Austria, Hungary, and Slovenia and used many of the basic principles in modern dendrochronology including crossdating and replication (Wimmer 2001). He took the analysis further by noting the climate response of the trees to local climate data (Seckendorff 1881).

> When counting the tree rings on the disks, particular sequences of tree rings were repeatedly found in most of the trees. As an example, on most disks we found the 1871 ring showing a wide latewood, and the narrow 1802 ring. The tree rings of 1862 and 1863 were very close and significant due to their obvious difference in the strength of the latewood.
>
> These significant tree-ring formations, which I named "characteristic tree-rings", were an excellent tool to determine the age even on trees grown on very poor sites. From the many discovered "characteristic tree-rings" we always found at least a few on each disk. …This method of age determination also helped to avoid counting false-rings.
>
> A comparison of tree-ring characteristics with temperature and precipitation for the dated years shows the relationship between tree growth and climate. Although, local site conditions are the major factor for tree-ring formations, the effect of particularly warm and cold years with low and high rainfall cannot be neglected. This influence (climate) may be smaller or bigger in a growing region, whether the climate is more of local or more of regional character.

> Very hot and wet summers, such as the hot summer in 1811 (a good vine year) and the hot and also wet year of 1846 are characterized with extreme tree-ring formations. While the 1811 ring is distinct because of its weak (small) latewood, the year 1846 is significant because of its wide latewood.
> … For now it is sufficient to state that climate has an effect on the formation of tree-rings and this effect can be softened by local site conditions but not revoked completely (Seckendorff 1881 as translated in Wimmer 2001).

Robert Hartig (son of Theodor Hartig) used tree rings to date events of hail, frost, and insect damage, publishing 34 papers from 1869 to 1901 on the anatomy and ecology of tree rings while he was a professor at the University of Munich (Studhalter 1956, Schweingruber 1988). Robert Hartig conducted a great deal of work in wood anatomy and was one of the first to look at the physiological basis for ring formation. Hartig (1888) categorized the rings of conifers into three sections of the spring zone, summer zone, and autumn zone. These divisions were later made into earlywood and latewood that we still use today (Studhalter 1956).
He also examined trees that were killed by pollution and noted their long-term growth decline before their death that made ring identification on the outside of the sections impossible. He was able to find the rings represented on the stem near the canopy of the tree and used these samples to crossdate the samples at the base and determine which rings were missing. Further work on hail, frost, and insect outbreaks was conducted by K. Rubner (1910) and I. W. Bailey (1925a, 1925b).

F. Shvedov worked on an early precipitation analysis using two black locust (*Robinia pseudoacacia*) trees and found a three to nine year cyclicity in the data so that he could correctly predict upcoming droughts in 1882 and 1891 (Shvedov 1892). His early work in dendroclimatology in Odessa in the Ukraine sets him apart as one of the early founders of dendroclimatology (Kairiukstis and Shiyatov 1990).

Jacobus C. Kapteyn, a Dutch astronomer, used crossdating on over 50 oaks collected from Holland and Germany to examine climatic patterns that might be recorded in those trees. His work was completed in 1880, but was not published until 1914 (Kapteyn 1914). He concluded that spring and summer rains were the most important climatic variables that affect tree growth in this area of Europe. Kapteyn was ahead of his time, employing modern practices such as crossdating, replication, and standardization. He used a 15-year running average to smooth his data and noted that he was removing any cycles greater than 15 years that might have been included in the wood. Kapteyn tested for missing rings, using crossdating and also identified precipitation cycles of about 12.5 years in his final chronologies (Schulman 1937).

The Early 1900s, Douglass, and Huber

A.E. Douglass (Figure 3.4) was the first researcher to use crossdating "...persistently and extensively…" (Studhalter 1956) from 1901 through the 1960s and has been named the "…undisputed…father of dendrochronology" (Schweingruber 1988). He developed the repeatable process of crossdating that is the cornerstone of dendrochronology today. Douglass was an astronomer by training and assisted Percival Lowell in finding sites with clear skies for observatories in the southwestern U.S. (Webb 1983). Douglass later had a disagreement with

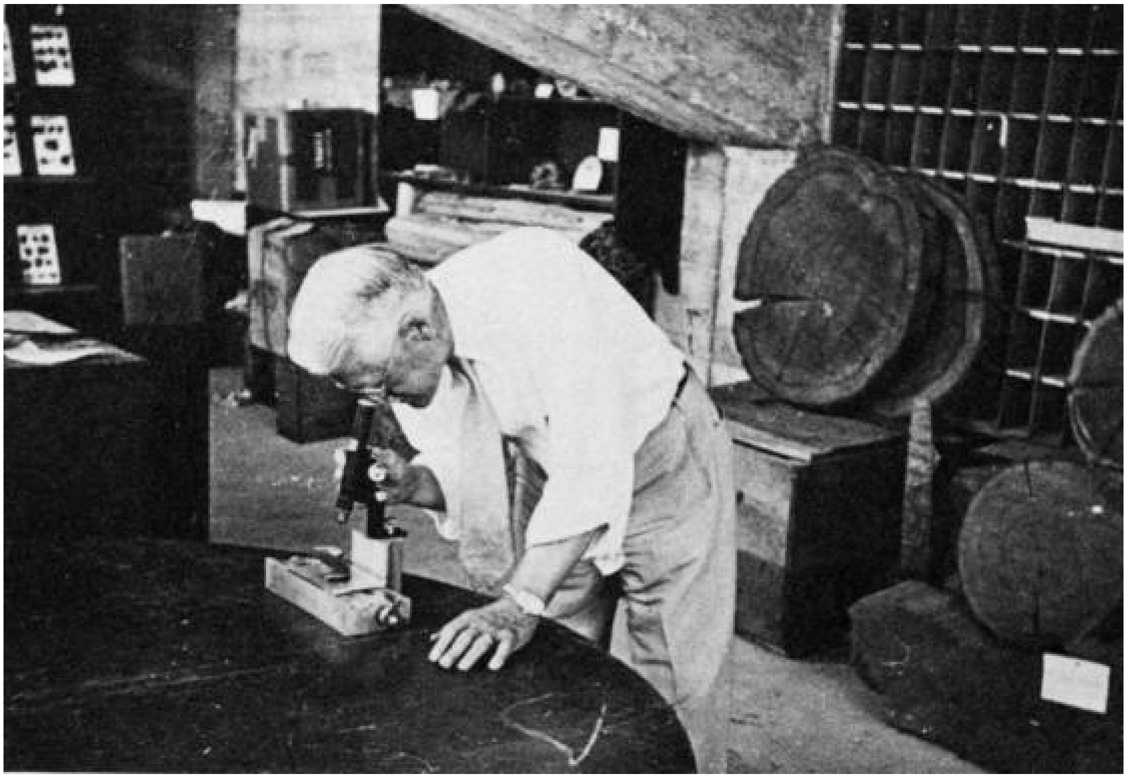


Figure 3. 4 A.E. Douglass (1867-1962) in the storage room of the Laboratory of Tree Ring Research underneath the football stadium at the University of Arizona in 1940 (from Webb 1983).

Lowell because Douglass would not publicly support Lowell's hypothesis that patterns on the surface of Mars were man-made canals.

On a horse–drawn carriage trip in 1901 near Flagstaff Arizona, Douglass noticed that a cross section displaying rings from a ponderosa pine (*Pinus ponderosa*) tree showed a variation in width of the rings. In 1904, he had the opportunity to examine a number of pine cross sections and found a distinct pattern of small rings on the first, third, sixth, ninth, eleventh, and fourteenth rings in from the bark. At that time, he documented what is now called the Flagstaff Signature, consisting of small rings in 1899, 1902, and 1904. During later research he noticed that rings from a tree in Prescott, Arizona (50 miles southwest of Flagstaff) had a similar pattern of small rings. This pattern was repeated on numerous logs in the area and after years of work, Douglass found that the pattern was repeated throughout the southwestern United States (Webb 1983).

Douglass moved to Tucson, Arizona in 1906 and took up a position as an Assistant Professor of Physics and Geography at the University of Arizona. While at the University he continued his work with tree rings, while teaching physics, and continuing his astronomical pursuits including acquiring funding for Steward Observatory. Douglass was interested in reconstructing a long-term record of sunspots. Knowing that sunspots were related to energy fluctuations in the sun and that the sun provides energy for the climate system, Douglass hypothesized that one could measure variations in solar intensity recorded in tree rings. He was later able to demonstrate that the trees could be recording cycles driven by climatic parameters (Douglass 1909) and that they were recording rainfall (Douglass 1914).

Douglass collected many species of trees from locations around the U.S. in California, Oregon, South Dakota, New Mexico, as well as Arizona from his base at the University of Arizona. He later collected more samples from England, Germany, Austria, Norway, and Sweden in the fall of 1912 during his sabbatical. In 1915, Douglass collected his first giant sequoia (*Sequoiadendron giganteum*) from a grove near Hume, California, in the same location that was sampled by **Ellsworth Huntington** in 1911. The sequoia collections yielded a 3,000-year chronology that extended back to 1305 B.C. By 1919, Douglass had collected 230 tree samples from the U.S. and Europe and he had measured 75,000 rings (Webb 1983).

Douglass had the right combination of skills and talent for dendrochronology. He was painstakingly meticulous, and he had a memory for dates. He memorized the entire chronology for the southwest during his efforts to date the archaeological structures in this region. Douglass also developed techniques that are still used today to facilitate dating, such as skeleton plotting which will be introduced later.

Douglass formed the world's first tree-ring laboratory in 1937, at the University of Arizona when space underneath the football stadium bleachers was allocated as a temporary housing for the lab. The Laboratory of Tree-Ring Research is still located there today. Douglass trained a number of students (Figure 3.5), most notably Edmund Schulman, Ted Smiley, Florence Hawley, James Giddings, and Emil Haury, who sustained the field of dendrochronology and it is due to all of their efforts along with their European counterparts of Bruno Huber, Walter Liese, Bernd Becker, Dieter Eckstein, and Fritz Schweingruber that dendrochronology is a highly regarded field of research today. I will discuss these later contributions to the field of

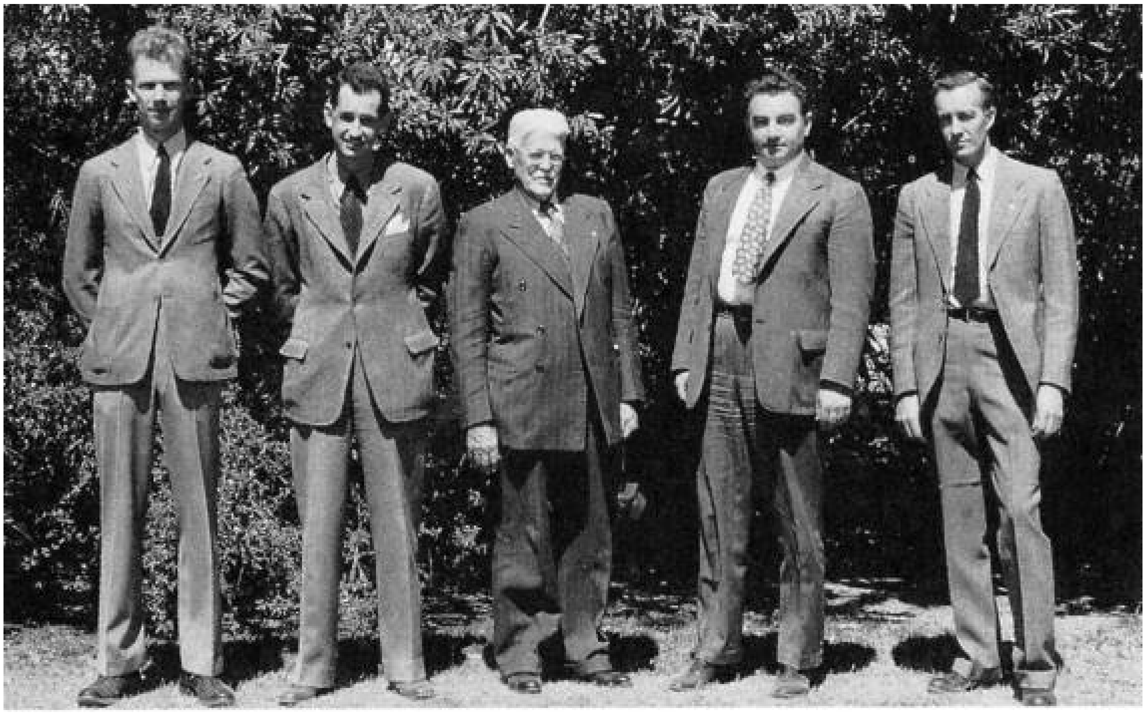


Figure 3. 5 A.E. Douglass and his students in 1946. From left to right: Fred Scantling, Sid Stallings, A.E. Douglass, Edmund Schulman, and James Louis Giddings (image from Nash 1999).

dendrochronology in chapters 7-11 which describe the methods and analyses applicable to each subdiscipline.

Bruno Huber was one of the main researchers in Europe to spend considerable time and energy in dating tree samples publishing over 39 papers from 1938 to 1970 on dendrochronology. From 1899 to 1969, he was a professor of forest botany in Germany at the Technical University of Dresden and the University of Munich (Schweingruber 1996). Huber was aware of Douglass' work and concluded the more complacent growth in trees from central Europe was due to the more temperate and humid climate of the region. Despite these difficulties, Huber was able to produce accurate chronologies and worked on new statistical techniques to quantify the strength of dating of different specimens (Liese 1978). Samples taken from old structures that contained wooden beams and posts were used by early European researchers, including Huber, to extend their chronologies back in time. Huber used oak beams from medieval buildings in Franconia to extend his chronology back to A.D. 1000 (Zeuner 1958). Huber (1935) also examined wood anatomy and determined that fluid from the roots in ring porous trees (wood types with large pores at the beginning of eaech ring such as oak trees) travels up the stem ten times faster than in diffuse porous trees (wood types with disbursed pores such as maple trees) even though ring porous trees only use their earlywood pores in the present year to transport fluid while diffuse porous trees use several years of scattered pores to transport fluid. Around the same time, K. Brehme, another German researcher, developed a chronology from larch (*Larix* sp.) trees in the Bavarian Alps extending back to A.D. 1300 and Wellenhofer and Jazewitsch used oak (*Quercus* sp.) trees from the Spessart Mountains in western Germany to build a chronology back to A.D. 1391 (Zeuner 1958).

Edmund Schulman was one of Douglass' early students who made his own contributions to dendrochronology. He conducted early work in dendroclimatology and expended much of his energy in finding old trees to produce long chronologies for climate reconstructions. These explorations lead him to find the bristlecone pines (*Pinus longaeva* and *Pinus aristata*) that are now considered to be the oldest living organisms that are not cloneal (Schulman 1954). Schulman (1956) also published the first chronologies from South America with the Chilean incense cedar (*Austrocedrus chilensis*) and the Chile pine (*Araucaria araucana*).

Florence M. Hawley was another of Douglass' students in the 1930s and she completed her PhD with the University of Chicago in 1934. She extended Douglass' work to the southeastern United States, trying to date moundbuilder artifacts from Tennessee and Mississippi. She developed some of the first chronologies from the southeastern United States under much scrutiny because of the belief at the time that trees in the eastern deciduous forest would not produce datable tree rings. She continued this research from a professorship in anthropology at the University of New Mexico.

The Modern Era and International Organization

The previous record brings the history of dendrochronology up to the 1950s and 1960s with the careers of Douglass, Schulman, and Huber. Since that time, many prominent dendrochronologists have made great strides in the science including Dieter Eckstein, Fritz Schweingruber, Bernd Becker, Mike Baillie, Gordon Jacoby, Hal Fritts, and Ed Cook who each published more than 100 papers in dendrochronology as determined from the online

Bibliography of Dendrochronology through 2006. The number of publications has risen dramatically so that Grissino-Mayer's online Bibliography of Dendrochronology now holds 11,202 citations (see the internet references in Appendix E). I will discuss the contributions to the field by many of the modern practitioners in the second half of this book.

International organizations that encourage dendrochronological research, teach dendrochronology, and provide venues for tree-ring research presentations have developed in the last century with a great influx of members and meetings over the past 20 years. The Tree-Ring Society (TRS) is the oldest society of dendrochronologists and was founded by A.E. Douglass in 1935. The journal Tree-Ring Bulletin was first published in 1934 and has since changed its name to Tree-Ring Research. It now has over 200 members from more than 30 countries. The Association for Tree-Ring Research (ATRR) started in Europe in 2003, providing a network for European dendrochronologists. A second tree-ring journal called Dendrochronologia was first published in 1983 and is another major outlet for dendrochronological literature. A new organization called the Asian Dendrochronology Association (ADA) started in 2006 and provides a network for Asian dendrochronologists.

A.E. Douglass started annual meetings on dendrochronology in 1934, which continued to run in 1935, 1936, 1937, 1939, and 1941. These first meetings included researchers from Arizona and New Mexico that had an interest in archaeology and climatology. The Tree-Ring Society continued to meet at various venues through the intervening years including a notable meeting in Tucson, Arizona in 1974 where the idea of regular international meetings arose and another major meeting occurred in Norwich, England in 1980. Regular international meetings on dendrochronology started at the International Conference in Ystad, Sweden in 1990 and continued with other international conferences since that time. These International Conferences on Dendrochronology have included the 1994 meeting in Tucson Arizona, which had 207 participants from over 35 countries, and meetings in Mendoza, Argentina (2000), Quebec City, Canada (2002), and Beijing, China (2006). The next meeting is planned for Finland in 2010. Smaller conferences have been developed around the world to encourage local research with EuroDendro being the longest running of these conferences. Their first meeting was in Lourmarin, France in 1989, followed by meetings in Liège, Belgium (1990), Travemünde, Germany (1994), Moudon, Switzerland (1996), Savonlinna, Finland (1997), Kaunas, Lithuania (1998), Malbork, Poland (1999), Gozd Martuljek, Slovenia (2001), Obergurgl, Austria (2003), Rendsburg, Germany (2004), Viterbo, Italy (2005), and Hallstatt, Austria (2008) (Dieter Eckstein personal communication). In recent times other regional conferences have been developed such as the Southeast Asian Dendrochronology Conference (1998), the Asian Dendrochronology Conference (2007), and the Ameridendro Conference (2008).

Fritz Schweingruber started an International Dendroecological Fieldweek in 1986 and Paul Krusic started the North American Dendroecological Fieldweek in 1990 (Speer 2006). These two educational outreach programs are in their 22nd and 18th years, respectively. These fieldweeks continue to be one of the main educational opportunities for researchers that do not have access to local dendrochronology courses. The success of the fieldweek model has led to the development of the South American Dendrochronological Fieldweek (now in its 4th year), a Southeast Asian fieldweek, and a summer course in Turkey.

A more lasting contribution of this international collaboration in dendrochronological research is the development of the International Tree-Ring Databank (ITRDB; Grissino-Mayer and Fritts 1997). This data archive and computer forum arose from the international meeting in 1974, during which participants expressed the need for a repository of tree-ring chronologies so that the work of individual researchers can be passed along and preserved through time. Hal Fritts founded the ITRDB and was its main proponent in its early years. In 1990, the National Oceanographic and Atmospheric Administration (NOAA) took over the operation of the ITRDB and founded the World Data Center – Paleoclimatology A (WDC) program in Boulder, Colorado. The databank currently holds more than 2000 chronologies from six continents. In 1988 the managers of the ITRDB started a computer forum to enhance communication between tree-ring researchers around the world. Today this forum has over 600 members from 32 countries that subscribe to the listserve. All of these international organizations, meetings, fieldweeks, and the ITRDB continue to foster an international tree-ring community.

Summary

Dendrochronology as a field has grown out of the prior work by all of the researchers mentioned in this chapter. From this work, you can see how we have accumulated knowledge over time and continue to improve dendrochronology as a science. We keep adding new applications, longer records, and larger spatial analyses. Chapter 7-11 in this book will describe each subfield in greater depth and discuss the modern recent history of dendrochronological research. Because the number of researchers and the amount of research has increased so tremendously since A.E. Douglass' time, it is hard to synthesize all of that work into one volume. I hope that the references in the remainder of this book will be a good guide to the varied publications in dendrochronology.

Chapter 4: Growth and Structure of Wood

Introduction

Tree rings are composed of individual cells that constitute the building blocks of the organism of the tree. One must understand the cellular level of tree growth in order to accurately identify the individual tree rings. A basic understanding of tree physiology is also important for comprehending the biological processes that link the environment to ring formation. Tree rings are the end result of a complex sequence of assimilation of natural resources by the tree. A cascade of chemical reactions and cell division ultimately produce the annual ring that contains the information dendrochronologists analyze. Kozlowski and Pallardy (1997) and Salisbury and Ross (1992) are suggested for further reading.

Tree Physiology

Gymnosperms (plants that produce naked seeds) are more primitive phylogenetically than angiosperms (flowering plants) and have less-developed and fewer cell types. Gymnosperms (also known as softwood trees or conifers) transport water from the roots to the leaves through tracheids (long narrow cells that comprise growth rings) in the outer living part of the xylem in the area of the sapwood (the region with living parenchyma cells). Angiosperms (also known as hardwood or deciduous trees) more efficiently transport most of the water and nutrients from the soil to the leaves in specialized, capillary-like cells called vessels. These vessels are larger in diameter than tracheids and transport water more efficiently but are more prone to embolism (air bubble formation during conduction that blocks water movement). Angiosperms are further devided into monocotyledons (or monocots) and dicotyledons (or dicots). A cotyledon is a seed leaf or a leaf that breaks out of the seed. The monocots (like palms and yucca plants) produce vascular bundles of xylem and phloem tissue but they do not produce a vascular cambium that results in growth around the stem of the plant which would otherwise produce annual rings. Therefore, monocots are not useful for dendrochronology, although researchers may be able to quantify the age of some monocots through incremental height growth patterns as the tree grows taller. Dicots, on the other hand, often produce annual rings around the circumference of the tree from cell division in the vascular cambium.

Most gymnosperms and dicots in seasonal climates produce one ring per year. The ring can be divided into **earlywood** and **latewood**. Earlywood is defined as cells that have large lumen (the opening in the center of the cell) relative to the cell walls. Latewood cells are always flattened and have a more compact lumen relative to the cell walls and consequently appear darker (Figure 2.5). Earlywood is usually produced in spring and early summer while latewood is formed in the late summer. However, this timing varies with species and environmental forces.

Apical meristem (or primary meristem) are located at the tips of branches and roots and are the origin for elongation of branches, roots, and height growth in a tree. **Secondary meristem** is produced in most gymnosperms and dicots and enables a tree to grow in circumference through time and produce tree rings. Cell division occurs in the **vascular cambium** (often simply called the cambium) which is a narrow layer of meristematic cells between bark and wood. During cell division **xylem** is produced toward the inside of the tree, becoming the wood structure that supports the tree, and **phloem** is produced towards the outside of the tree and becomes the inner bark. A c**ork cambium** forms the outer bark of most trees. The walls of all woody cells continue to thicken up to a cell-type specific extent within a few days or weeks before the cells die, lose their protoplasm, and start to function for the tree as conducting or strengthening tissue. Water transport is driven by **transpiration** (the evaporation of water) through the stomata in the leaves of the tree and the cohesion of water molecules throughout a connected column from the leaves all the way down to the roots. Transpiration is the pump that drives water (and subsequently nutrient) uptake in the roots. The phloem cells remain alive much longer than the xylem cells and transport the products of photosynthesis (sugars and hormones) down the tree. Less frequently, a series of thin-walled ray cells are also produced during cell division in the cambium resulting in a radial cell component that connects the outside of the tree to the inside. Heartwood forms in the middle of the stem as a result of an active production of substances, mainly phenols, which are deposited to close down the structure and guarantee that the wood is resistance to decay (Figure 4.1). The lighter colored outer wood is called the **sapwood** and in conifers is the area that tranports water up the tree from the roots to the canopy.

Visualize a tree as a series of stacked cones representing a complete sheath of wood that is put on the tree each year. The tree grows upward by cell division at the apical meristem (or shoot tip) and outward from cell division in the secondary meristem causing the cones to stack upward and grow outward. When a dendrochronologist cores a tree, a sample is removed from bark to pith, collecting the full number of rings produced at the height of the core. The **pith** is the bundle of cells produced by the upward growth of the apical meristem, allowing trees to reach to greater heights and creating the cambium initials that start secondary thickening of trees (Figure 4.2).

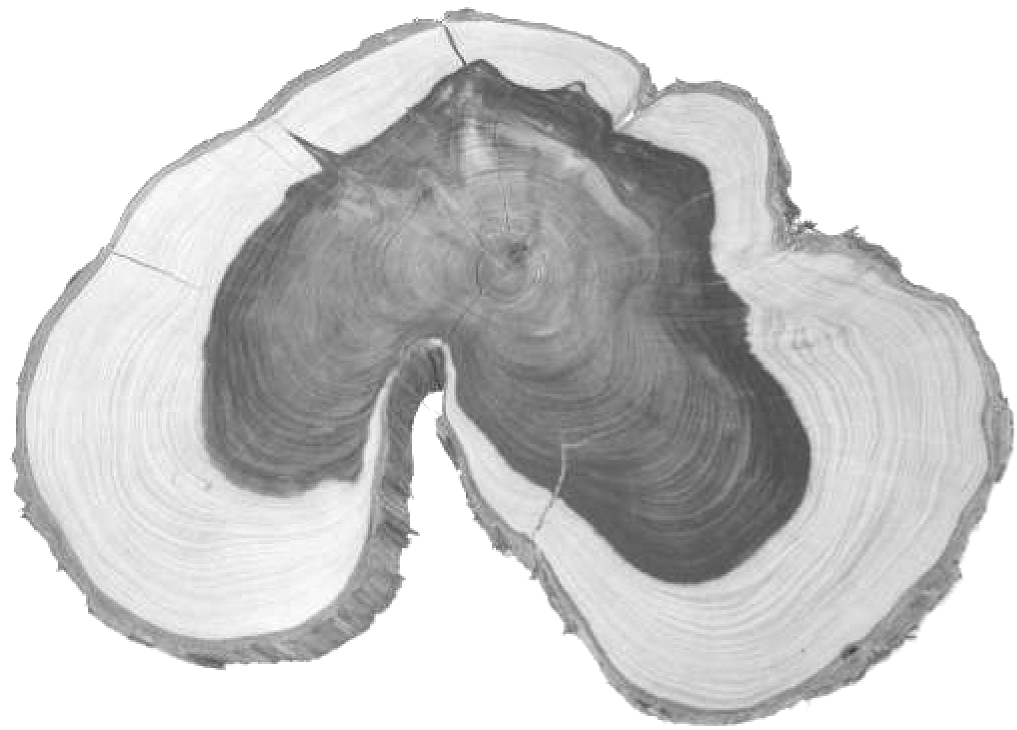


Figure 4. 1 A juniper from Jordan showing lobate growth demonstrating poor circuit uniformity where the rings pinch out around the circumference of the section. Notice the darker inner wood called heartwood and the lighter colored outer wood called sapwood. See figure 1.2 for and example of good circuit uniformity.

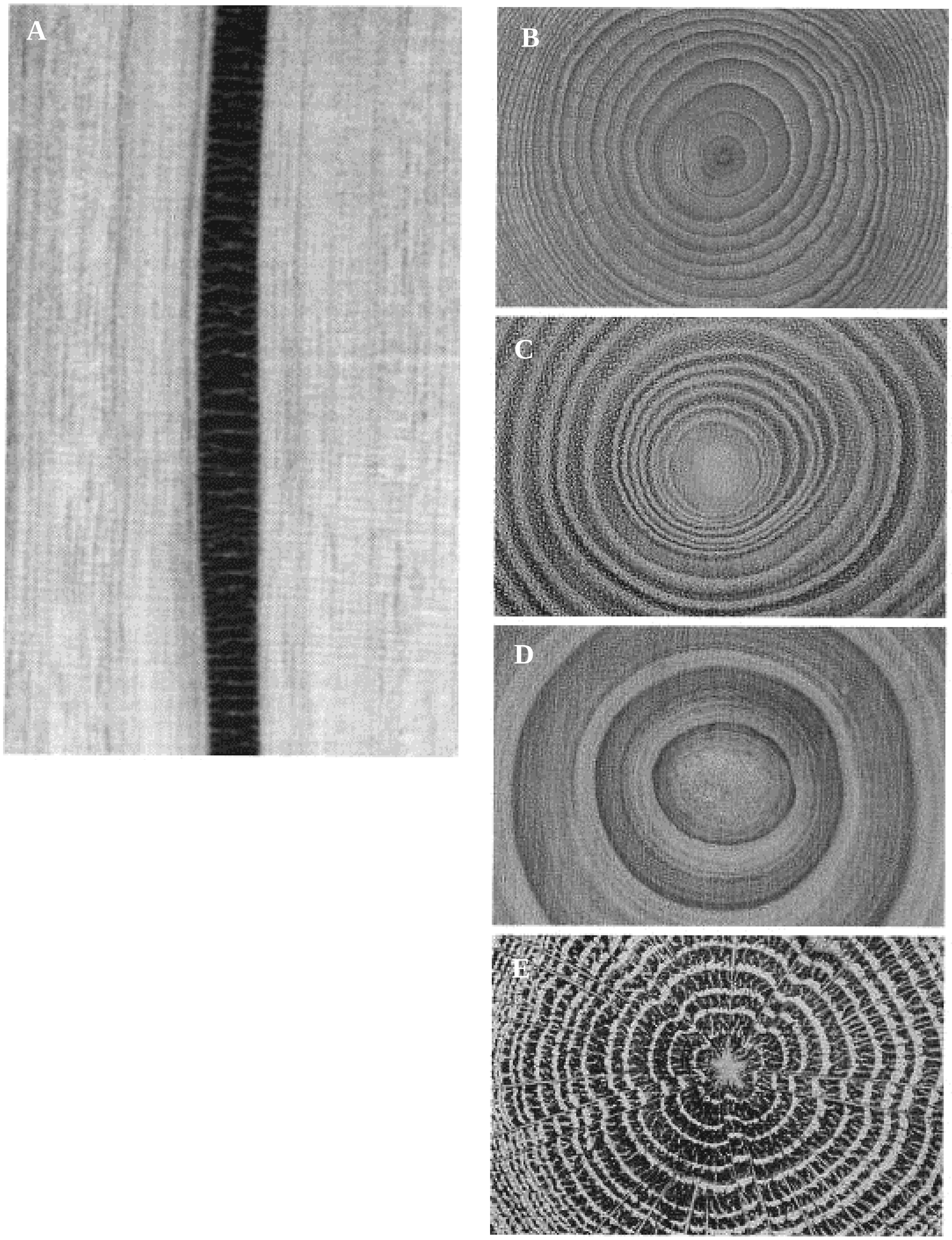


Figure 4. 2 Pith characteristics. Pith is the very center of the tree that is formed by the terminal leader as the tree extends in height each year. If one hits the pith when coring the tree, that date will provide the exact age of that tree at that height. A) Longitudinal section of butternut with a chambered pith, B) beech, C) catalpa, and D) sumac, and E) oak (graphic from Hoadley 1990).

Basic Wood Structure

All wood samples can be examined from three distinct views, or planes, which provide a different perspective on the cells that compose the wood (Figure 4.3). The **cross sectional view** (also called the **transverse view**) is what we see on the surface of a stump when a tree is cut down. In this view, you can clearly see the cross section of the **tracheids** in coniferous trees, which are elongated tube-like cells that make up the majority of the wood and function to transport fluids and nutrients vertically in the xylem of the tree. This is the view that dendrochronologists examine most frequently. If you look at a side view along a cut from the bark to the pith of the tree, you will be examining the **radial view** of the section (think of the radius of a circle). In this case, you can see the full length of the tracheids, but the ring boundaries are often obscured. The last view is a cut down the outside of the tree, basically parallel to the pith column. This is the **tangential view** (tangent, or perpendicular, to the radius), and can often be seen in furniture as the veneer cut from a tree. Each view provides a different perspective that a wood anatomist can use to identify the type of wood being examined.

Cell Features and Types

Gymnosperms, such as pine (*Pinus* sp.), spruce (*Picea* sp.), and juniper (*Juniperus* sp.)(Figure 4.4), produce simpler wood structure (Figure 4.5) than hardwoods and are mainly composed of elongated tracheids that are connected by boredered pits between the tracheids and resin ducts may occasionally occur (Figure 4.6). Tracheids make up most of the cells in conifer wood and function as structural and conducting elements, transporting nutrients along with water from the roots. Bordered pits are evident on the tracheids' cell walls that allow water transport from one tracheid to another. Parenchyma are another cell type that can be found in gymnosperms. These

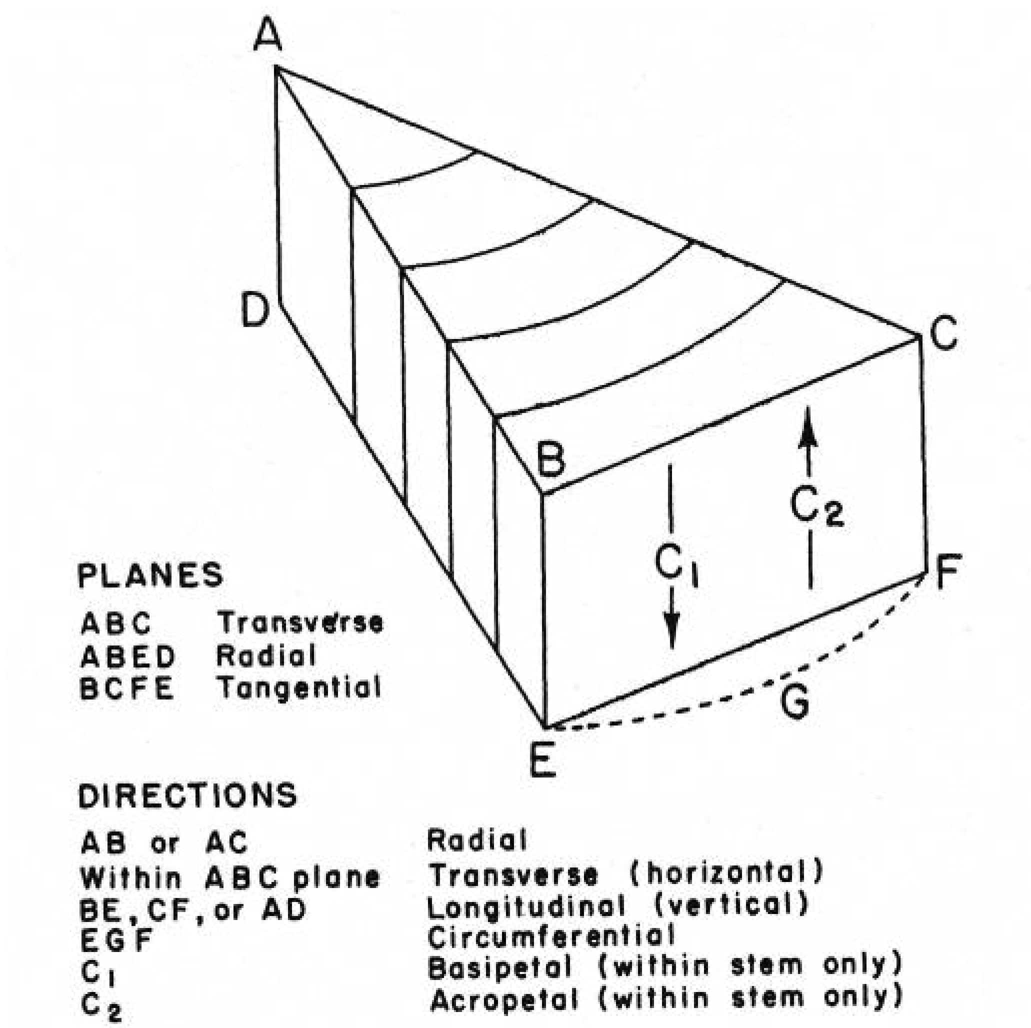


Figure 4. 3 Planes of wood structure. Wood samples can be sectioned to expose three primary surfaces used in wood identification. The cross sectional (or transverse) view, the radial view, and the tangential view (from Fritts 1976).

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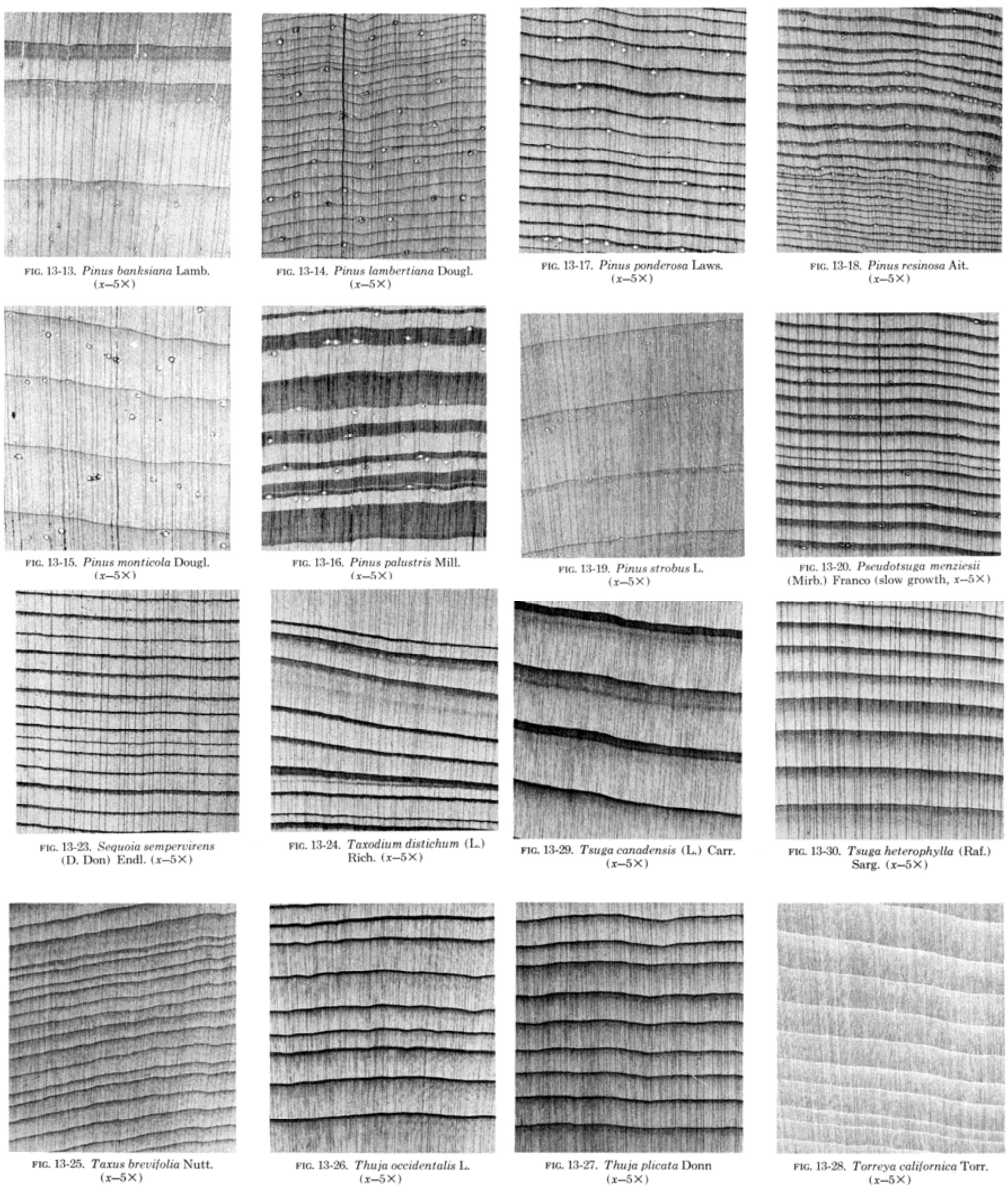


Figure 4. 4 Gymnosperm wood examples. Examples of species with coniferous growth such as pine (*Pinus*), Douglas-fir (*Pseudotsuga menziesii*), coast redwood (*Sequoia sempervirens*), bald cypress (*Taxodium distichum*), hemlock (*Tsuga*), yew (*Taxus*), and cedar (*Thuja*) (graphic from Panshin *et al.* 1964).

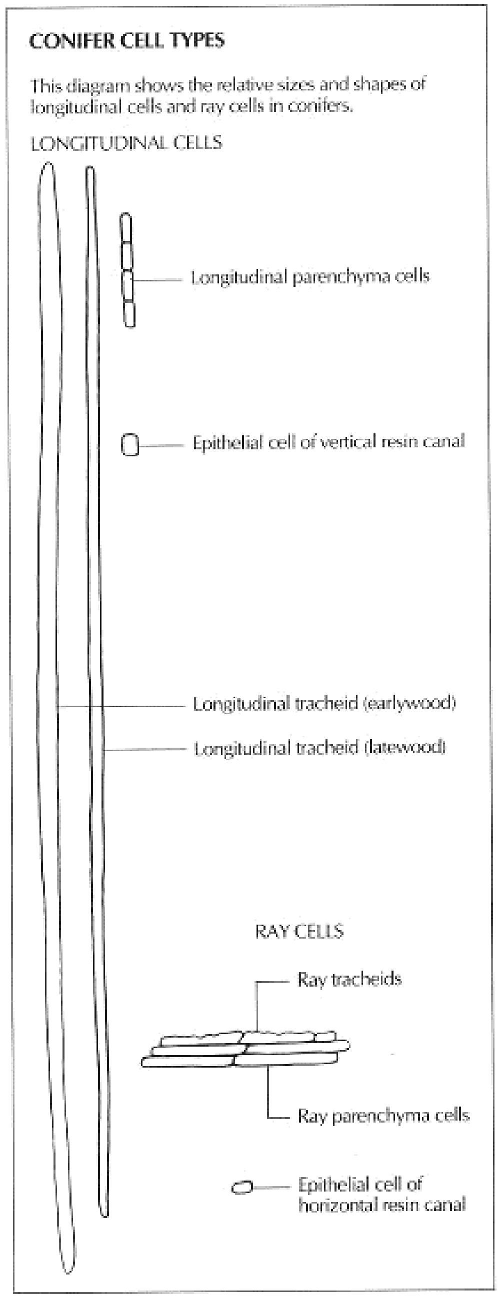


Figure 4. 5 Gymnosperm cells types. Gymnosperms only have a few cell types which are called tracheids, parenchyma cells, ray cells, epithelial cells, and resin ducts (graphic from Hoadley 1990).

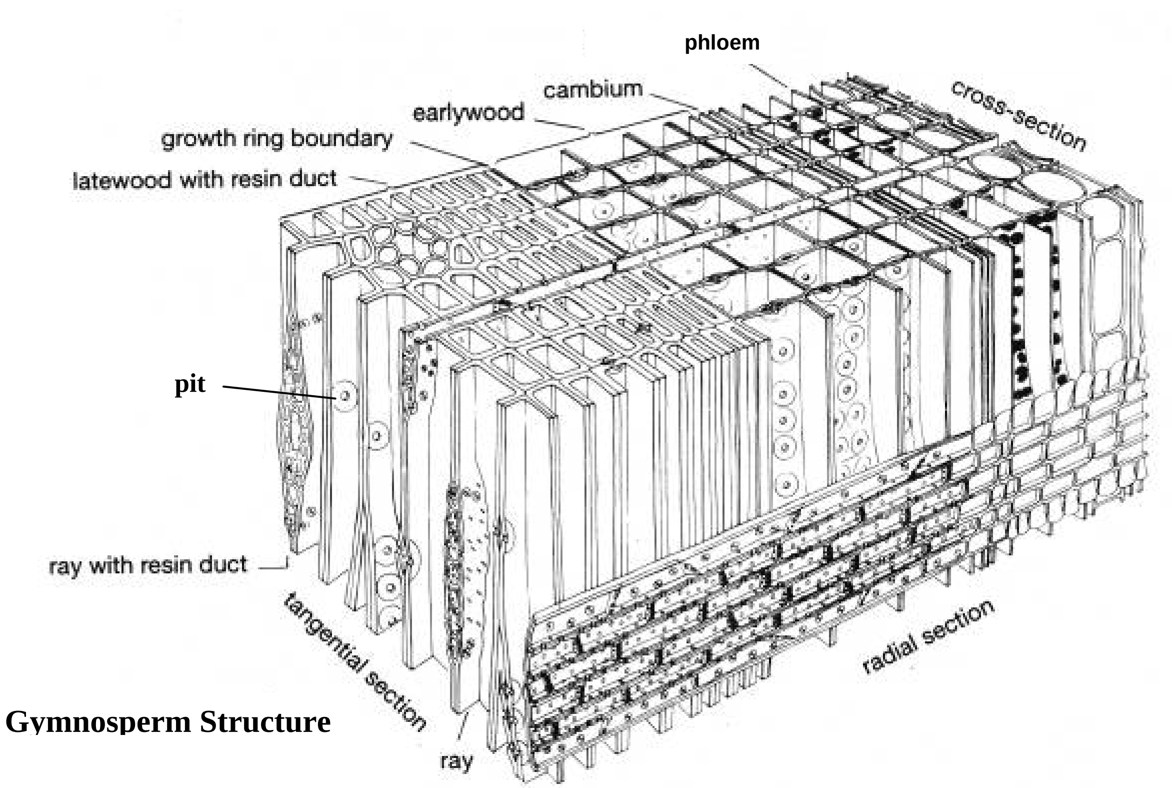


Figure 4. 6 Gymnosperm wood structure. In coniferous wood, the diameter of the cell, cell wall thickness, and size of the lumen determine the ring structure (from Schweingruber 1996).

cells are alive and have a complete protoplast in the lumen of the cell. In a cross sectional view, they can be identified as a normal cross section of a tracheid cell, except that the **vacuole** (central cavity of the cell) is dark with cell material. Finally, resin ducts that transport resin throughout the tree to seal off wounds can be found on the cross sectional view of many coniferous genera (Figure 4.7). Because of the function of this resin, conifers are relatively resistant to decay. Thickening of the cell walls and flattening of the cells are the main indicator of annual ring structure in coniferous wood (Figure 4.7). Bordered pits in the tracheid walls and resin ducts can be present, but pits do not occur in all conifers.

Angiosperms have more complex wood structure than gymnosperms (Figure 4.8). Fibers provide the key structure and support for the tree, but angiosperms also produce vessels that are used for the main water transport in the tree. Angiosperms may have large and small vessels along with fibers, tracheids, and parenchyma cells (Figure 4.8), all of which are evident in cross section. Pits are very evident in hardwood species in the radial section and allow for water transport between individual vessels. Parenchyma cells are more common in hardwoods, and actually form the ring boundary in some genera of diffuse porous species. A three-dimensional wood block of a hardwood sample shows that vessels dominate the view, but fiber cell size is still important for differentiating ring boundaries in some genera (Figure 4.9). Rays form perpendicular to the ring boundaries and are very prominent in hardwoods, providing efficient transport and storage of nutrients, photosynthetic products, and some metabolic wastes to the heartwood (Figure 4.10).

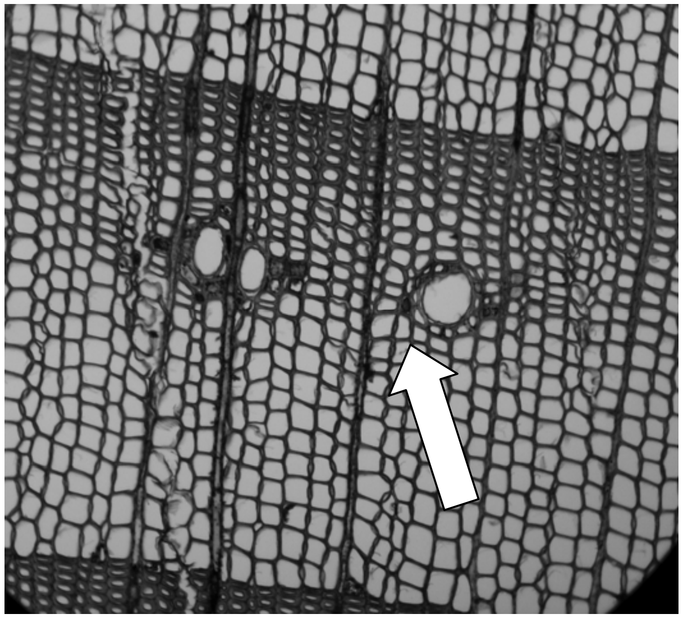


Figure 4. 7 Resin ducts in a gymnosperm. Resin ducts are produced in most conifers. The resin duct is a large hollow vessel that is surrounded by guard cells. When the guard cells relax, they allow resin to flow through the resin duct. The tree uses this resin to seal off wounds. Compare to vessels in hardwood – not the same type of cell or function (photo by Jim Speer).

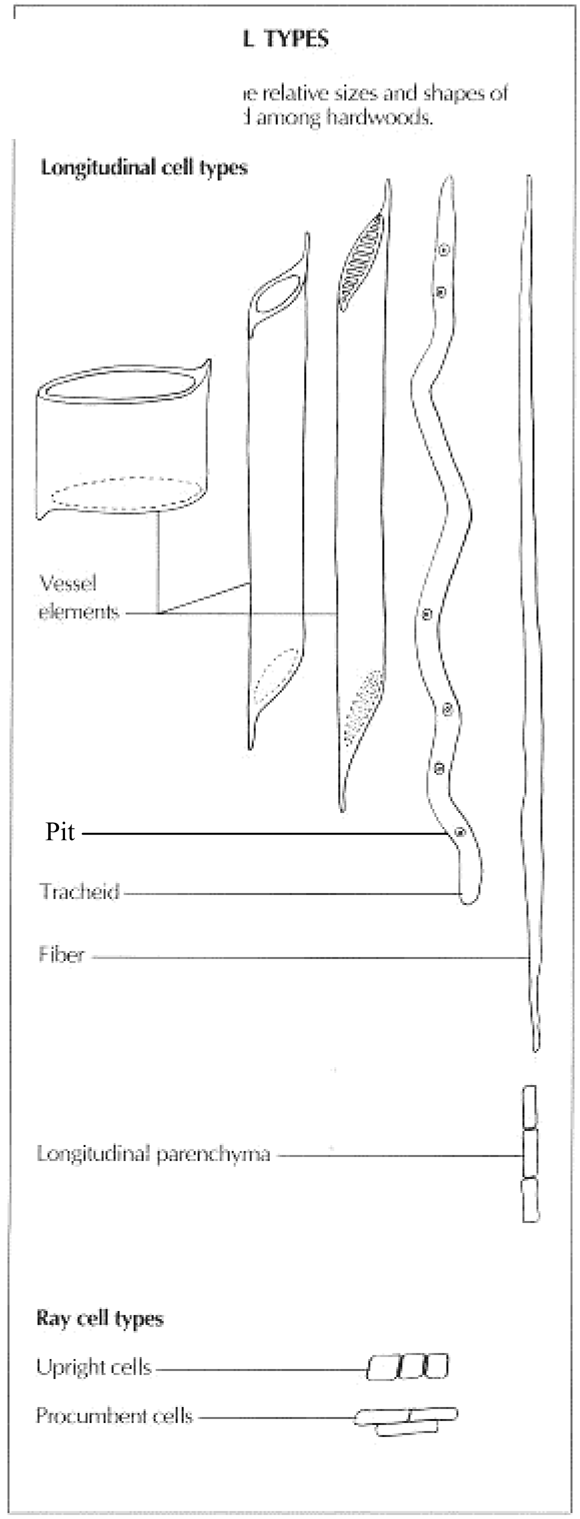


Figure 4. 8 Angiosperm cells types. Angiosperms have more complex cell types which are vessel elements, tracheids, fibers, parenchyma, ray cells, and pits (graphic modified from Hoadley 1990).

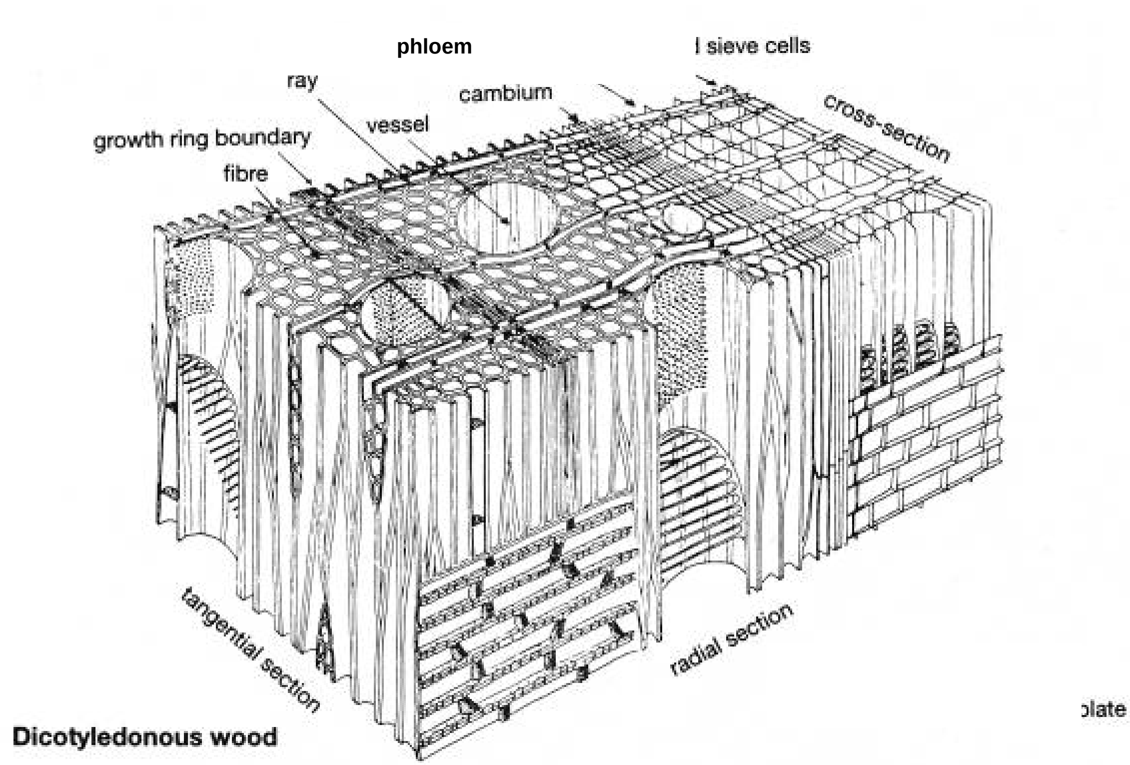


Figure 4. 9 Dicotyledonous angiosperm wood structure. Angiosperms, such as this diffuse porous wood, have different cellular structure than gymnosperms and are composed of multiple vessels and more prominent rays. Ring boundaries, however, may still be defined by the size of the fibers, size of the lumen, and the thickness of their cell walls (from Schweingruber 1996).

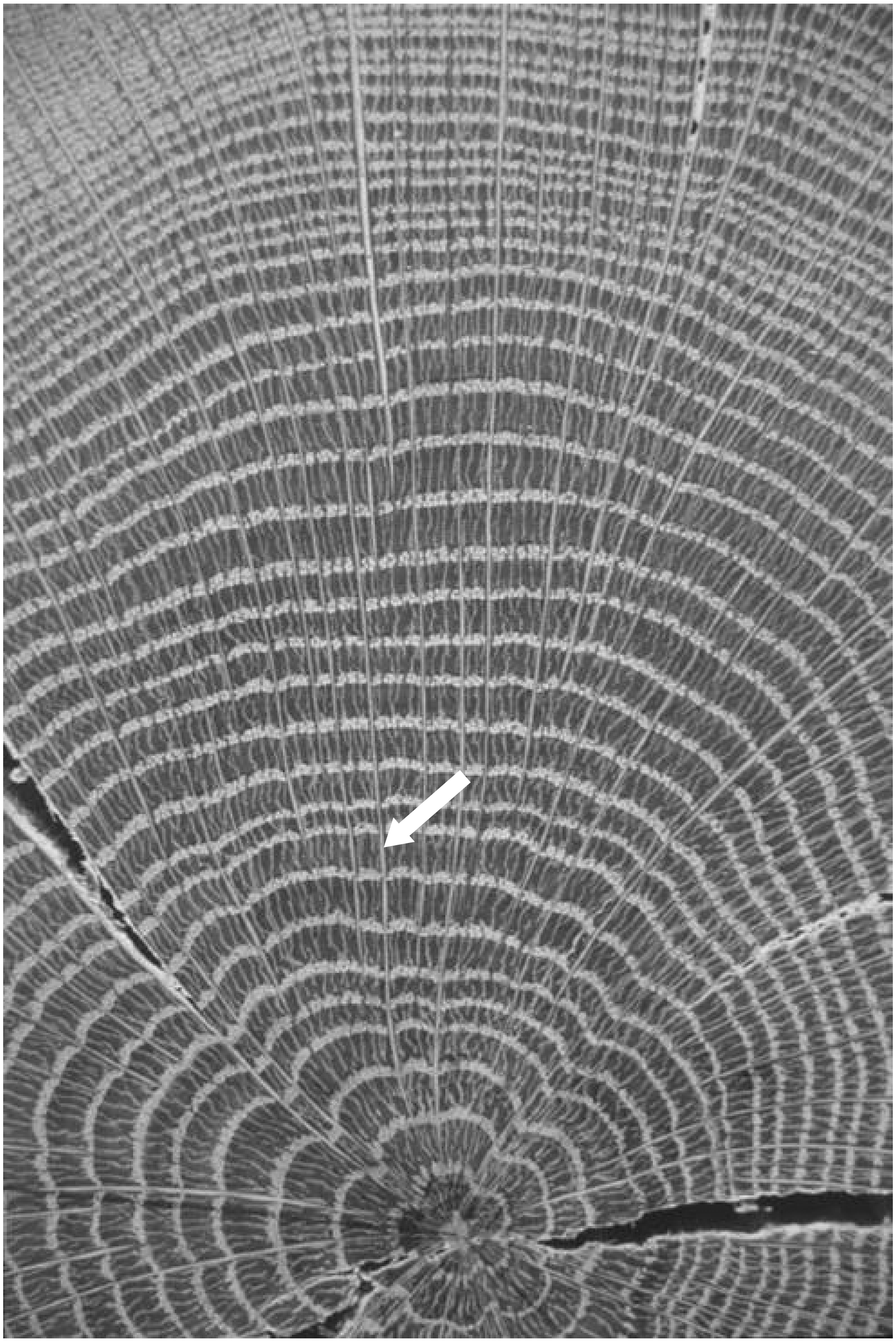
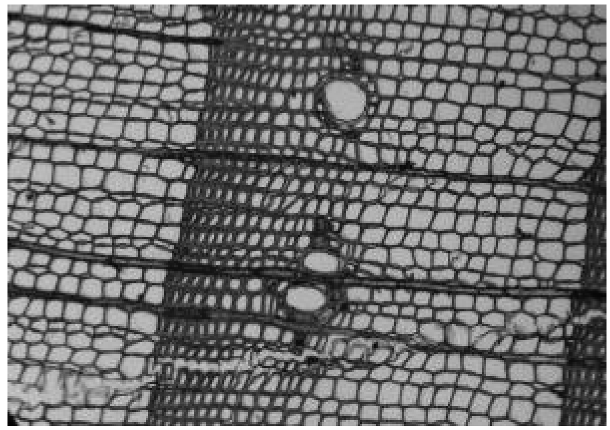


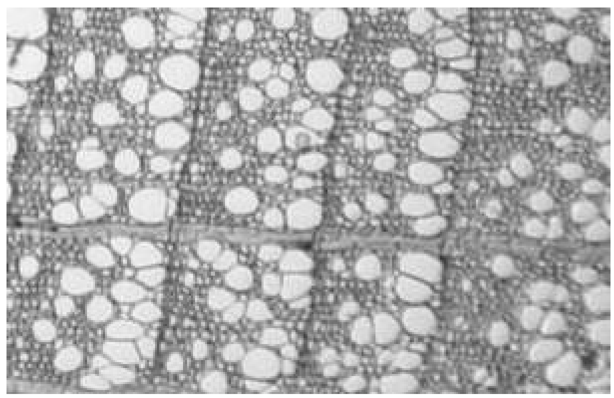
Figure 4. 10 Wood rays in an oak. Rays are wood cell structures that transport materials horizontally (radially) through the tree and are most evident in ring porous and diffuse porous tree species (photo by Jim Speer).

Forms of Wood Structure

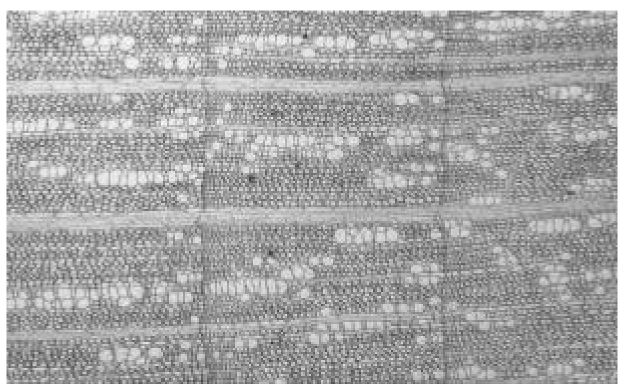
Two main wood structures can be identified, which are the non-porous woods of the gymnosperms and the porous wood types of the dicotyledon group of the angiosperms (Figure 4.11). The dicots are further broken into ring porous, semi-ring porous, and diffuse porous wood types (Figure 4.12). In **non-porous** wood structure the ring boundaries can be identified by examining the size and cell wall thickness of the tracheids. The presence of vessels differentiates the gymnosperm wood from angiosperm wood. Vessels are an advanced evolutionary trait of angiosperms that enable the trees to more efficiently transport water up the tree. They can be large or small (Figure 4.13) and their distribution in the ring can help a dendrochronologist identify the ring boundaries. Large vessels occur at the beginning of the growth ring in ring porous genera. Small vessels may form as solitary individuals, as vessel multiples, vessel chains, nested vessels, or as wavy bands and can occur anywhere in the ring (Figure 4.14). **Ring porous** wood structure is defined by a row of vessels that are produced at the beginning of the growing season before leaf-out. Because these vessels are formed early in the growing season when photosynthates have yet to be produced, the tree uses stored reserves from the previous growing season. Ring porous genera, *e.g*. oak (*Quercus* sp.) and ash (*Fraxinus* sp.), are the most distinct of the angiosperms with an obvious row of vessels occurring at the beginning of the growth ring (known as the earlywood zone) (Figure 4.15). **Semi-ring porous** genera, *e.g*. hickory (*Carya* sp.) and elm (*Ulmus* sp.), have some vessels that form at the beginning of the ring, but also have smaller vessels distributed throughout the ring (Figure 4.16). The earlywood zone is not as consistent and distinct as with ring porous genera. **Diffuse porous** genera, *e.g*. maple (*Acer* sp.), birch (*Betula* sp.), and aspen (*Populus* sp.), have small vessels distributed throughout the ring that have no relationship with the ring boundaries (Figure 4.17). This varied distribution of



Gymnosperm



Angiosperm



Angiosperm

Figure 4. 11 Gymnosperm versus Angiosperm wood types. Gymnosperms do not have pores and angiosperms have either ring porous with a row of vessels at the beginning of each ring or diffuse porous woods that have vessels distributed throughout the ring. All of these tree samples are growing from right to left in these images (photos by Jim Speer).

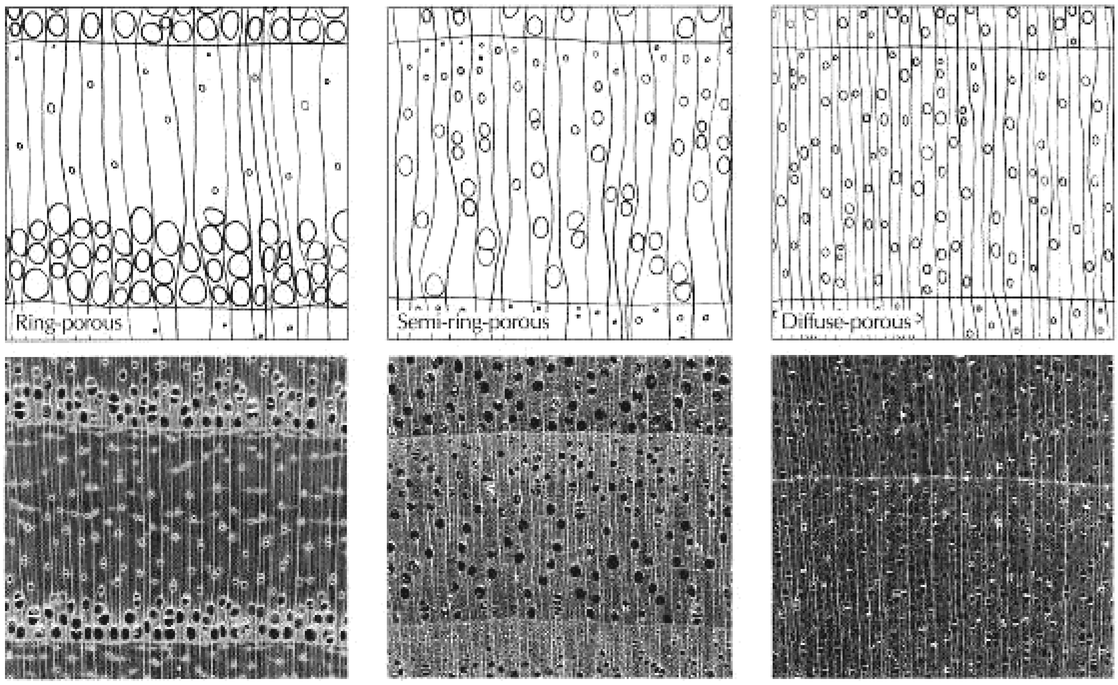


Figure 4. 12 Classification of ring porosity. Gradation from ring porous wood to diffuse porous wood with semi-ring porous as an intermediate stage (graphic from Hoadley 1990).

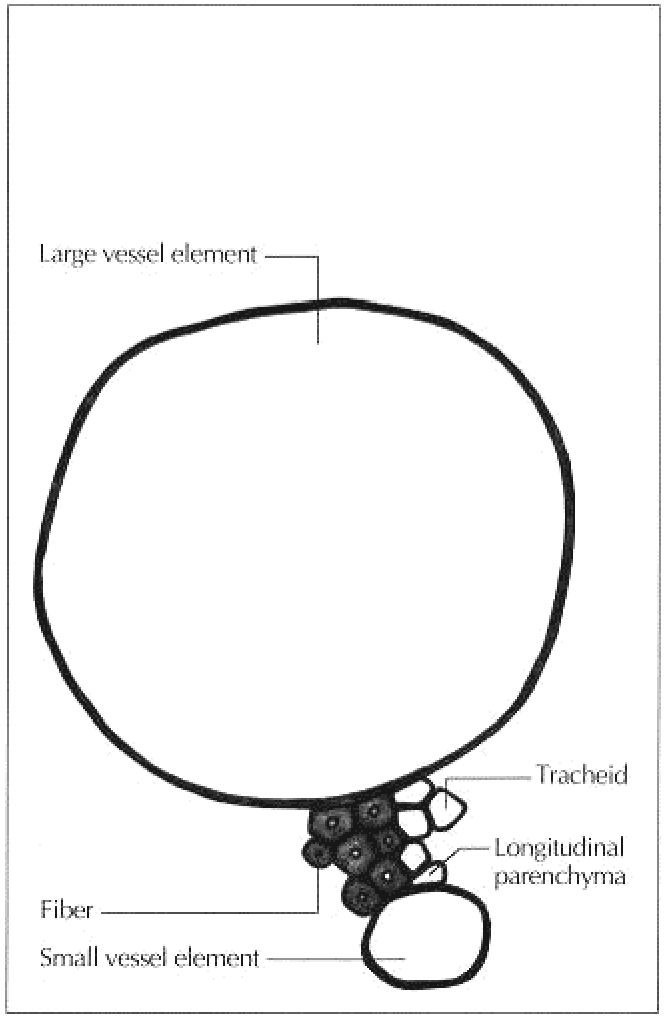


Figure 4. 13 Relative size of hardwood cells and wall thickness in ring porous species. In diffuse porous species, the disparity in size of the cells may be smaller (graphic from Hoadley 1990).

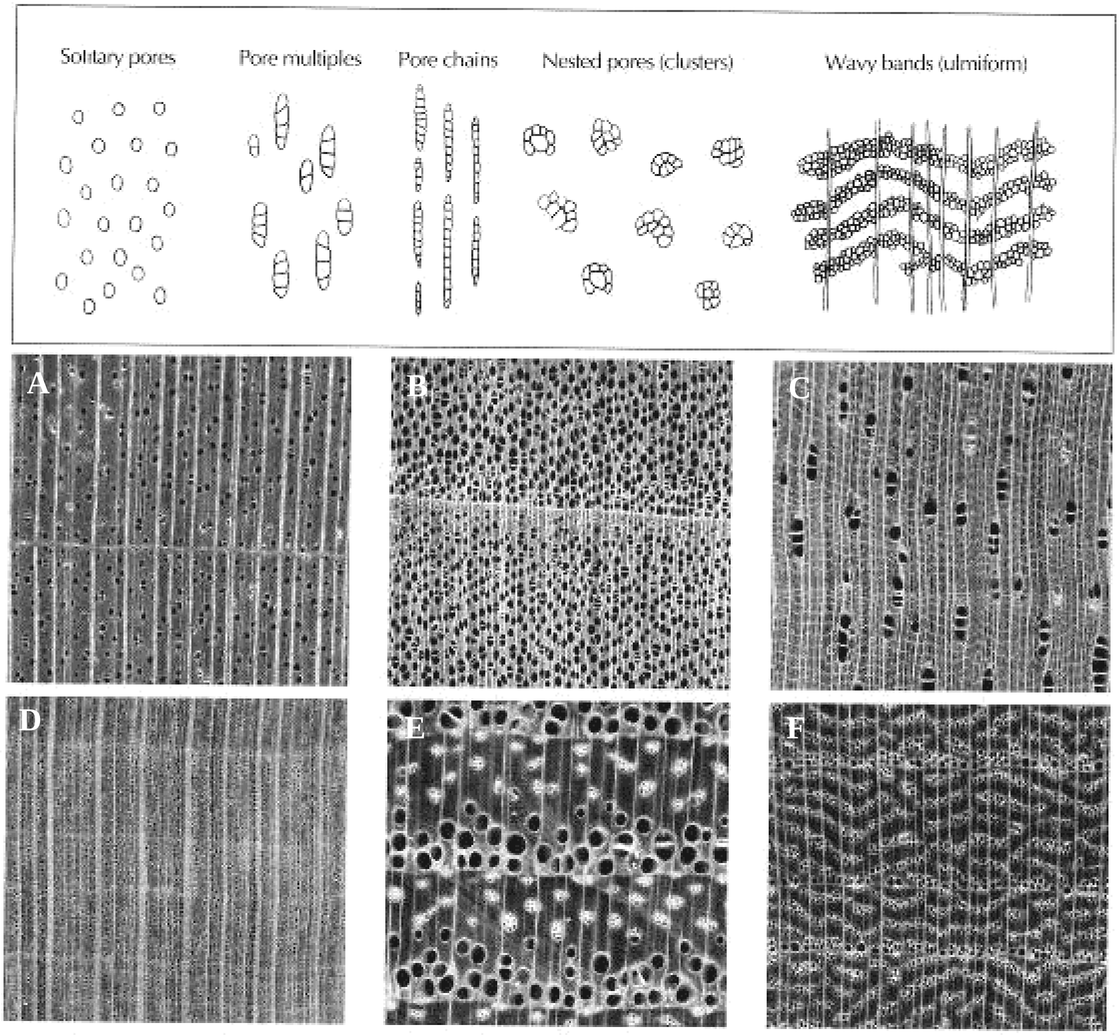


Figure 4. 14 Pore arrangement in angiosperms. Pores can be arranged in many different patterns in angiosperm wood. This arrangement helps with wood identification. A) *Acer* with solitary pores, B) *Populus* with pore multiples, C) *Dyera* with pore multiples, D) Ilex with pore chains, E) *Gymnocladus* with nested pore clusters, and F) *Ulmus* with wavy bands. All images are at 15x magnification (graphic from Hoadley 1990).

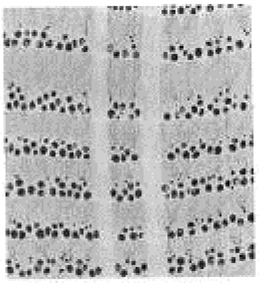


FIG. 13-83. *Quercus bicolor* Willd. (x–5×)

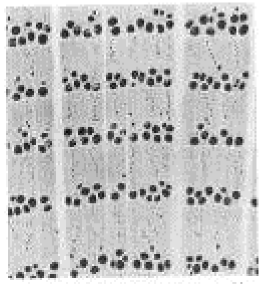


FIG. 13-84. *Quercus coccinea* Muenchh. (x–5×)

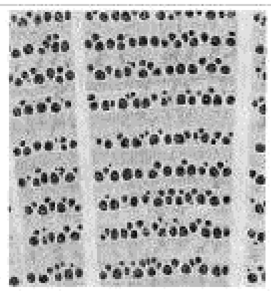


FIG. 13-85. *Quercus stellata* Wangenh. (x–5×)

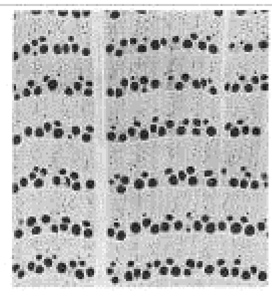


FIG. 13-86. *Quercus velutina* Lam. (x–5×)

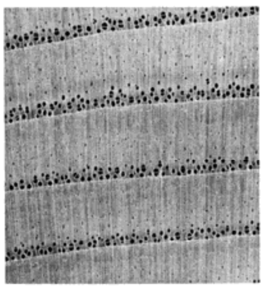


FIG. 13-57. *Fraxinus americana* L. (x–5×)

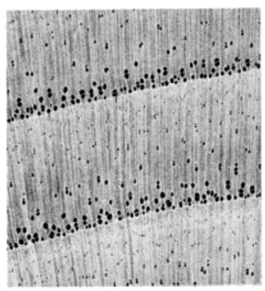


FIG. 13-58. *Fraxinus latifolia* Benth. (x–5×)

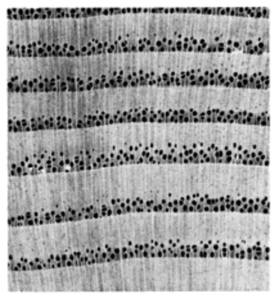


FIG. 13-59. *Fraxinus nigra* Marsh. (x–5×)

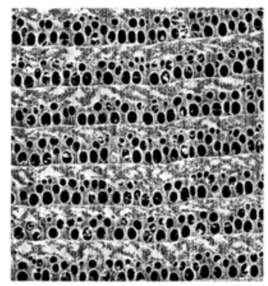


FIG. 13-48. *Castanea dentata* (Marsh.) Borkh. (x–5×)

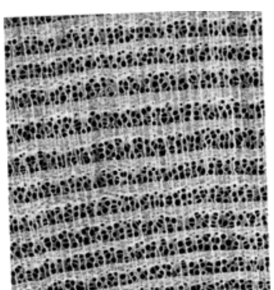


FIG. 13-91. *Sassafras albidum* (Nutt.) Nees (x–5×)

Figure 4. 15 Examples of ring porous woods. Ring porous genera such as oak, (*Quercus* sp.), ash (*Fraxinus* sp.), chestnut (*Castanea* sp.), and sassafrass (*Sassafrass* sp.) (graphics from Panshin *et al.* 1964).

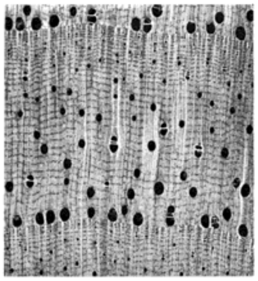


FIG. 13-45. *Carya cordiformis* (Wangenh.) K. Koch (x–5×)

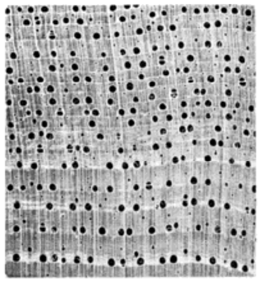


FIG. 13-46. *Carya glabra* (Mill.) Sweet (x–5×)

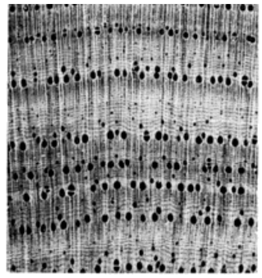


FIG. 13-47. *Carya ovata* (Mill.) K. Koch (x–5×)

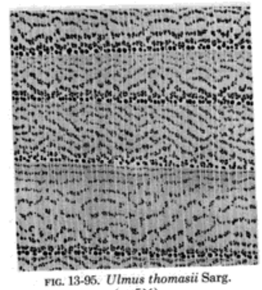


FIG. 13-95. *Ulmus thomasii* Sarg. (x–5×)

FIG. 13-93. *Ulmus americana* L. (x–5×)

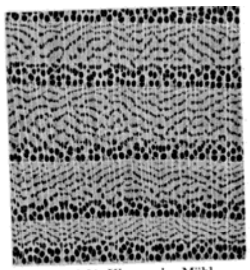


FIG. 13-94. *Ulmus rubra* Mühl. (x–5×)

Figure 4. 16 Examples of semi-ring porous woods. Semi-ring porous genera include hickory (*Carya* sp.) and elm (*Ulmus* sp.) (graphics from Panshin *et al.* 1964).

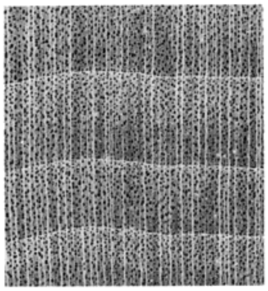


FIG. 13-31. *Acer macrophyllum* Pursh (x–5×)

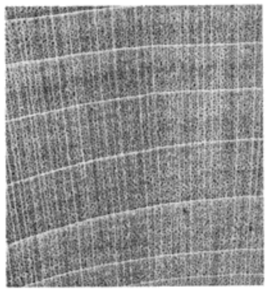


FIG. 13-32. *Acer rubrum* L. (x–5×)

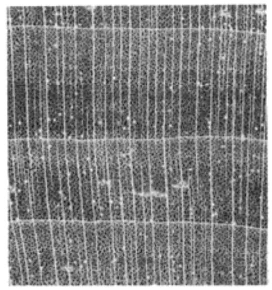


FIG. 13-33. *Acer saccharinum* L. (x–5×)

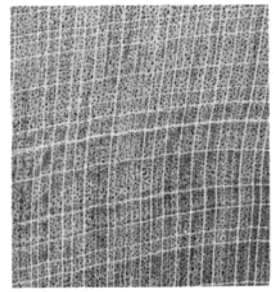


FIG. 13-34. *Acer saccharum* Marsh. (x–5×)

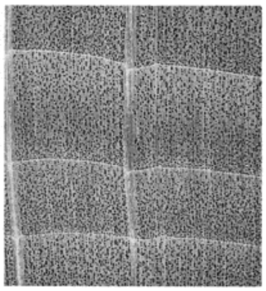


FIG. 13-37. *Alnus rubra* Bong. (x–5×)

FIG. 13-40. *Betula alleghaniensis* Britton (x–5×)

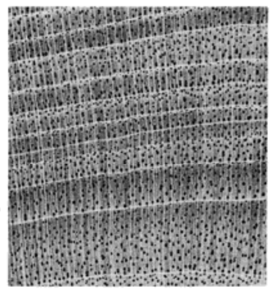


FIG. 13-42. *Betula lenta* L. (x–5×)

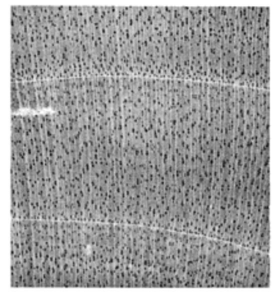


FIG. 13-43. *Betula papyrifera* Marsh. (x–5×)

FIG. 13-44. *Carpinus caroliniana* Walt. (x–5×)

Figure 4. 17 Examples of diffuse porous woods. Diffuse porous genera showing no association between the pores and the ring boundaries. Genera include maple (*Acer* sp.), alder (*Alnus* sp.), birch (*Betula* sp.), and musclewood (*Carpinus* sp.) (graphic from Panshin *et al.* 1964).

vessels often obscures the ring boundaries, making ring identification in diffuse porous genera particularly difficult. These trees also produce a large number of vessels, but the vessels have nothing to do with the annual ring structure, are generally smaller, and can be randomly distributed throughout the rings. In some cases, 80% of the field of view is taken up with these vessels. Because the vessels are not associated with the ring boundaries, the cell wall thickness of the fibers should be examined to determine the ring boundaries, similar to analysis of non-porous species.

Reaction Wood

Trees growing on a slope or that are tilted will produce **reaction wood** to maintain or re-obtain their vertical orientation. Gymnosperms produce **compression wood** on the downhill side of the tree which is composed of thick walled and rounded tracheids. Angiosperms produce **tension wood** on the uphill side of the tree with reinforced cell walls acting to pull the tree up straight (Figure 4.18). The differing response causes the pith to be displaced upslope from center in a conifer and downslope from center in a hardwood tree. In cross section, the cell walls may be obviously thickened in compression wood (Figure 4.19), while in the radial view, spiral thickening along the outer surface of the tracheids may be evident in tension wood only under high magnification. I will demonstrate in Chapter 10 how reaction wood can be used to determine the date of mass movements such as landslides.

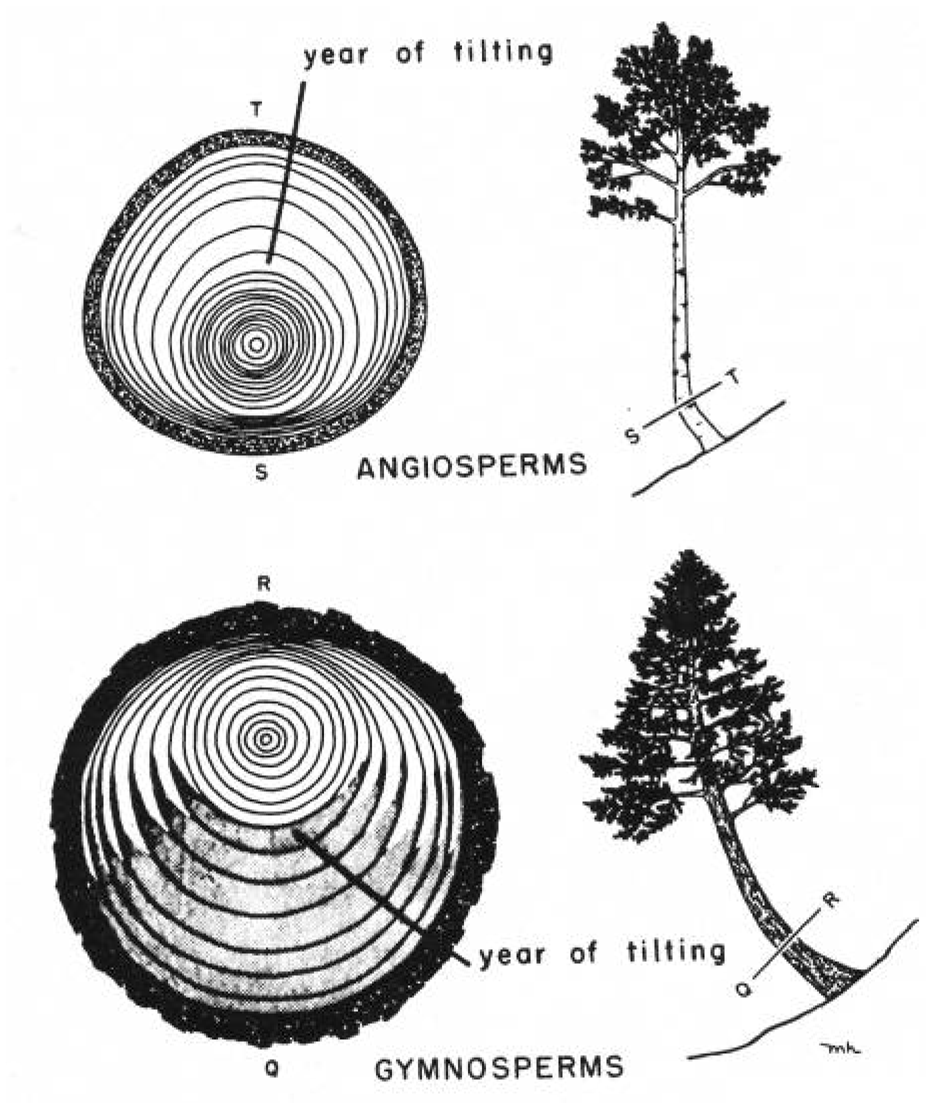


Figure 4. 18 Reaction wood. Angiosperms and gymnosperms react differently to the pull of gravity on a steep slope. Gymnosperms will produce compression wood on the downhill side of the tree to effectively push the tree back up straight, while angiosperms will put tension wood on the uphill side of the tree to pull the tree back up straight. Both of these types of reaction wood produce larger rings while smaller rings are produced on the opposite side of the tree. This reaction can be used to determine the date when a slope shifted causing the tree to react (from Fritts 1976).

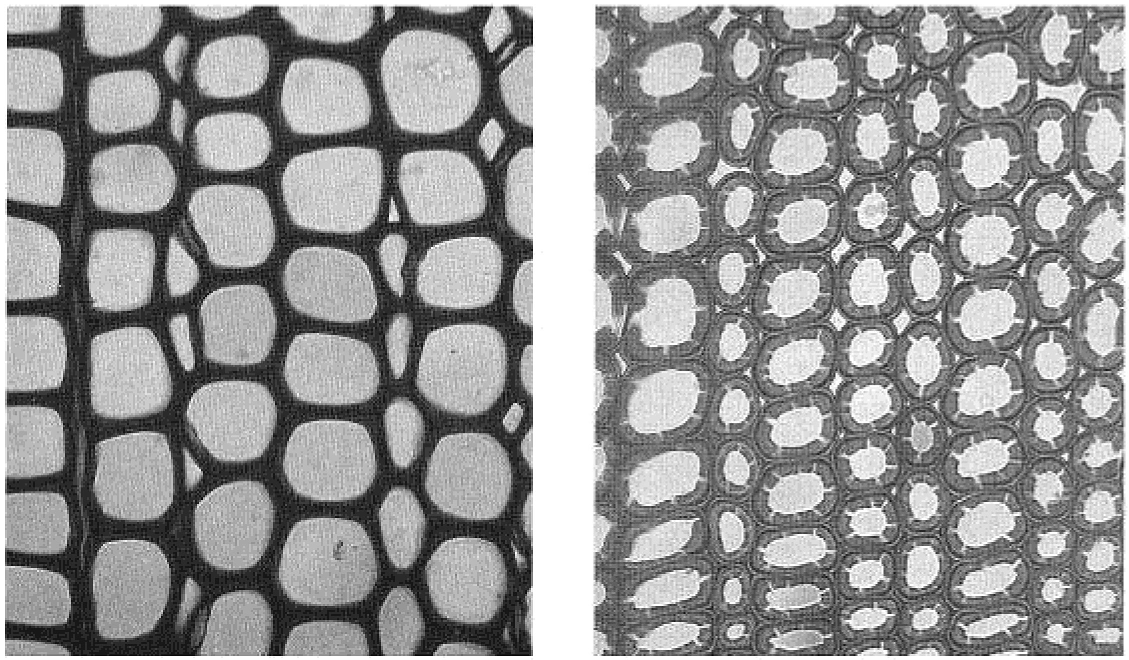


Figure 4. 19 Microscopic cross sectional view of compression wood in a conifer (right image). Note the cell-wall thickening of this pine compared to the normal cells in the image to the left (graphic from Hoadley 1990).

Growth Initiation and Absent Rings

Growth hormones (such as auxin and cytokinin) trigger cell division, cell elongation, and fruit development. During years of good environmental conditions, growth hormones are produced in abundance at the apical meristem and are transported down the stem in the phloem of the tree, initiating growth all along the cambium (Figure 4.20). In stressful years, however, insufficient growth hormone production may fail to initiate growth for some parts of the stem, especially near the base of the tree (Figure 4.21). The results of this phenomenon are locally absent rings that are only present in certain regions of the stem. Growth hormones tend to move from the tip of the branches to the tips of the roots so that a tree is more likely to be missing rings near its base.

Ring porous genera often produce vessels at the beginning of the growing season before leaf out, suggesting that these vessels develop from cambial derivatives which overwintered in an undifferentiated state. This phenomenon likely results in the observation that ring porous trees usually do not produce locally absent rings. However, ring porous trees can produce rings so closely packed together that it can be difficult (if not impossible) to differentiate the ring boundaries.

Growth Throughout the Year

Trees continue to growth throughout the year, with different parts of the tree developing at different times of the year (Figure 4.22). Krueger and Trappe (1967) examined growth in three different parts of Douglas fir trees. Most stem diameter increase occured from March through November, although some of that activity can be due to water draw up. Shoot elongation will

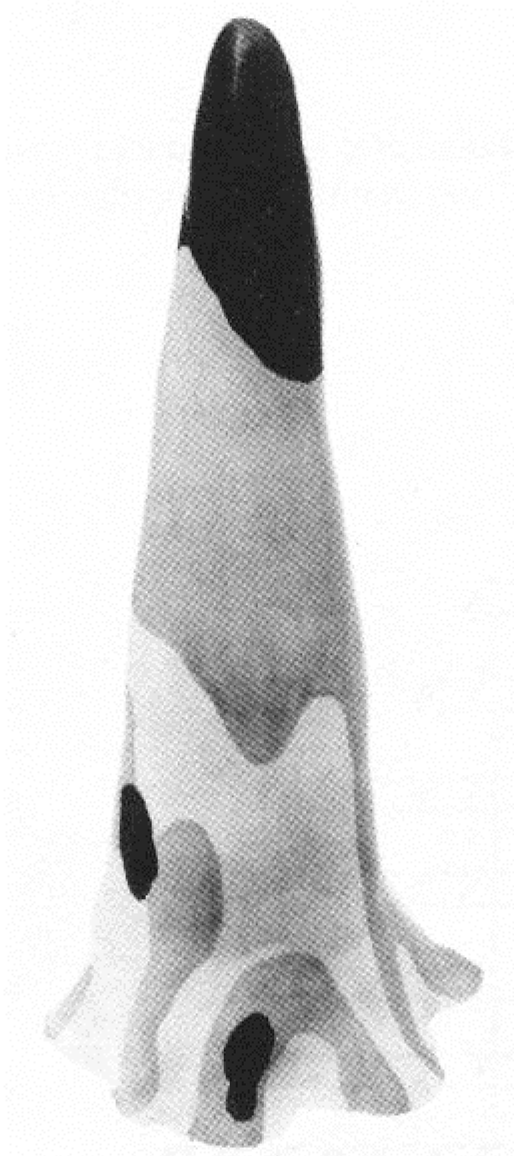


Figure 4. 20 The Auxin model of tree growth: the darker area at the top of the modeled stem is new auxin production whereas the lighter shades of gray represent past years of auxin production. Auxin is a growth hormone produced in the canopy of the tree. Auxin triggers cell division in the canopy driving the production of tree rings through secondary growth. In stressful years, not enough auxin is produced, resulting in a lack of secondary growth initiation, causing areas around the stem to not form a ring during some years. This also explains pinched rings around the circumference of a cross section (from Nogler 1981 as cited in Schweingruber 1996).

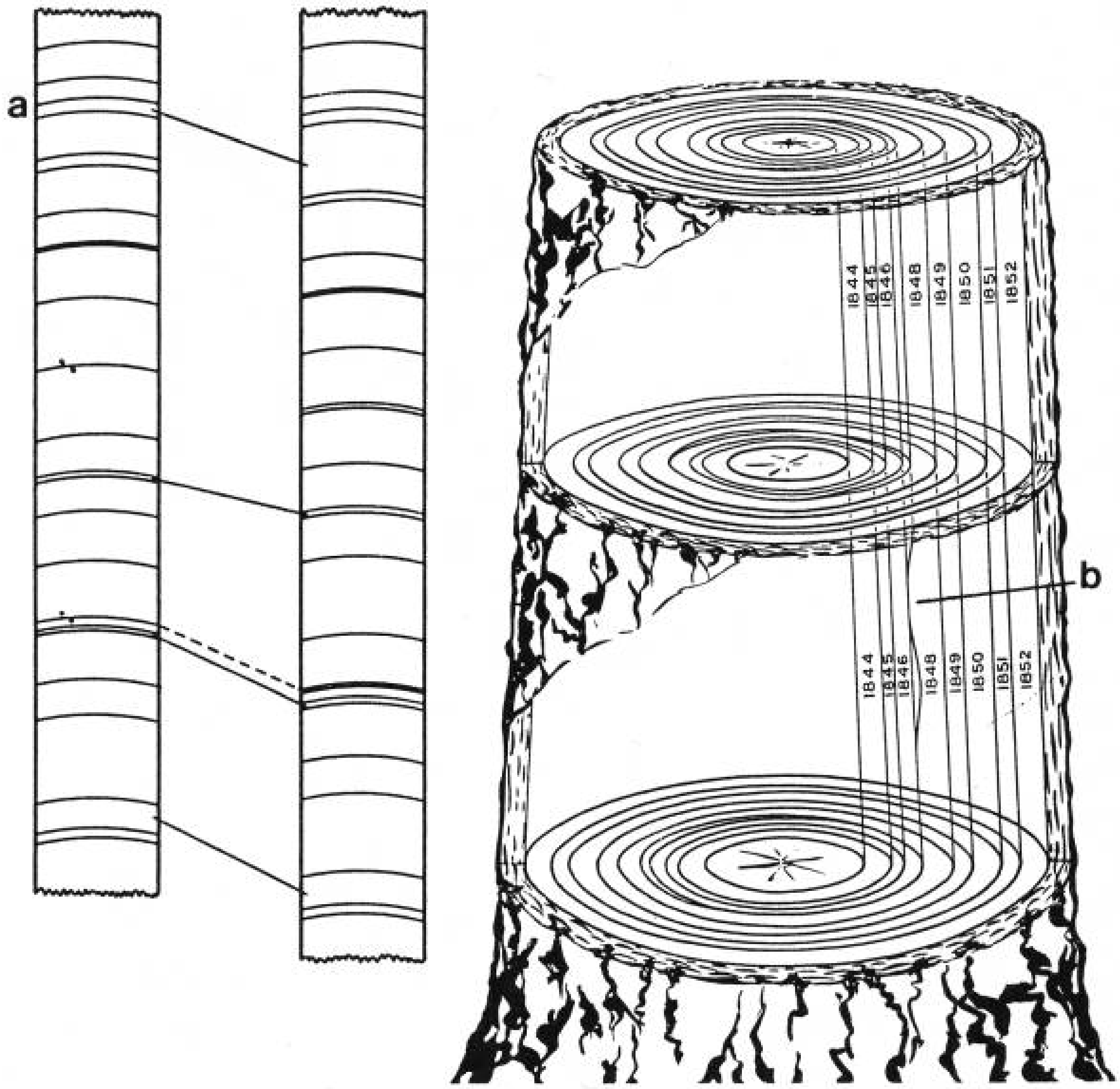


Figure 4. 21 Three dimensional ring production. It is important to think of tree ring production in three dimensions. Each ring is formed on the trees like a sheath wrapping around the stem. Based on the environmental conditions and the growth hormones produced in each year, a ring may be absent around a cross section or vertically from one section to another. The absence of rings is why crossdating is important for determining the complete chronology for each tree and stand (from Stokes and Smiley 1968).

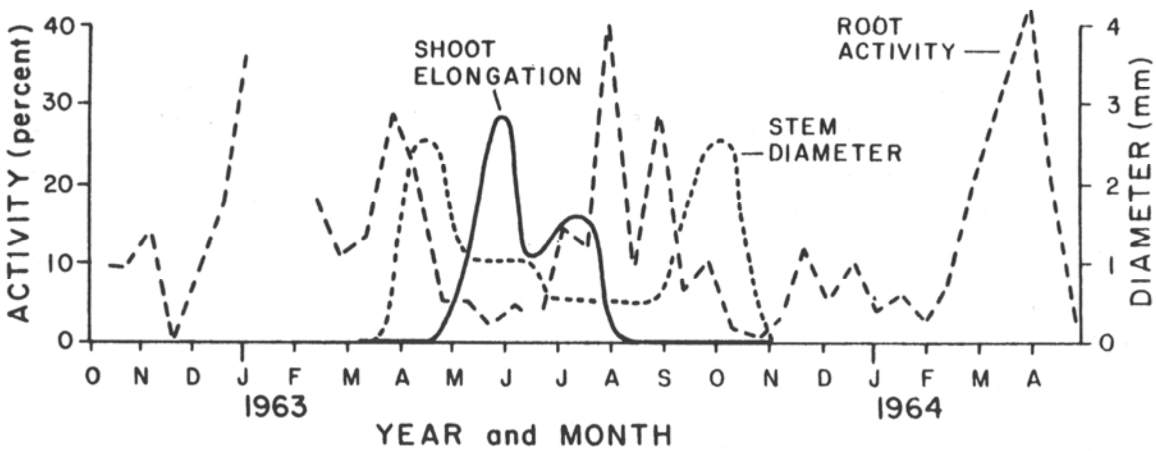


Figure 4.22 Tree growth throughout the year. Trees have the capacity to grow some part of the organism in just about any month out of the year. The measurements were made on growth of the stem, shoots, and roots on Douglas-fir trees (data from Krueger and Trappe 1967 graphic from Fritts 2001).

frequently occur over a shorter period of time (May through August in this example), but root growth can occur in just about any month of the year. This activity throughout the year, gives trees the potential to record climate from many different times of the year.

Ring Anomalies

Rings are produced in many different forms that may confuse a dendrochronologist, but close examination of a full cross section usually enables the appropriate identification of these problem rings (Speer *et al.* 2004). **Micro rings** can be produced that are only two cells wide, with one cell of earlywood and one cell of latewood in gymnosperms (Figure 4.23a). Micro rings are difficult to find on a cross section, but a well sanded surface and the aid of crossdating can help the dendrochronologists to locate them.

False rings occur when the limiting factors reduce growth rates and cause the tree to shut down during some part of the year; but then that limiting resource returns and the tree continues to grow. False rings can be used to record various environmental events such as severity of monsoon events in precipitation-limited climates. In northern Michigan, false rings have been documented as being more frequent in trees that are growing quickly and located in co-dominant or intermediate canopy positions (Copenheaver *et al.* 2004). In most cases, these false rings can be identified because the cell walls gradually thicken into a pseudo latewood, but then they gradually thin back out (Figure 4.23b). If you follow an individual **radial file** (a row of cells radiating out from the center of the tree that originated from an individual cambium cell), you will be able to observe this cell wall thickening into the false ring and then gradually the cell walls will thin back to earlywood cell widths. This contrasts with the abrupt transition in cell

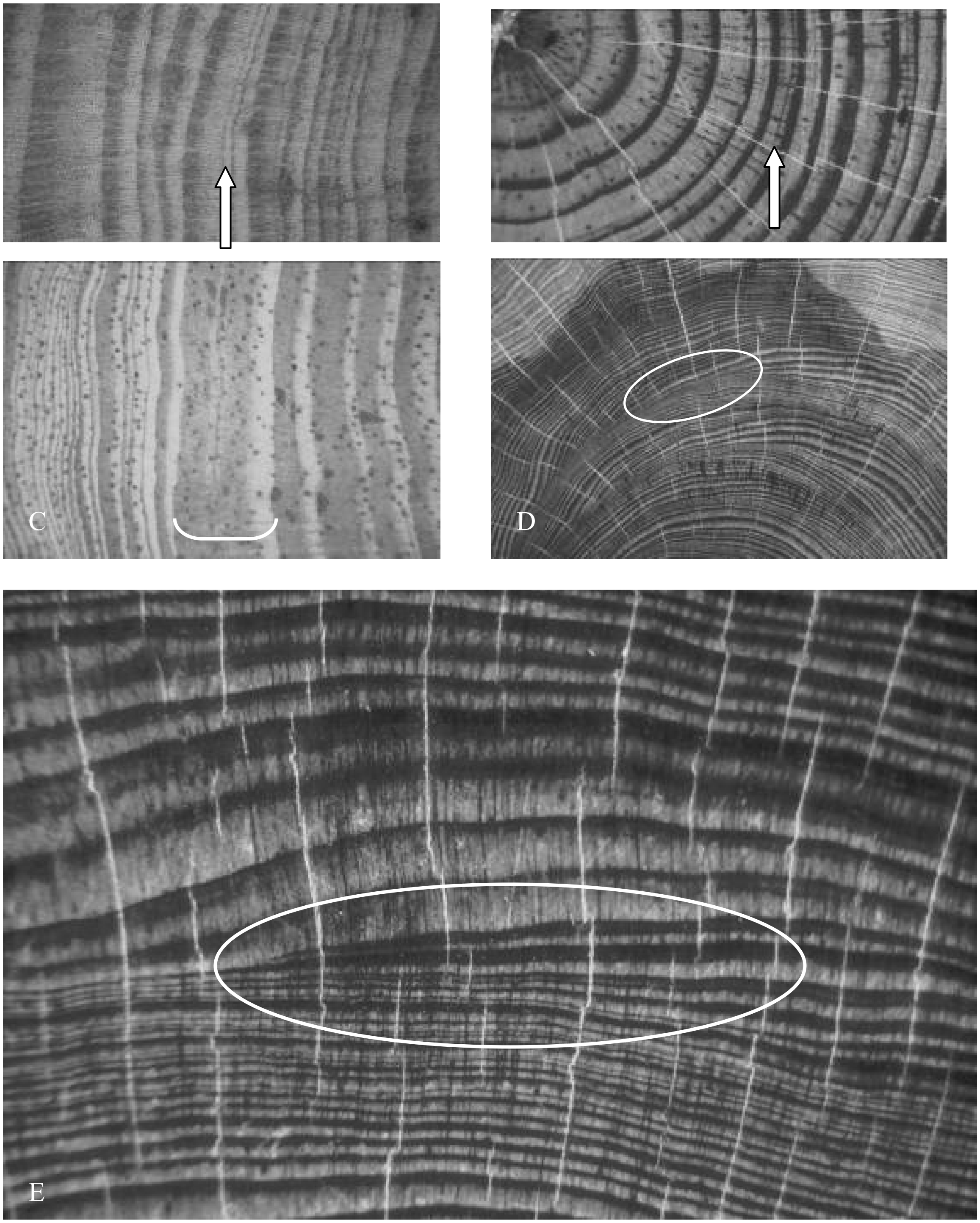


Figure 4. 23 Ring anomalies in *Pinus occidentalis*. Trees can produce a whole series of anomalous ring forms that need to be properly identified for successful cross dating. A) **Micro rings** may be only a few cells wide. B) **False rings** form when tree growth begins to shut down because of limited environmental resources, but starts again because of the return of input from the limiting factor. False rings can usually be identified in coniferous and diffuse porous ring structure, because the cell walls gradually thicken, appearing to be latewood, but then gradually

return to normal earlywood cells. It is useful to follow a radial file of cells through this false ring boundary. If you find a single radial file that does not complete the latewood but remains earlywood cells through this boundary, then it is likely to be a false ring. C) **Diffuse ring boundaries** arise when the normal process causing trees to go dormant for part of the season do not occur. The pictured sample is from the Dominican Republic at 19.5 ºN Latitude where trees are dormant during the January through March dry season, in other words, they stop growing because of lack of moisture. If a year has unusually high precipitation during the dry season, the tree is not forced to become dormant and continues to grow, producing a diffuse ring boundary and no clear distinction from one year to the next. D) **Pinching rings** are produced when the tree is damaged or nutrients are limiting so that growth is not initiated all the way around the stem. E) Five normal size rings pinch to very small size and some disappear completely. You can see that coring this tree at different locations will produce widely varying chronologies, making the use of cross sections necessary instead of cores (photos by Jim Speer).

wall thickness associated with a true annual ring. In conifers, if you can find one radial file that does not shut down completely, this is likely to be a false ring boundary.

Some trees (especially in tropical climates) form **diffuse ring boundaries** when growing conditions are optimal and the tree is never forced to cease growing for part of the year. Therefore, annual boundaries are diffuse without any real change in cell wall thickness between years (Figure 4.23c). Often the ring in the second year is composed largely of latewood cells because the tree never enters dormancy and it continues to produce thick cell walls in anticipation of the end of the growing season.

Dendrochronologists prefer to have **circuit uniformity** in the cross sections of trees that they examine. A well formed tree will have the same amount of growth around the circumference of the cross section that is cut from a stump of a tree, so that taking a core sample from any place around the stem will yield the same number and width of rings (See Chapter 5 for more details on sampling methods). When viewing the cross section, it should appear as a bull's eye target with a regular pattern of rings around the center (like Figure 1.2). Many tree species do not have **circuit uniformity** so care must be taken to collect measurements of what would be the average amount of growth for each year. Teak (*Tectona grandis*) wood and some juniper species (*Juniperus* sp.) produce a lobed growth pattern around its circumference so that it is difficult but not impossible for the researcher to determine normal growth on the stem of the tree (Figure 4.1). Some trees that do not exhibit circuit uniformity have **pinching rings** around the circumference of the cross section. In this case, one or more rings will pinch out so that two different cores from the same tree at the same height will yield vastly different ring counts (Figures 4.23d and

4.22e). If too many rings pinch out too frequently, it is very difficult, if not impossible, for the dendrochronologists to locate these missing rings, even with crossdating.

These ring anomalies can occur in any of the wood types (non-porous, ring porous, semi-ring porous, and diffuse porous), although I have never experienced absent rings in ring porous wood. Trees with ring porous wood structure conduct most of their water in the vessels in that single year of growth, although some water is transported in small-sized latewood vessels and tracheids in a relatively (compared to gymnosperms) reduced area of sapwood. Rings can be very small with little more than earlywood vessels produced over a series of years, making ring identification difficult (Figure 4.24).

Cell division is continuous along a radial file, but can occur at different rates around the circumference of the tree. The different rates of growth are not a problem when the ring is continuous around the circumference of a cross section, but when rays interrupt the rings it is possible for them to become misaligned. A dendrochronologist examining a series of rings in an oak tree, for example, should match the width of the rings on either side of the ray before visually crossing the ray to follow the rings on the other side (Figure 4.25).

Other ring anomalies may be found in the wood as well. Some of these are caused by environmental conditions and others are caused by interactions with other organisms. In the mid and high latitudes, **Frost rings** occur when the air temperature drops well below freezing during the growing season. There are two competing hypotheses about how frost rings form. Some suggest that frost rings can form when water freezes in the lumen of a cell and explodes the cell.

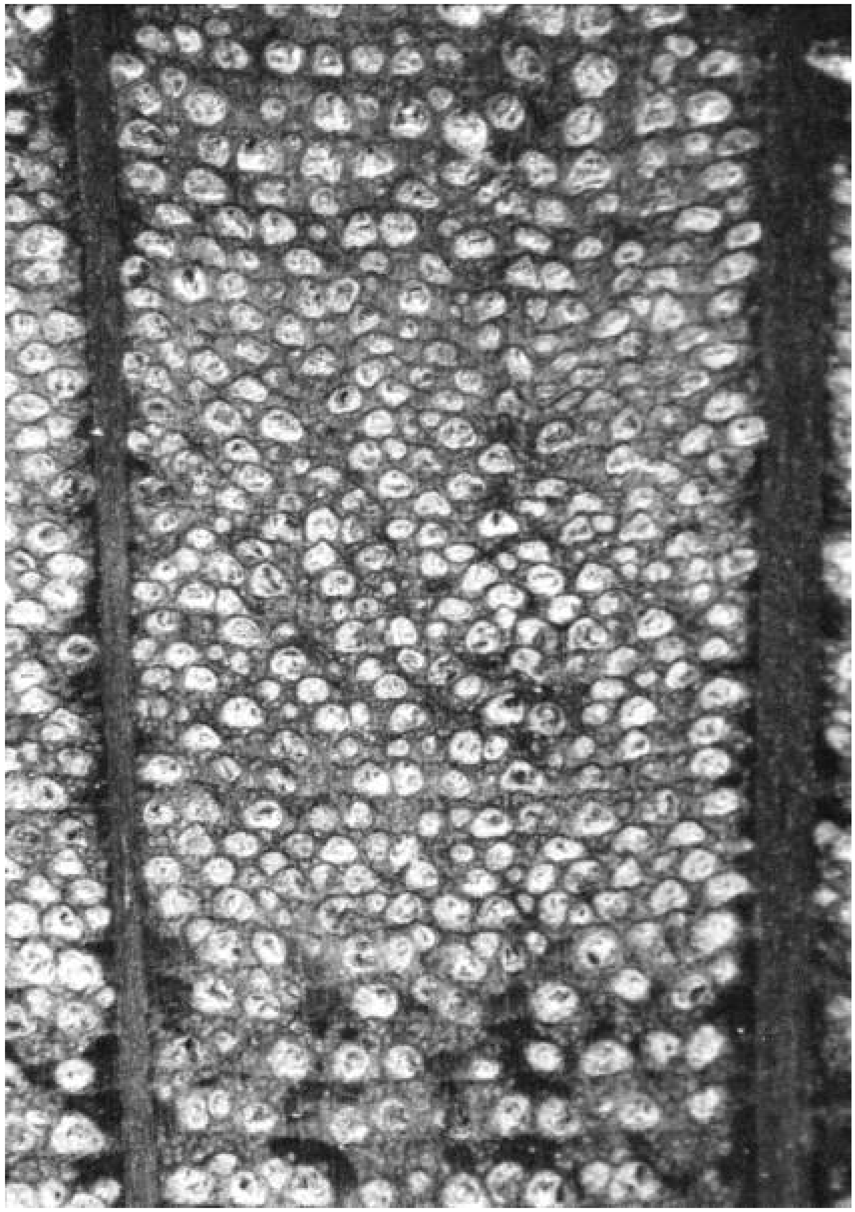


Figure 4. 24 Suppressed ring porous wood growth. Ring porous trees (in this case an oak) always produce pores at the beginning of the growing season, but those pores may be packed so tightly that the determination of ring boundaries is difficult. This section shows about 36 rings (graphic from Baillie 1982).

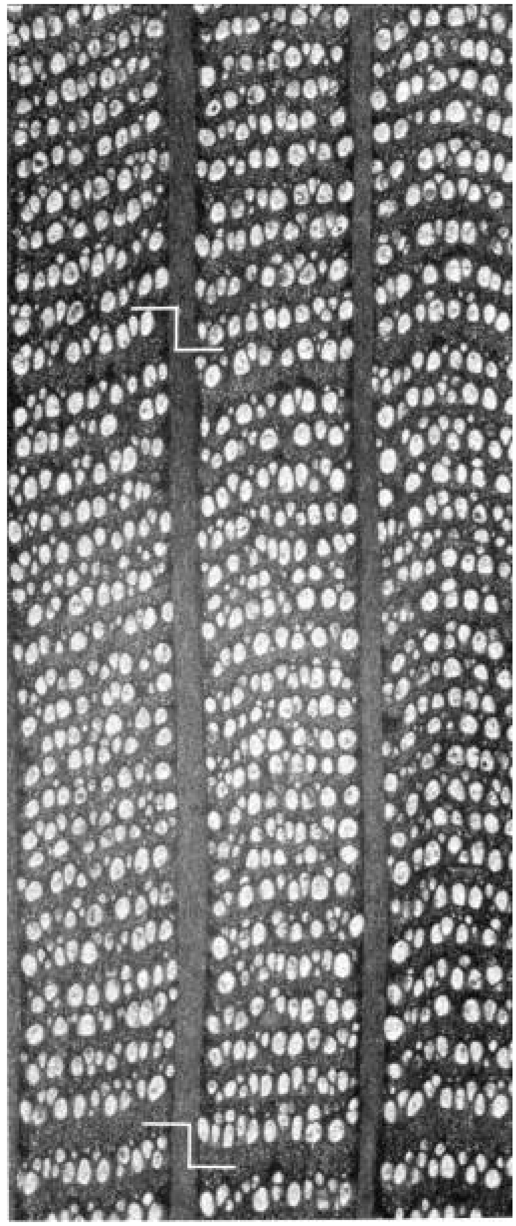


Figure 4. 25 Offset of wood growth across rays. Radial files produce cells at their own rate. When crossing a ray, it is possible for the ring not to be strictly aligned. It is, therefore, important for dendrochronologists to make sure that they follow the same ring when crossing a ray. This is done by a quick mental crossdating check to make sure that the ring widths are the same size on either side of the ray for a number of the surrounding rings (graphic from Baillie 1982).

Later, as the cambium differentiates, these crumpled tracheids get crushed producing a distinctive frost ring (Bailey 1925, Glock 1951) (Figure 4.26). Another explanation is that the water in the stem near the ground or in the ground itself freezes, but transpiration from the canopy continues to draw water, collapsing the outermost conducting cells that are not yet lignified similar to the collapse of a straw when drawing on a thick milkshake. These distinct frost rings can be observed in the wood of high elevation trees and, as we saw in the history of dendrochronology, can become important marker rings.

Some aphids suck sap from sieve cells damaging the cambium and producing **pith flecks.** They can be observed in the cross sectional view as a cluster of bubbly-textured wood (Figure 4.27). This aphid damage cannot be used as a marker ring unless it results from an unusual outbreak of the insect so that the damage makes a distinct marker ring that is synchronous between trees.

Fire scars are another distinctive anatomical feature that is caused by localized cambial mortality due to the high temperature of the fire. Charcoal is not necessarily a part of the fire scar as the scar is formed where the cambium was killed off, because of the high temperature of the fire. The bark will often slough off after the cambium has been killed leaving exposed wood. The living cambium on either side of the scar will then grow quickly, completing the scar structure in the tree. Fire scars can be identified based on distinct cellular characteristics (see Smith and Sutherland 2001). Living cambium cells on the edge of the dead cambium will differentiate at an accelerated rate to cover the injured area and seal off the damaged wood (Figure 4.28). This results in a distinctive growth curl after the fire scar occurred. Based on a close examination of the area where the scar occurs in the tree ring, dendrochronologists can

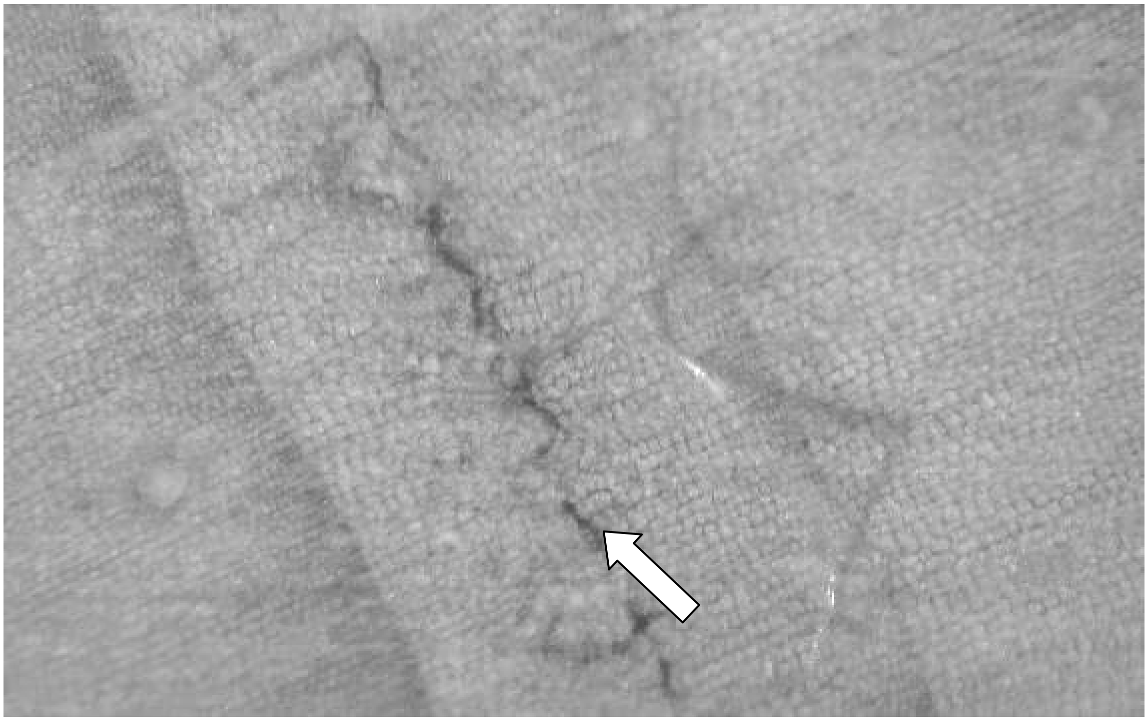


Figure 4. 26 Frost Ring. Frost rings occur when freezing temperatures are reached during the growing season. The cold temperatures make the water in the cell lumen expand and destroy the integrity of the cell walls so that the cells become crushed (photo by Jim Speer).

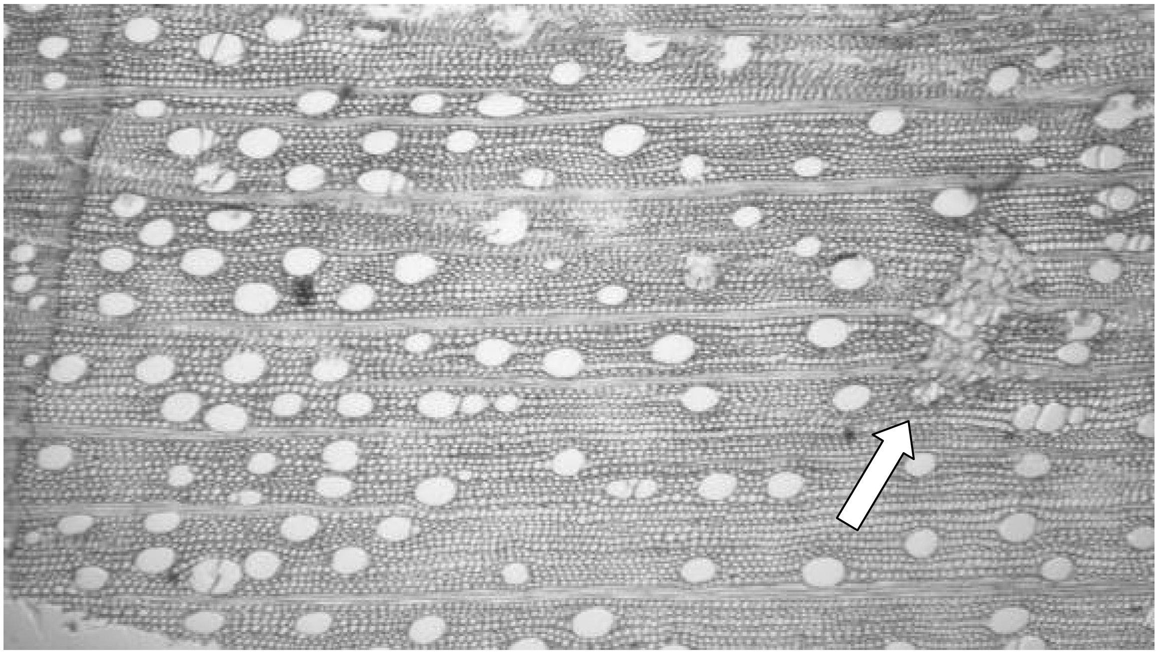


Figure 4. 27 Aphid damage to cells of a red maple (Acer rubrum) tree. The aphids are active in the cambium layer and move vertically up and down the tree, feeding on the newly developing wood and damaging the meristematic tissue (photo by Jim Speer).

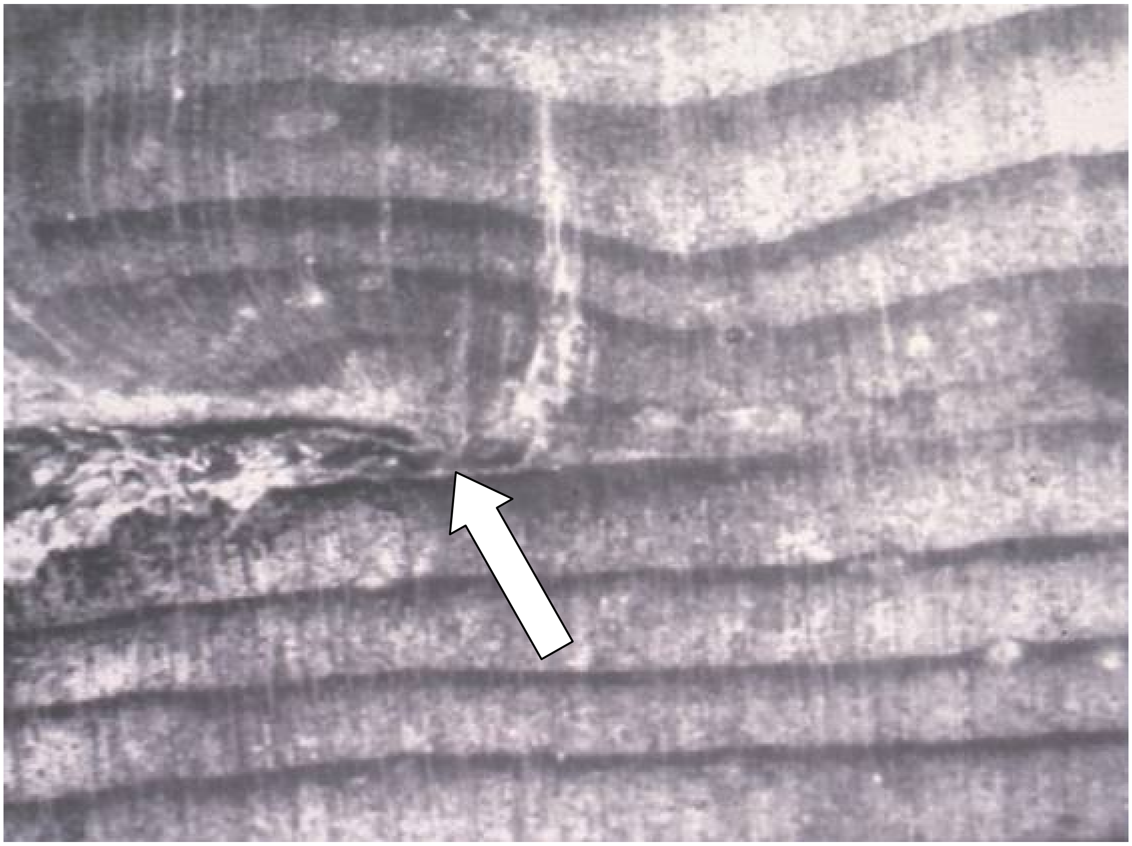


Figure 4. 28 Fire scar in ponderosa pine. From the left of the picture, the area where dead cambium meets the living cambium is visible. The accelerated growth of the living cambium cells creates the growth curl, healing over the injured area to the left (photo by Jim Speer).

determine the season of the fire, based on how much of the ring was developed before the injury (See Chapter 8 for more details). Multiple fire scares in conifers usually occur on one aspect of the tree because the wound caused by the first fire event makes the tree more susceptible to scarring by subsequent fires.

Summary

With this basic knowledge of wood anatomy, cell structure, and tree growth, you can start to analyze tree rings and to differentiate ring boundaries. We will explore sample collection and preparation in the next chapter. You will find that the most important process for identifying ring boundaries is to have a good polished cross sectional surface with which to work. The ring boundaries can only be identified if you are able to see the structure of each individual cell under the microscope. Therefore, before you analyze a sample you have to prepare the surface to the best of your ability.

Chapter 5: Field and Laboratory Methods

Introduction

Good research starts with well-planned and executed field practices. Two important components of field work addressed in this chapter are basic field methods for sampling dendrochronological projects, and designing your sampling scheme so that you can accurately describe the patterns observed in the environment. Field work will always bring up surprising circumstances and unexpected situations that you will have to adapt to in the field. While this chapter describes some basic field practices, modification of your sampling plans may be needed due to the field area and its specific challenges.

Gear

Before going into the field, you must assemble the gear that will be needed for sampling. The basic tools for dendrochronological fieldwork include at least two increment borers, straws in which cores are stored, map tube for holding cores and straws, diameter tape, permanent markers (like Sharpie© pens), golf tees or chop sticks for clearing wood stuck in a borer, a field notebook, rope, compact drill kit-rifle cleaning kit, digital camera, global positioning system (GPS), and a hand saw. Along with this basic gear, it is good to have a field vest to keep all of the gear organized. With these tools, you can sample most basic dendrochronological projects and travel relatively lightly. Your field equipment will change depending upon the project; for example, a stand-age structure study will require two 100m measuring tapes to lay out plots, while fire history may require a chainsaw to take cross sections. Table 5.1 gives a list of recommended field gear.

A golf tee is the perfect tool for removing small pieces of wood that may remain in the borer tip or for widening paper straws that might have been crushed. A bamboo skewer, chopstick, or dowel can serve the same purpose. A rope may be necessary to remove a stuck increment borer (see the Spanish windlass technique below). A digital camera is an important piece of equipment to record the site characteristics, tree characteristics, and field methods. WD 40 should be used to clean the increment borer, unless you are sampling for a chemical or isotope analysis. A sharpening kit (with a small wedge stone and a cone sharpening stone) should be on hand for sharpening dull or chipped increment borers. A cruiser pack (an empty backpack frame often used while hunting) with bungee cords is an excellent piece of equipment to carry out a large number of cross sections. Beeswax can be used to lubricate the increment borer when coring hardwood trees. When the borer is just removed from a tree, it is warm from friction. The beeswax can easily be melted onto the warm borer tip at this time. WD 40 can also be used as a lubricant and to break down excess sap when coring pitchy pine trees but should only be used when necessary. Fingerless gloves are recommended to obtain a better grip on the borer while leaving your fingers free for the delicate work of packaging a core in a straw. Finally, always carry lots of water, a first aid kit, and a two way radio for unforeseen issues that might arise in the field.

It is always important to take enough field notes to provide a complete site description for later publications that will come out of your work (see Appendix D for some sample field notecards).

Table 5. 1 Basic checklist of gear needed for dendrochronological sampling. Portions of this equipment will be needed for different field projects, but this list should provide a good foundation of the equipment that you might need.

Equipment	Project	Notes
Increment borer	All	Bring duplicates in case of breakage or jamming.
Map tube	All	For storage of samples
Straws	All	Paper or plastic
Permanent markers	All	Fine point and ultrafine point Sharpie© work very well
Diameter tape	All	Diameter at Breast Height (DBH) is a standard forestry measure that we often take as part of our tree description
Masking tape	All	For joining plastic straws or making minor repairs
Hand lens	All	To examine rings in the field
WD40	All	For cleaning increment borers and for lubrication
Beeswax	All	For lubrication and water barrier on borers
Hand saw	All	For taking small wood sections
Golf Tee, chopstick, or dowel	All	To remove pieces of wood from the tip of the increment borer
Long 9/16 inch drill bit with handle	All	For drilling out jammed wood. Do not use this from the cutting end and be careful of the cutting tip
Rifle cleaning kit for a 22 with cloth pads	All	For cleaning increment borers. Paper towels and the spoon can also be used to clean the borer shaft.
Weight lifting or bicycling gloves	All	Fingerless gloves for hand protection while preserving the dexterity of your fingers
Rope	All	For starting a borer or to remove a stuck borer from a tree with the Spanish windlass technique
Backpack	All	To hold all gear
Field vest	All	To provide easy access to the frequently used gear
Compass	All	For orienteering and field measurement
Knife	All	Always helpful, but don't use on the increment borer tip
Nylon climbing rope	All	Useful for the Spanish Windlass technique or to help with laying out plots.
Sharpening kit	All	For resharpening increment borer bits. Mainly used in camp on long field trips or in the lab between trips.
First aid kit	All	Always have one on hand for minor injuries and possible broken limbs
Camera	All	Very important for documenting field sites and field techniques
Topographic maps	All	Important for mapping sample locations and for orienteering
GPS unit	All	Important for mapping locations of field samples
Chainsaw	Fire History	For taking larger cross sections
Chaps	Fire History	Safety protection for the legs
Helmet with ear protection and face shield	Fire History	Safety protection for the head
Gloves	Fire History	Safety protection for the hands
Plastic wedges	Fire History	For keeping chainsaw cuts open when cutting whole sections
Scrench chainsaw tool	Fire History	Tool for work on the chainsaw
Round sharpening file	Fire History	For sharpening dull chainsaw blades
2 in1 fuel and oil can	Fire History	For carrying extra fuel and oil
Small pry bar	Fire History	To pry out cut cross sections
Plastic wrap or fiber tape	Fire History	To securely wrap fire history samples so that no pieces are lost and to protect delicate samples
Cruiser pack with bungee cords	Fire History	Empty frame pack for taking out many cross section samples
50-100m tape measures	Stand-Age Structure	For setting up plots
Boomerang increment borer handle	Optional	For coring on trees with deep fissures in the bark. This is a homemade item of a bent increment borer handle.
Increment borer starter	Optional	Helps you push the borer into the tree with your body mass

Much time and effort is often taken to get into the field and to locate a field site, so you should collect as much information as possible while you are in the field. The vegetation should be noted for the canopy as well as the shrub and even the herb layer as this understory vegetation can often give more information about the long-term moisture conditions on the site. Slope, aspect, and the location of trees relative to each other and prominent landmarkes are also important pieces of information that should be recorded. A global positioning system (GPS) is a good tool to locate and later map the locations of specific trees that have been sampled. Occasionally the importance of indivudal samples will require that the samples be tagged with permenant marking such as an aluminum tag that has been stampled with a specific sample identification number. In this case, it is good to carry a lightweight hammer and nails. A digital camera can also be used to collect data in the field and is a great way to record the appearance of the sampled trees.

A good case study of proper field techniques can be observed with the current effort to extend the bristlecone pine (*Pinus longaeva*) chronology further back in time (Tom Harlan personal communication). Individual trees in the White Mountains of California can live to be over 4,000 years old. Many previous sampling trips have provided a very long chronology from these amazing trees with such noted historical figures as Edmund Schulman, Val LaMarche, and Wes Ferguson having taken samples from this area. Today, Tom Harlan is trying to extend that chronology further back in time and is completing an exhaustive sampling protocol throughout the high elevation zones of the White Mountains. To locate the oldest samples, the researchers have documented the locations of past and current samples and mapped out the locations of old versus young samples. Currently they are trying to increase the sample depth between 6,000

B.C. and 10,000 B.C. By relocating previously sampled trees of great age and locating remnant wood in the correct time period, Tom Harlan has been able to continue to collect very old wood and extend the chronology back in time. While working on this project the researchers have found it difficult to relocate old sample due to poor field notes and proper archiving of those notes and the samples. Because of these difficulties the current project is very aware of the need for good notes. Every sample that is collected today is permanently tagged with a metal tree identification tag that is nailed into the wood. A photograph of the tree or log is taken with a white board stating the tree ID, its location in Latitude and Longitude (from a GPS measurement), the date of the photograph, and the initials of the field team collecting the samples. This quality of documentation ensures that the samples can be relocated in the future and that this chronology can continue to be developed.

Paper or plastic straws may be used to protect the core. Paper straws are hard to find and do not work very well under extremely wet conditions, but they allow the core to dry without molding. Plastic straws are convenient because they can be found at any fast food restaurant, but care should be taken to slit the straw so that the air can circulate. Masking tape may be used to hold plastic straws together or longer clear plastic straws can be used for longer cores. The clear plastic straws also allow cursory examination of the cores to see broad ring patterns or if the core is broken in many pieces. Plastic straws can also be sealed with a stapler or melted shut with a lighter depending upon your own preferences. Paper straws can be joined by pinching the paper straw against the core and then sliding, with a twisting motion, a second straw over the first. Plastic straws should be slit or a hole punch can be used to ventilate the cores so that mold does not form. Whenever a core is packaged in a straw, the straw should be labeled with a site designation (usually three letters) a tree number (usually two, sometimes three numbers), and an A or B for the first and second core taken from a tree. For example, a second core taken from the third tree sampled from Shakamac Park might be labeled SHA 03 B. The date, your initials, the tree species, and any other relevant field notes can also be recorded on the straw. Following the United States convention, the tree genus and species is noted with the first two letters of the genus and the first two letters of the species, for example *Pinus ponderosa* is PIPO.

Site Selection

Site selection is the first important consideration in choosing where to sample (see the Principle of Site Selection in Chapter 2). Often times the study area will be outlined by local land managers or by the goals of the research. Once the study area is determined, specific sites need to be chosen that will adequately represent the area and topic that is being examined. Individual sites can be chosen through a random selection technique to represent the broader landscape or targeted sampling can be used to explore specific signals.

Random Versus Targeted Sampling

When in the field, remember to use the principle of site selection and observe how the environment is likely to affect the site on which you are working. Most science consists of observing patterns, and from that, determining the process that drives that pattern. It is important, therefore, to observe the patterns on the landscape and to document those patterns in your field sampling. The sampling protocol may control what can be observed on the landscape, so researchers should be explicit about their sampling regime. Often, random sampling is used to facilitate extrapolation of conclusions to the broader landscape. Square or circular plots are randomly located to sample a representative area of the forest type. Random sampling locations in a field area can be determined either before you go into the field by using geographic information system (GIS) or Excel, or while in the field using a compass bearing and random number generator. Randomly choosing plots before you enter the field is useful because it removes the bias of the observer who gravitates, however unconsciously, toward "good" trees. Another advantage of choosing plots before going into the field is the ability to develop a stratified random sampling regime so that samples are spread out over different vegetation types. This method requires time spent in the field to locate the pre-chosen plots with a global positioning system (GPS). It is also possible to generate random samples in the field by finding a stand that you want to quantify, then randomly selecting a compass bearing and distance, using a random number generator for a number between 1 and 360 degrees and then from 1-100m distant. Once you locate the randomly generated spot, you can start your transect or plot at that point.

In many of the applications of dendrochronology, targeted sampling instead of random sampling is necessary. If your purpose is a climate reconstruction, the oldest trees located in the most climatically stressful areas should be targeted. This is because not all trees and all landscape positions record the same climate signal. We need to select trees that will be sensitive to climate, record a coherent stand level signal, and have the longest record available. Although a few young trees can also be sampled to make sure that the outer rings are well represented, because older trees may be suppressed on the outside. For surface-fire-regime fire history reconstruction, the specific trees recording the longest and most complete fire histories also need to be targeted. In this example, a general reconnaissance should be conducted so that the researcher knows the samples that are available in the field site. The trees that will yield the longest and most complete fire history based on a count of externally visible fire scars and wood preservation, should be sampled. Fire history in a stand-replacing-fire-regime can be sampled following the methods of a stand-age structure in which the establishment date approximates the age since the last fire (Heinselman 1973). Finally, if you are interested in gap dynamics in a dense forest, the gap making trees need to be targeted to acquire death dates and trees immediately within and responding to that gap should be sampled to record the date of gap occurrence.

Plots, Transects, or Targeted Sampling

Some basic decisions have to be made about how to sample the trees on the landscape. This decision varies based on the research goal. Circular and square plots work well for sampling a given area for stand-age structure. Circular plots are easy to set up from a given center point and a known radius and require fewer decisions about whether a tree is considered in the plot or out of it. Square plots are a little harder to lay out with tape measures and a compass, but result in plots which have a well defined sampling area. Transects functionally become long rectangular plots and allow you to sample across gradients (such as an elevation, aspect, or moisture gradient). A nested band transect is useful for sampling stand-age structure. For this type of transect, you can run a tape measure out 50m. Everything within 1m of either side of the tape should be cored at ground level. To increase the sample depth in the older age classes, all trees greater than 20cm diameter at breast height (DBH) within 2m of either side of the tape and all trees greater than 30cm DBH within 3m of either side of the tape should be sampled as well. These size categories will change depending upon the forest type being sampled and the purpose of the study.

Coring a Tree

The height at which you core a tree is dependent upon the question that you are asking. If you are interested in the exact age of the trees for examination of successional processes in a stand-age structure, the trees should be cored at the base so that the sample is taken as close to the point of germination as possible. This will yield the most accurate age of the tree. A number of problems exist with sampling this close to the root collar of the tree. Many trees have lobate growth at the base of the tree that is associated with root activity just under the soil. This irregular growth could confound a climate reconstruction. Also, it is harder to core a tree at the base where you are restricted to using your upper body strength to take a core. The increment borer handle can also hit the ground while trying to core at the base of the trees. To avoid this, one will often excavate an area at the base of a tree so that the handle can turn freely. Shorter borer handles can also be used to get closer to the base of the tree or a borer handle can be bent to create the "Brown Banana Boomerang Borer" handle (also known as the Quad B) that bends back towards the operator and allows the person coring to get closer to the ground or to core deeper in between large fissures in the bark. A power borer is also an option which uses a large chainsaw engine connected to a drilling attachment that converts the motion of the chain into torque like a drill. These machines can be dangerous as they create a lot of torque and they are not sold in most stores.

Heart rot due to root disease, basal injury, or browsing by animals is more likely to be encountered at the base of the tree than at breast height. Unless tree establishment dates are needed, we usually take cores at approximately breast height (1.4 m) even though the initial years of tree growth will not be represented because the tree would not have grown to breast level in its first years. Coring at breast height is advantageous because the whole body can be used to build momentum for coring, and the most common forestry measure in North America is diameter at breast height, so that samples taken at this height can tie into the extensive data and literature compiled by forest researchers.

The first question that most lay people and forest managers ask is whether coring the tree causes damage to the tree. The simple answer is yes, coring the tree opens up the tree to pathogens that can cause rot and discoloration in the tree, but the tree has natural defenses to combat injuries where the bark is broken. Many conifer trees will exude pitch into the core hole, sometimes even within a few hours, effectively sealing off the core hole. Angiosperm trees compartmentalize the wound by creating a barrier that stops the spread of fungus once it comes into the tree. The main issues associated with coring are that the researcher leaves behind a whole in the tree and is likely to cause some local discoloration of the wood around the bore hole. If the trees are of great economic importance, such as orchard trees, one can spray a fungicide in the bore hole until bark grows over the opening, but this is costly and takes a lot of time. It is possible to go back and find some of the original trees that A.E. Douglass cored in the 1920s and they are doing fine today.

Two cores should be taken from all trees sampled so that crossdating can begin at the tree level, in other words, the two cores from the same tree can be dated and compared with one another. More cores can be taken to obtain a solid core or to try to get older rings in a tree. When these two cores are averaged together, we have a better estimate of overall tree growth. If the tree is growing on a slope, the cores should be taken parallel to contour to avoid reaction wood in the tree. Conifer trees will produce larger rings (compression wood) on the downhill side of the tree to keep the tree growing upright. In hardwood trees, the larger rings (tension wood) develop on the uphill side of the tree, therefore, a core taken parallel to contour avoids the larger rings of reaction wood and represents the average ring growth at that height in the stem. Be careful when two people take cores from the same tree at the same time. The cores should be taken at different heights so that the increment borers do not meet inside the tree and damage each other.

To start an increment borer, push the bit of the increment borer into a fissure in the bark of the tree as you turn the handle in a clockwise direction (Figure 5.1). The fissure in the bark gives you a starting place and allows you to avoid coring through a thicker area of bark. Although, on trees located near roads, grit may accumulate in the fissures which could dull the increment borer. Starting a borer is an easy process in softwoods but can be exceedingly difficult in trees with smooth bark such as sugar maple and beech or in hardwood trees such as oak or hickory trees. To aid in starting a borer in hard trees, you can also use an increment borer starter, which consists of a metal plate that can be positioned against your chest and a shaft that fits into the opening on the increment borer bit at the handle. This allows you to push with your chest as you turn the borer by hand. The starter also helps you to make sure that you are coring straight into the tree, perpendicular to the stem. If you wobble as you core into the tree, you will cut an irregular core until the shaft of the borer is solidly seated inside of the tree.

Once the borer is started, the borer handle simply needs to be turned in a clockwise direction until the the tip of the borer has passed the center of the tree. You can measure how far you have

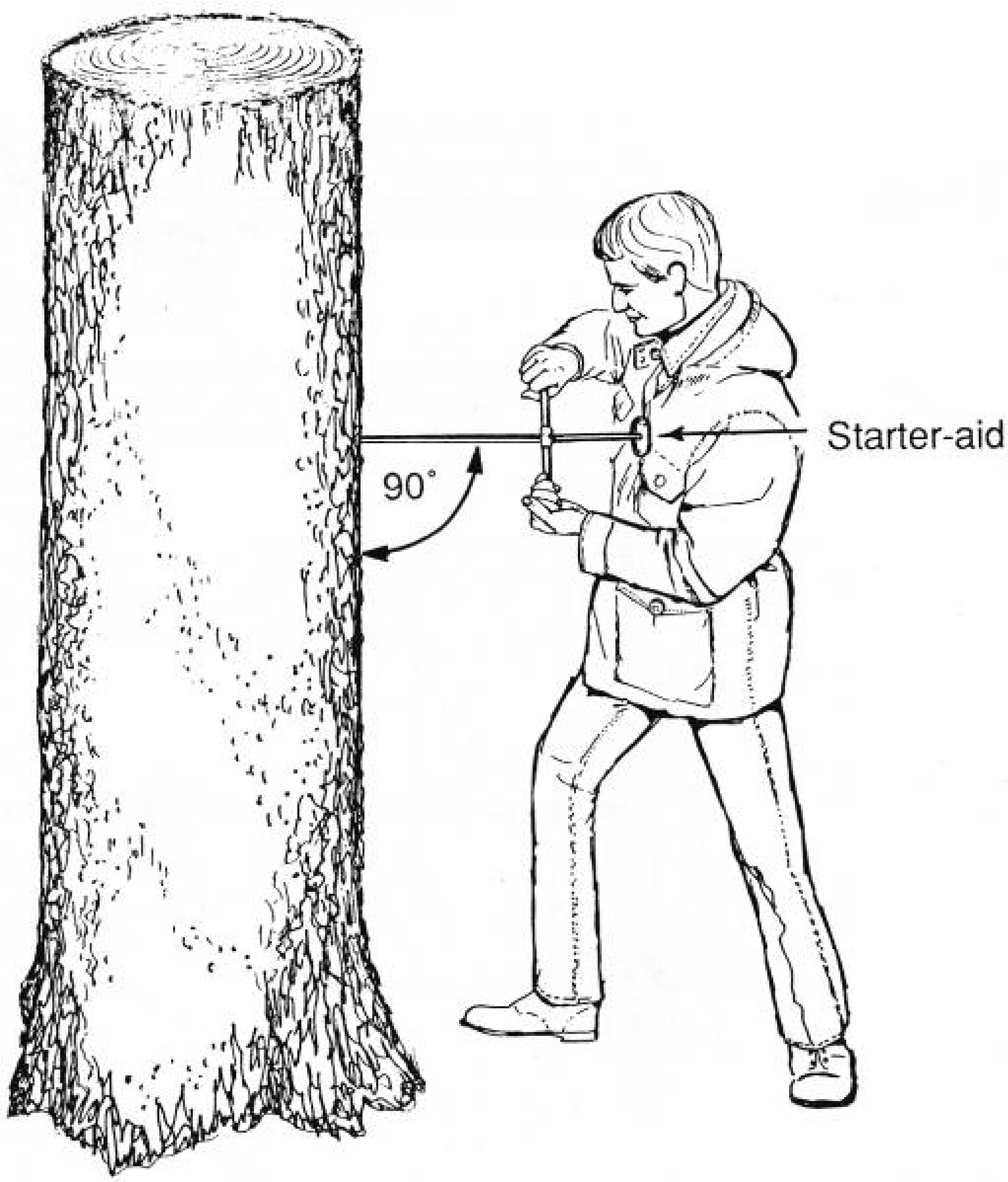


Figure 5. 1 Starting a borer. When starting an increment borer, push the borer into the tree with equal pressure on the shaft of the borer as you turn it into the tree. Starting an increment borer is especially hard on smooth barked hardwood trees. A starter may be used when coring a hard tree. It is made of a metal plate that can be placed against the chest and a shaft that is inserted into the increment borer bit at the handle. This allows you to push with your chest as you turn the handle of the borer (from Jozsa 1988).

cored into the tree by holding up the spoon so that the knob on the spoon is at the borer handle and see how far into the tree the borer has penetrated. With larger trees, this may take a second person standing back to observe if the spoon makes it to the half way point into the tree. You should always keep two hands on the borer handle and make sure that you provide even pressure along the shaft. Do not bend the increment borer shaft. As you core into the tree, feel the resistance to turning the increment borer. If the borer starts to turn easily, you may have cored into a pocket of rot in the tree and are at risk of getting the borer stuck. At this time stop and remove your core and then the borer from the tree. If, as you core into the tree, it becomes very difficult to turn the borer, more than you would expect from the friction of having more of the borer shaft in the tree, the core may be twisting up inside the shaft and you are at risk of a jammed increment borer. Stop and remove your core. A jammed borer usually is the result of a poorly sharpened bit but can be exacerbated by rot in the tree. It takes a lot of time to clear a jammed increment borer, so it is better not to get to that point.

Testing for a Compressed Core

It is possible to check the depth of your core in the shaft of the increment borer to see if it is jamming up. This procedure is only recommended when coring softwoods such as pine. If you stop coring for any period of time in the hardwoods, the wood fibers relax back on the borer and you risk breaking the borer when you start to core again. On a conifer, you can stop and push the spoon into the shaft of the borer until you feel resistance on the spoon, which means that you have hit the bark of the core in the shaft. Hold your thumb on the spoon at the opening of the shaft, marking the depth of the spoon in the shaft. Then carefully extract the spoon, making sure that you are not taking part of the bark with you. Put the spoon up to the tree bark along the increment borer shaft (Figure 5.2). The distance from the bark to the handle of the borer should be the same distance that you measured inside of the shaft for the depth to the core. If your marking thumb is one or more inches from the handle of the borer, then you have a jammed core and should remove the core and the borer immediately.

Taking and packaging a core

The increment borer bit cuts and pushes away the wood surrounding a pencil size core of wood inside the tree, so that once the borer is completely turned into the trunk, the only area of the core still connected to the tree is the inner disc of material just at the cutting tip (Figure 5.3). The inside shaft of the increment borer is tapered to a smaller diameter at the tip, so that the spoon, inserted into the shaft, is forced to pinch into the end of the core (Figure 5.4). When the increment borer is then turned in the counter-clockwise direction, the core is broken off inside the tree and can be extracted by pulling the spoon out of the borer shaft. At this point, the core is placed into a straw to protect it and maintain the proper order of any wood fragments that come out of the increment borer. The shaft of the increment borer should be used as a third set of hands holding your core while you package it in a straw (Figure 5.5). Remove the spoon only far enough out of the shaft to slide the exposed core into the straw. Pinch down the end of the straw to seal the core in the paper straw or use masking tape to close plastic straws. Do not simply fold over the end of the paper straw or leave the tape as a flagged end. That flagged end will become stuck on other cores in the map tube and take up more space than is needed. The straw is then labeled with the site designation, the tree number, and the side of the tree that the core is taken from (usually coded as an A or B core). Once the cores are neatly packaged in a straw they should be placed in a map tube to protect them from breakage or getting lost. Remember that

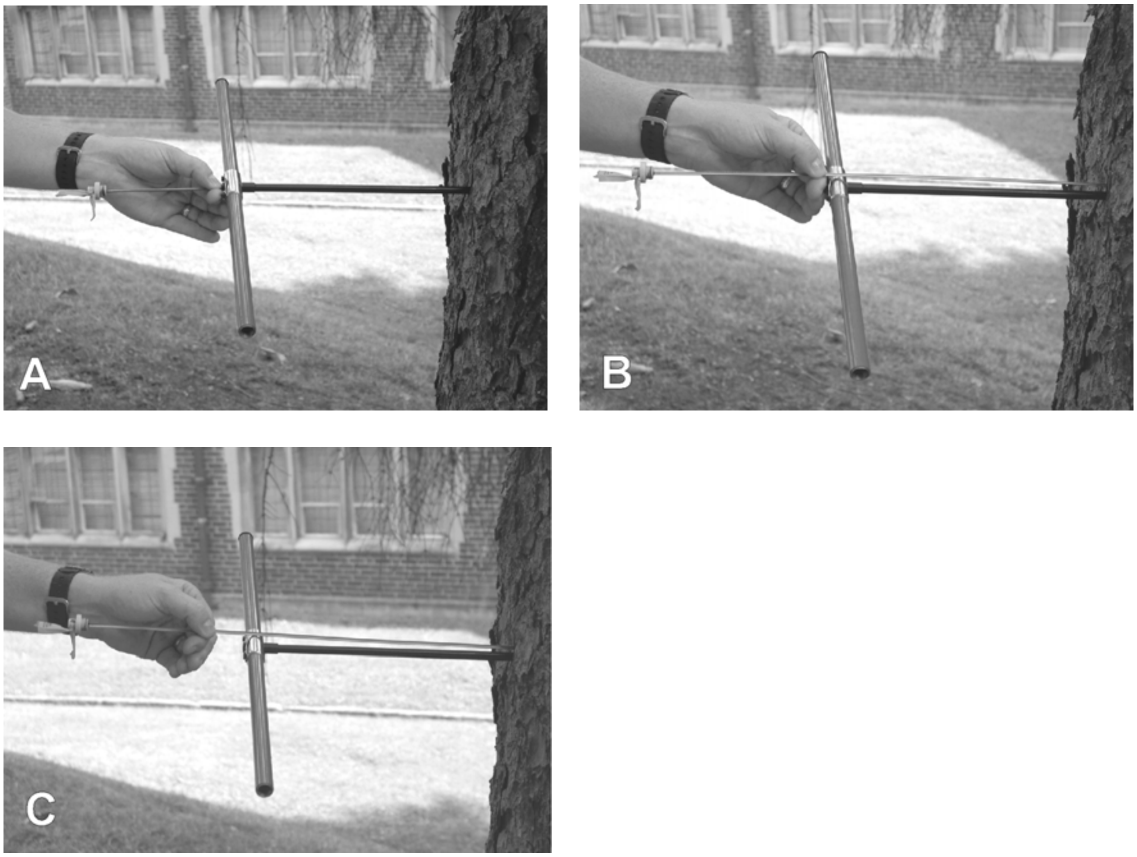


Figure 5. 2 Measuring for compressed wood in an increment borer. In pine trees, you can use the spoon to measure if the wood of the core is binding up inside of the increment borer shaft. In the image, you can see that the thumb marking the depth of the core in the shaft is about 2 inches from the handle, when measured against the tree in image C. This means that the core has twisted and jammed up inside the borer and should be removed immediately (photographs from Henri Grissino-Mayer; Grissino-Mayer 2003).

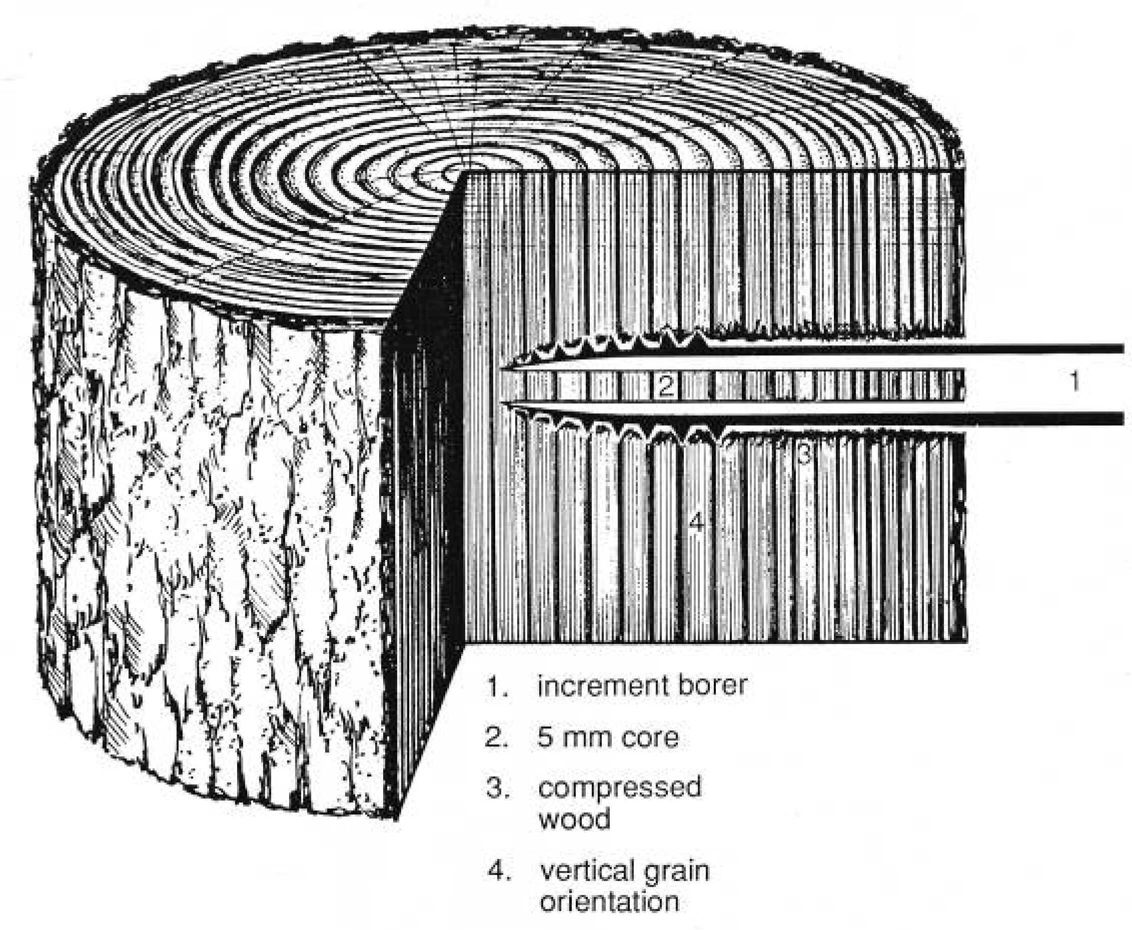


Figure 5. 3 Coring a tree. As the borer is turned into the tree, it cuts away the wood around the increment borer and compresses the wood away from the borer. The core stays in its original orientation and fills the borer as you core into the tree so that when you extract the core, you have a full sample of rings from the bark to the pith (from Jozsa 1988).

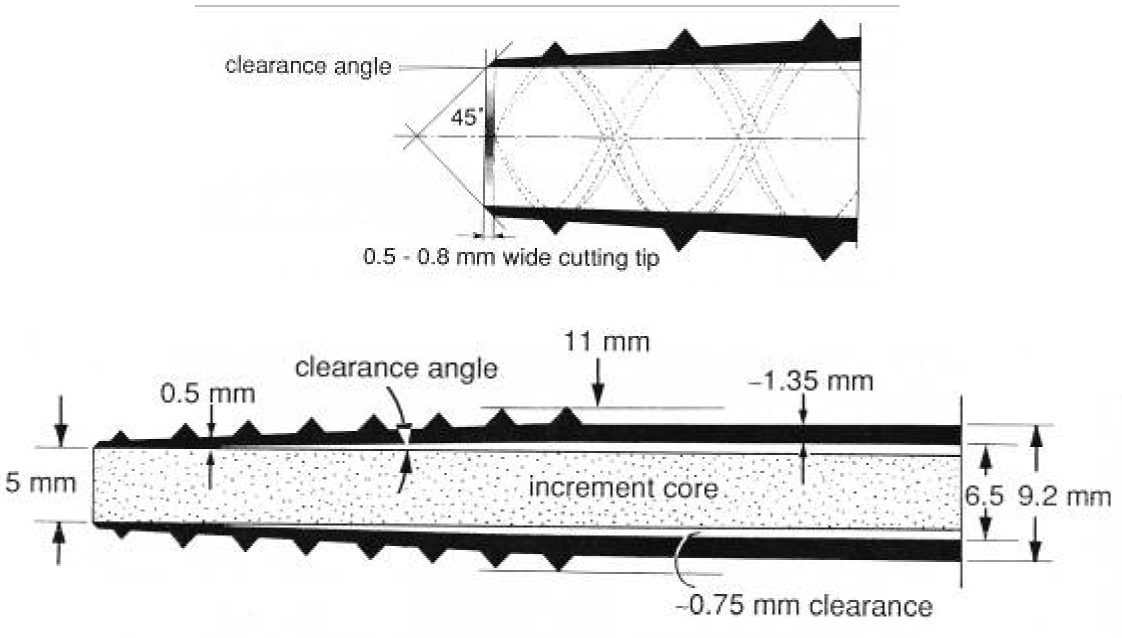


Figure 5. 4 Tip of an increment borer. The tip of the increment borer shaft is tapered so that the diameter of the core is smaller than the diameter of the inside of the increment borer. This allows the spoon to pass by the core and to pinch into the core near the pith of the tree (from Jozsa 1988).
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Figure 5. 5 Extracting a core. To extract the core from the tree, turn the borer a half turn in the counterclockwise direction, which breaks the wood off inside the tree, allowing you to pull the core out with the spoon. Once you extract the spoon with the core on it, slide paper or plastic straws over the core from the bark end. It is easier if you leave the core in the borer so that only a few inches of the core can be seen while you slide the straw over the core. The shaft of the borer acts as a third set of hands and reduces the possibility of losing pieces of the sample (photo by Jim Speer).

plastic straws should be slit to ventilate the cores and to keep mold from forming. These cores can be removed from the map tube at the end of the day and bundled together in newspaper or with string so that they can air dry. Once the cores have been bundled in newspaper, I have found that cores can be placed on the dashboard of the field vehicle to help them dry out.

Removing an increment borer from the tree

When removing the increment borer from the tree, turn the borer in a counterclockwise direction. The borer should gradually come out of the tree as you turn it. A borer may become stuck in a tree if left too long because the wood that was pushed out of the way will relax back on the shaft of the borer. If this occurs, apply a sharp backward jerking force on the borer as you turn the borer counterclockwise so that the spiral threads of the borer bite back into the wood of the tree (Figure 5.6). As a last resort, a rope can be used to create a Spanish windlass to remove a stuck borer. Note that the clip that keeps the handle of the increment borer connected to the shaft can vibrate loose or come undone. Be very careful when pulling back on the increment borer handle to make sure that this clasp is engaged or the handle can come off in your hands which could be dangerous when coring on steep slopes. Some tape or a rubber O-ring can be used to make sure that this clasp does not come loose.

Cleaning an Increment Borer

Increment borers are made out of metal and are susceptible to rusting. If the borer shaft becomes rusty, the metal will be weakened and the cutting edge can be pock-marked from the break down of the metal by the rust. To avoid these problems, increment borers should be cleaned with a

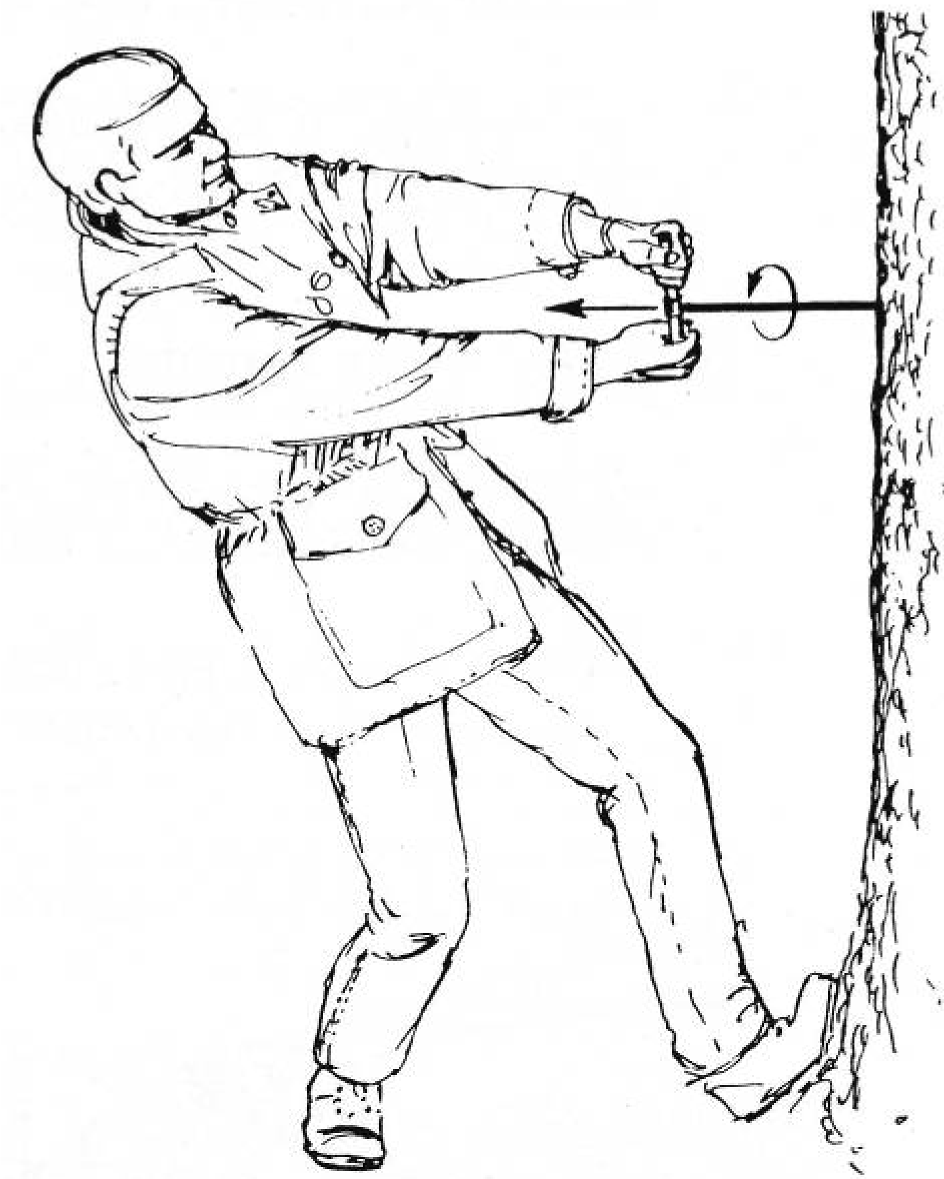

Figure 5. 6 Extracting the increment borer. Normally you can extract an increment borer by turning the handle in a counterclockwise direction with equal pressure along the shaft of the borer. When the borer becomes stuck in a pocket of rot, you have to pull and turn at the same time while being careful that the handle clip on the borer shaft does not release resulting in a backwards fall (from Jozsa 1988).

dewatering agent (such as WD-40©) and paper towels or steel wool. A .22 gun cleaning kit can be used to clean inside the shaft of the borer, but one should take care not to push the brush to far past the cutting edge or it may be damaged. I prefer using the spoon of the increment borer with a postage stamp sized piece of paper towel wrapped around the teeth of the spoon. The cleaning agent should be sprayed along the outside and inside of the shaft with special attention paid to the tip of the borer. Then the paper towels can be run up and down the inside of the shaft. The papertowel usually comes off of the teeth of the spoon and then can be pushed out the cutting end of the borer (as long as the piece of towel is not too large). I repeast this process until the paper towel coming out is clean. This cleaning process should be done at the end of each field trip as a minimum and could be done at the end of each field day, especially if you are coring trees that tend to be moist such as in the eastern deciduous forest in the spring.

Sharpening an Increment Borer

The tip of increment borers become dulled through regular use and could become chipped if they encounted a rock or some metal. This cutting edge is the most important component in getting a good straight core without many breaks or twisting. The tip should be inspected regularly through a microscope or with a hand lense to check its condition. Increment borers can be sent for professional sharpening, but they remove so much metal that this can only be done 2-3 times before so much metal is removed from the tip of the borer that the borer can no longer be used. A sharpening kit can be purchased from the forestry catelogs or at some better hardware stores. The kit should include three whet stones (a rectangular, wedge, and conical stone) that are about three inches long and some honing oil. Increment borers can be sharpened at the microscope so that you can closely watch how you are affecting the cutting edfe of the borer or you can work on the borer in your lap and check the cutting edge periodically in the microscope. Sharpening the tip of an increment borer is a delicate process and it is best if you can get some instruction from someone who is skilled at it, but I will describe the general procedure below.

The rectangular stone is only used in dire circumstances where the tip of the increment borer is chipped. The tip of the borer must be worked back below that chip. Remember that the tip of an increment borer is tapered so that the core that is cut is a smaller diameter than the inside of the borer shaft. This allows the spoon to pass by the core and attach at the tip of the core so that it can be removed. If you sharpen the tip of the borer back too far, you remove this taper and ruin the borer. Put some honing oil on the whet stone and holding the stone perpendicular to the shaft, rub the stone back and forth to grind down the tip past the bottom of the chip in the cutting edge. If the chip is more than $1/8^{th}$ of an inch deep, then the borer will not be able to be fixed.

Under normal circumstances with a dull borer that does not have chips out of the tip I start with the wedge stone to sharpen the tip and the threads of an increment borer. The stone should be help at a 37-45 degree angle to the axis of the shaft. A 37° angle will make a sharper borer, but it will not hold its edge as long. A 45° angle will hold its edge longer, but it may be harder to start in some wood types. The wedge stone should be used to sharpen the outer bevel of the cutting tip while the borer shaft is continually rotated. You do not want to hold the borer steady and work back and forth on one part of the cutting tip, because the cutting tip is a circle and you will wear down one side. So through constant rotation of the borer shaft and swiping the wedge stone in the opposite direction of that rotation, you can sharpen that rounded edge. You can apply some pressure as long as you are careful to be consistent in the amount of metal removed around the circumference of the cutting tip.

The conical stone is only used to remove the tiny metal burs that are bent into the shaft during this sharpening procedure. Insert the conical stone into the end of the cutting tip and gently rotate it to remove these burs. You are not really sharpening the inside of the cutting tip; only the outer edge does the cutting and you do not want the conical stone touching all of the inside edge of the cutting tip at any time. If you put too much pressure on the cutting tip and force the conical stone into the tip, it will flare out the tip of the borer, ruining it. Only a little work with the conical stone is needed and then the cutting edge can be checked for sharpness.

You can look at the cutting tip through a microscope and you should see the shiny metal surface where you just sharpened around the cutting tip. To check the sharpness of the tip, you can use *many* layers of paper towel and turn the tip of the borer on the towels. It should cut out a series of small disks of the paper towel. If it does not, then the borer is not sharp enough. This test should be done carfully, because if the borer is sharp and you don't use enough paper towels, you will cut little disks out of your finger which is not a pleasant experience.

The threads of the borers can also be sharpened in similar maner to the tip of the increment borer. Use the wedge stone and constantly rotate the borer while running the wedge stone in the opposite direction along the edge of the threads. You will need to do this on both sides of the threads and remembers that increment borers have either two or three threads that will need to be sharpened.

When you are done, both the cutting edge and threads should be sharp and you should take care in handling the increment borer. It is easy to cut you finder tips on the sharpened threads. It is also easy to damage you newly sharpened tip, so be carefull as you return the increment borer shaft to the handle of the borer for storage and always be carefull when you are coring in the field to make sure that grit and stones do not come in contact with the tip of the increment borer.

Spanish Windlass Technique for Retrieving a Stuck Borer

A borer may become stuck in a tree if you encounter a pocket of rot or if you leave the borer in the tree for too long. If you cannot get the borer unstuck by pulling and turning the handle, you can use a Spanish windlass to remove the stuck borer. I should note that this technique can be very dangerous as much tension is put on the rope and the increment borer handle during this procedure, so the utmost caution should be exercised. For this procedure, you need to have a tree directly behind you and a rope. Take the rope and wrap it around the handle and clip of the borer, making sure that the clip will not release prematurely. Then take the rope and wrap it around the tree directly behind the borer. Bring the end of the rope back and tie the rope to itself (Figure 5.7). You have now made one continuous loop of rope linking the tree and the borer. As you turn the borer, the rope will twist and shorten, eventually providing the backward pressure needed to remove the borer from the tree. There is a high amount of pressure pulling the borer out of the tree, so when the borer bit gets into the bark, the borer will be forcefully pulled from the tree. Hold onto the borer handle and be careful you do not get hit by the handle or the bit of the borer. Make sure that you do not let go of the handle of the borer because the borer can fly through the air in an uncontrolled fashion and possibly hurt someone or damage the increment

Figure 5. 7 Spanish windlass. The Spanish Windlass technique uses the force generated from a twisting rope to provide backward pull on the increment borer, enabling you to remove a stuck borer from a tree. You need to connect the rope around the handle of the increment borer and a tree directly in line with the increment borer, then twist the handle of the borer counterclockwise. The increment borer will come out of the tree quickly when most of it has been rotated out of the tree, so be careful with this technique. You should keep a tight grip on the borer to control it as it comes out so that you or the borer does not get hurt.

borer bit. Some researchers will release the tension on the windlass before the borer leaves the wood, but be certain that the borer bit is in solid wood at this point so that you do not have to go through the process of retying the windlass.

Laboratory Methods

Once the cores are brought in from the field in their paper or plastic straws, the laboratory work begins. This consists of preparing the wood by drying, mounting, and sanding the cores, and then analyzing the cores through such methods as skeleton plotting, and measuring. Chapter 6 discusses the analysis of wood using computer and statistical methods.

Preparing Core Samples

While the cores are still in their straws, they can be dried in a drying oven for 24 hours at 60°C, for a week in a fume hood with continuous airflow, or for 20-25 seconds on high in a microwave oven. If you are lucky enough to live in a dry climate, cores can also be air dried as long as the plastic straws are well ventilated. If the core is immediately glued to a mount when it is still wet, it will develop cracks as it dries and shrinks, making it hard to be certain that no wood was lost in the field. Drying the cores on too high of a temperature may cause some wood types to twist. Also if the research project is examining wood chemistry or isotopic analysis, a high drying temperature may volatilize some chemicals in the wood.

Once the core is dried, it is mounted on a prefabricated wooden core mount (see Stokes and Smiley 1968; Phipps 1985 for a review of laboratory techniques). The best mounts are narrow enough to view two mounted cores side-by-side in a stereozoom microscope at 20X magnification. Professionally manufactured core mounts can be purchased that are made from poplar wood and measure 1.25cm X 0.75cm X 1.2 m in size. The mounts have a half circular groove routed into them to take the 4.3 and 5.15 mm cores that are the standard dimension of increment cores. The cores should be mounted using water soluble white glue so that the cores can be removed from the mount and remounted, if necessary, by soaking them overnight in a water bath.

Mounting cores. Before the core is mounted, all of the information from the straw should be copied on to the core mount. This should include the sample ID, the tree species, the date the sample was taken, and the initials of the person taking the core. Once the mount is prepared a line of glue can be extruded into the core mount groove and the core can be carefully mounted in the groove. The core has two cross sectional views and two radial views. Imagine the circular core squared on four sides: two opposite sides are cross sectional views and two are radial views (Figure 5.8; see chapter 3 for a description of these wood sections). Care must be taken to mount a cross sectional view facing up, otherwise the ring boundaries may not be evident after sanding. The radial view of the core is often seen as being coarse because of the torn tracheids, or shiny because of the side view of the long tracheids (Figure 5.9). Also, the tangential view can be examined to align the tracheids so that their long axis is mounted vertically. String, binder clips, masking tape, or heavy weights can be used to hold the cores in place as the glue dries (Figure 5.10). If you do not restrain the core, it will soak up moisture from the glue and curl out of the core mount. The glue will usually dry in about two hours. I personally prefer using string as it allows you to pull the core tightly into the core mount and is flexible enough to provide pressure

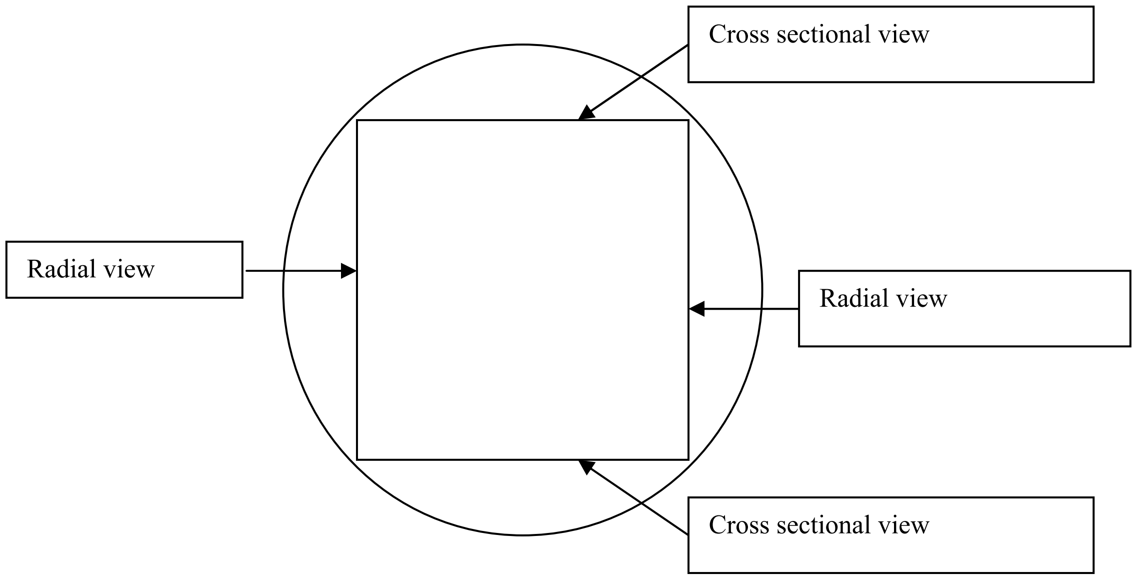

Figure 5. 8 Schematic of the different sides of a core. The circle represents looking at the end of a core, where the core has two cross sectional views and two radial views. The researcher must take care to mount a cross sectional view facing up in the core mount, or the rings will not be clear (drawing by Karla Hansen-Speer).

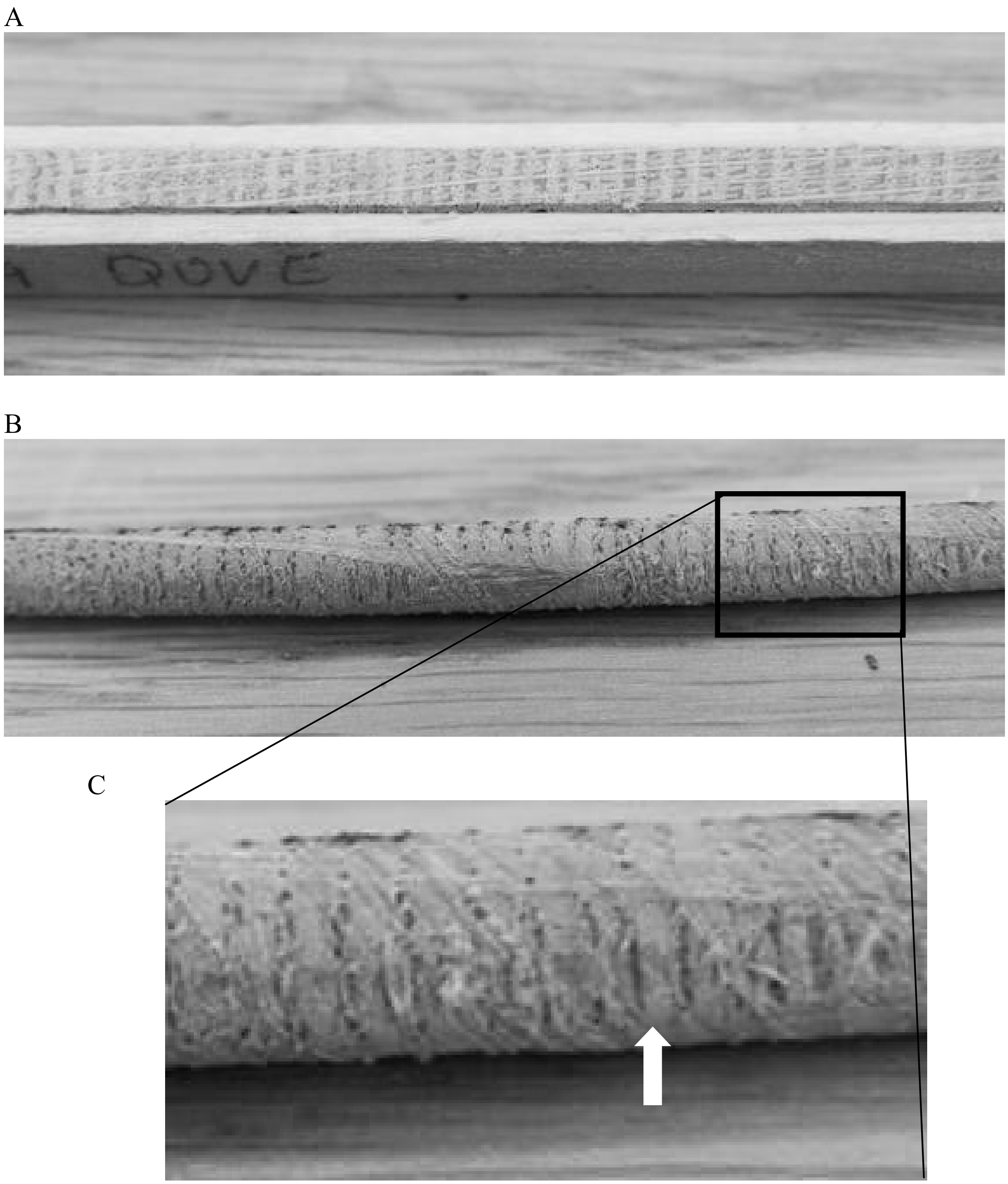

Figure 5. 9 Core orientation. The core should be mounted with the cross sectional view facing up. A) A core correctly mounted with rings facing up. B) An unmounted core. C) The arrow points to an example of torn tracheid. The tracheids are torn on the radial view so that the surface looks rough or shiny. The vertical fibers on the end of the core can also be used to determine proper orientation of the core (photo taken by Tony Campbell).

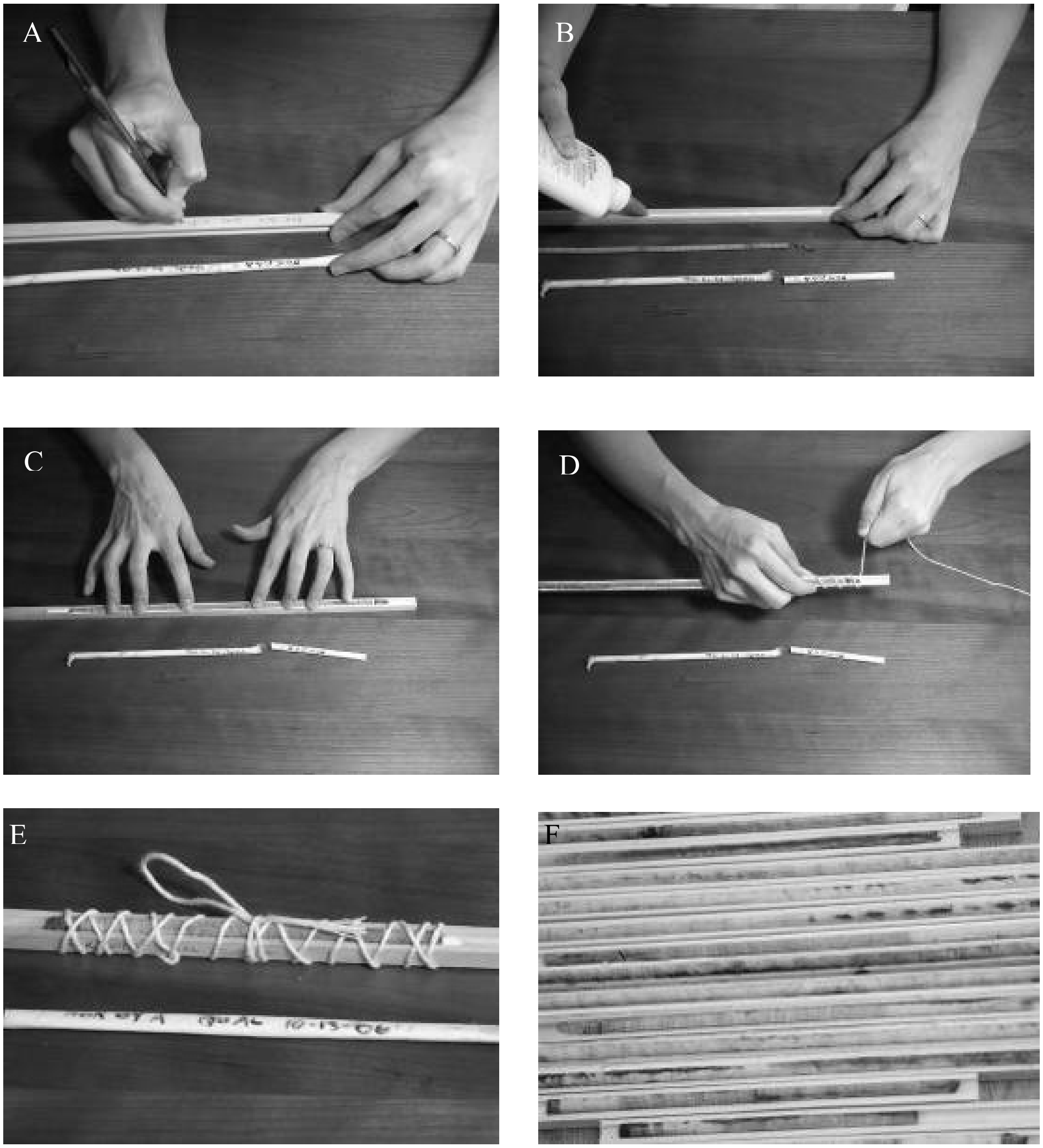

Figure 5. 10 Mounting cores. Once the cores have been dried, they are mounted on prefabricated wooden core mounts with water soluable white glue. The information from the straw is written on the side of the core mount (A).   A thin bead of glue is extruded into the groove (B). The core is delicately removed from the straw and pressed into the groove (C). The core is then secured to the core mount to keep it from curling as it absorbs the moisture from the glue (D). The string can be tied off and the mount should sit for at least two hours before it can be sanded (E). Once the string is removed all of the cores are ready for sanding (F). String, tape, binder clips, or weights can be used to hold the cores in place while the glue dries (photos by Jim Speer).

wherever the core is broken. The string can also be reused many times. One drawback of using string is it leaves fibers behind that can be observed under the microscope when the core is being examined. For drying the glue quickly, some researchersa at the University of Arizona will microwave their cores for 20-25 seconds which drives off the moisture in the glue causing it to dry quickly.

Untwisting cores. Cores may become twisted from a dull or nicked tip of an increment borer. If a twisted core is mounted without treatment, then the core will vary between the cross sectional view and the radial view as you move along the core mount. You can use a Low Pressure Steam Jet Generator (or a tea kettle with a molded aluminum foil spout to direct the steam) to moisten and heat the core so that it can be untwisted (Figure 5.11). Gentle continuous pressure should be applied to the core counter to the direction of twist while the core is moved back and forth through the jet of steam. This process usually takes about 30 seconds for each twist. Be careful not to burn your fingertips. The technique is especially difficult with short lengths of core. Cores can also be microwaves with a wet paper towel for a short period of time to get the same effect of moistening and heating the core so that it can be untwisted.

Sanding cores. Once the glue is dry, the cores needs to be sanded with progressively finer sandpaper from ANSI 80 grit (177-210 µm) (mainly used for hardwoods), 120 grit (105-125 µm), 220 grit (53-74 µm), 320 grit (32.5-36.0 µm), and 400 grit (20.6-23.6 µm) (Orvis and Grissino 2002) (Figure 5.12). The first sanding grit is used to flatten the core surface for subsequent polishing and takes the longest. The progressive sequence of finer belts allows you to efficiently remove the striations created from the previous sanding belt as you polish the core

Figure 5. 11 Untwisting cores. If a core is twisted (usually due to a nicked or dull increment borer), then the cores can be straightened over a jet of steam (photo by Jim Speer).

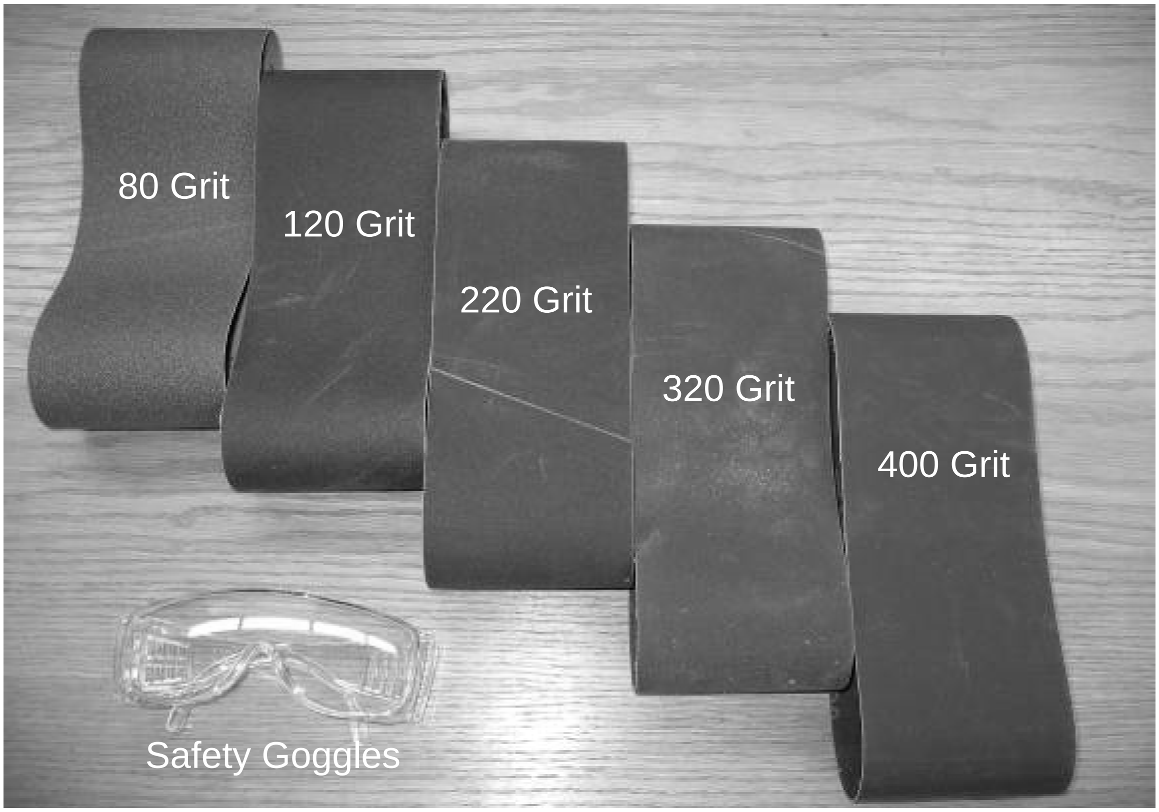

Figure 5. 12 Sanding belts. Cores and cross sections should be surfaced using progressively finer grades of sandpaper from 80-grit to 400-grit. You should also use a dusk mask, ear plugs, and eye protection while using an electric sander (photo by Michael Glenn).

to a better finish. The final surface should be polished so that each individual cell of the cross sectional view can be clearly seen under a microscope with 7-40 X magnification. A 4” X 24” belt sander with a flat top for sanding cores is often used although some researchers use an orbital sander and others even use a drill press with a sanding disc attached to it. The drill press technique has merits because you can look down on the core surface as you sand it to determine when it has been sanded enough. It is also possible to use a razor blade to surface the cores. A sharp razor blade with a steady hand and polishing with superfine steel wool can create a clean suface. This razor blade technique is particularly useful for dendrochemistry and isotopic analysis where contamination from saw dust should be avoided. I personally use the belt sander and invert it so that the belt faces up and clamp the sander handle to the table. This creates a flat, stable surface on which you can sand the cores. It is a good practice to change the angle of the core between sanding grits (sanding along the length of the sander then switching to a 45 degree angle from the axis of the sander) so that you can see the striations from the previous belt (Figure 5.13). Once those striations are removed, you can move on to the next finer level of a sanding belt. Hand sanding film at 30, 15, or 9 μm can be used to provide a finer polish to the finished surface. Sandpaper with the ANSI grit rating is a general value of the roughness of the surface even though many different sized particles may be used in the sandpaper. Sanding film with a micron rating is made of particles with a specific size as determined by a geologic sieve, and therefore, the sanding film provides a better surface than the equivalent sandpaper grit. You should be carful not to sand the surface of a core down too far. About half of the core should be left when all sanding is done, so that you have the largest area of wood to look at under the microscope. The final polish on the cross sectional view is most important for allowing the proper identification of ring boundaries. Some researchers use ethanol or isopropel alcohol on

Figure 5. 13 Sanding cores. Cores can be sanded on a belt sander (4 X 24" belt sander recommended for the surface area that it provides) with progressively finer grits (50, 120, 220, 320, and 400 grits) to polish the cross sectional view until the individual cells are apparent under a microscope at 40X magnification. In this picture the operator is sanding the core at a 45 degree angle from the axis of the sander so that he can see the striations made from the previous grit. Once those striations are sanded off of the core, it is time to move on to the next finer grit. Repeated visual examination of the core helps determine when the core has been sanded enough. Of course, the final test is to examine the core under the microscope (photo by Jim Speer).

pine trees to remove excess resin. The surface can also be buffed with suede leather but if the surface is too polished, then it may be hard to make pencil marks on the surface. Many researchers have experimented with wood dyes to bring out the ring boundaries, but in my experience, a well polished surface (even on maple wood) is superior to any dye for the identification of ring boundaries.

Preparing Cross Sections

Cross sections can be sanded with the same belt sander that is used on cores. First, the sample needs to be securely mounted to the table. You can use four layers of masonite peg board as a working surface. Cut dowels into pieces about one inch long to fit into the peg holes. Put multiple cross sections on the peg board and use the short dowels to securely fasten each sample to the board. These dowels, placed around the circumference of the section, will enable you to sand the sample while it stays in place. You can also use a friction pad (rubberized pad) to hold the sample in place. The same series of sandpaper used on cores is also used on cross sections, but if the surface of the cross section is particularly uneven from the original chainsaw cut, you may start with a coarse 50 grit (125-149 µm) sandpaper or cut a clean surface with a band saw to remove the saw cuts. Once a flat surface is obtained on the cross section with a band saw or 50 grit sandpaper, continue to work through the finer grits of sandpaper in the same way you would prepare cores. While sanding, always keep the sander flat on the sample and keep it in continual motion. Do not start or stop the sander on the section because this will cause gouging in the wood. The sander should be running when it is placed on the sample and running when it is removed from the sample.

A thick gum eraser can be used to clean sandpaper belts, greatly extending their usable life (Figure 5.14). These large erasers can be purchased at wood working supply stores. Hold the eraser against the belt surface while it is running. The gum from the eraser clumps up the saw dust and resin, removing them from the spaces between the sanding medium on the belts. This cleaning should be done after the use of any grit belt before the belt is removed from the sander.

Analysis of Cores and Cross Sections

At this stage, the cores and cross sections have been prepared and are ready for visual analysis and crossdating. The goal of crossdating is to assign calendar dates to each annual ring, and one way to start is to mark a visual ring count of the decades on the wood. Use a #2 pencil to initially denote the decades because you will probably need to erase and change them as you continue analysis. You can start your inspection from the outside of the tree (bark side) if you know the date of death or cutting, or the inside (pith) if the sample you are working with has an unknown death date. Starting from the pith, cores can be marked from zero as the innermost ring of the tree with every tenth ring marked with a single pencil dot to designate the decade year. Every fiftieth ring receives two dots, a hundredth ring receives three dots, and a millennial ring gets four dots (Figure 5.15). When the core is briefly scanned it is easy to count up the total number of rings, and the dendrochronologist can refer to this relative time scale if there is any question on the dating of the core. This is a conservative technique that does not assume an accurate date of the wood until those marks are erased and real calendar years are marked on the samples. Another technique is to start from the outermost, bark side ring and use it as an anchor in time for when the tree was cored, counting back from that outermost ring and assuming calendar years as you work backwards in time from the bark of the tree. This is a faster technique because it

Figure 5. 14 Cleaning a sander belt. Sander belts lose efficiency before the grit is worn down as they become covered in a layer of resin and dust from the wood. You can clean sander belts using a rubber gum eraser that can be purchased at most woodworking stores. The eraser pulls the saw dust from within the grit of the sandpaper and clumps it together, shooting it from the sander. If cleaned, sander belts can be re-used some 20 or more times before the grits wear down (photo by Jim Speer).

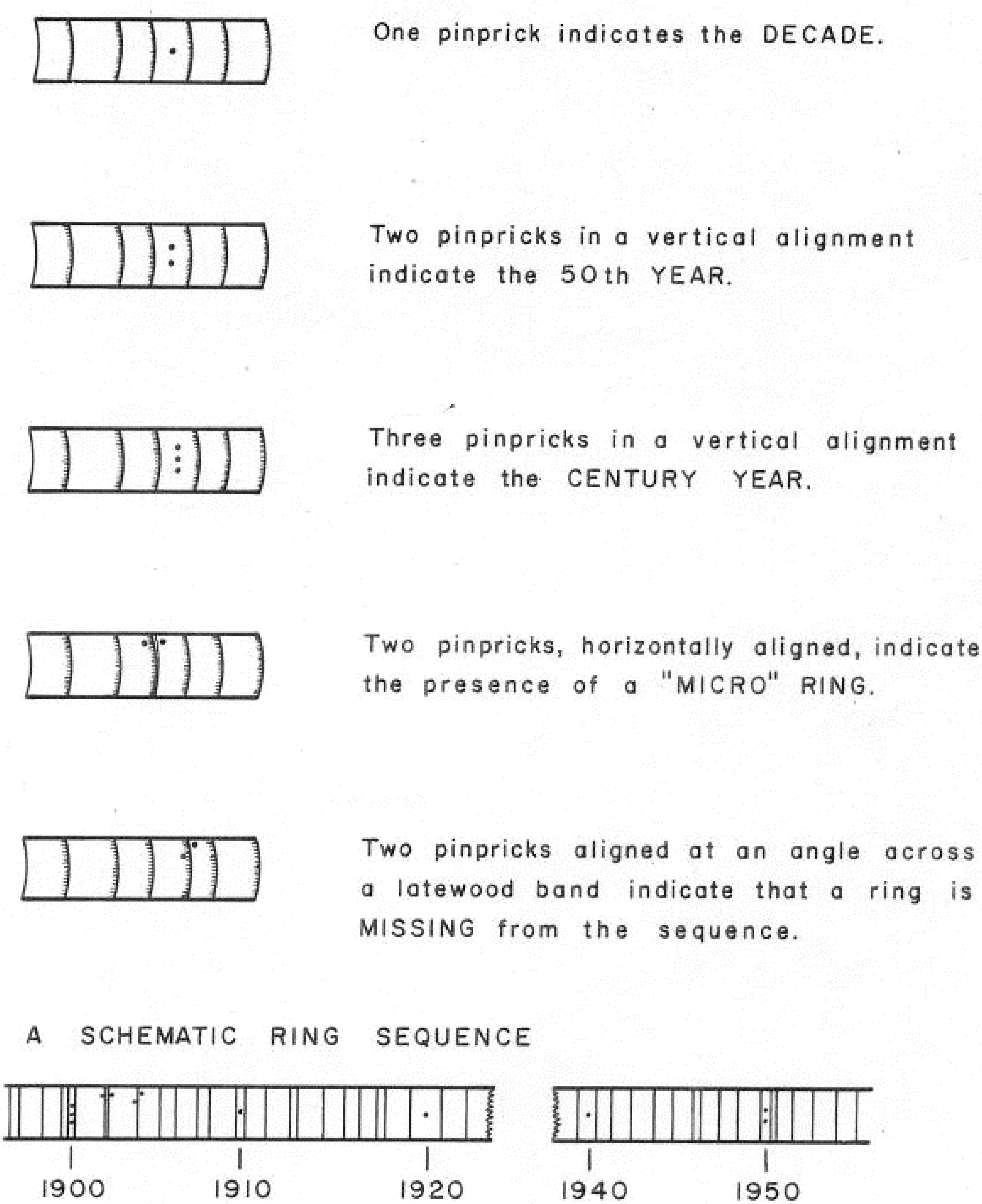

Figure 5. 15 Marking the wood. A systematic method of marking the wood provides a temporal frame of reference so that you do not lose count of the rings. One dot is used on every decade year, two dots every 50 years, three dots every 100 years, and four dots every millennium. This allows you to quickly scan the wood and determine the date anywhere along the sample. Micro and missing rings are indicated with dots across ring boundaries (from Stokes and Smiley 1968).

does not require re-marking the wood, but it can be misleading because these are not truly dated rings until the process of crossdating is complete. In this process, one dot is still used for decade rings, two dots for 50 years, three dots for centuries, and four dots for millennia, but in this case the millennium mark coincides with A.D. 2000 and the first century mark coincides with A.D. 1900. If you are working with dead wood with an unknown outer date, you still have to use the relative marks from the inside of the core until the core is crossdated against a master chronology.

Skeleton Plotting

Skeleton plotting is the basic technique invented by A.E. Douglass described in the early 1900s and used by many dendrochronologists around the world for the first attempt at dating a sample (Stokes and Smiley 1968). Most dendrochronologists today use the same plotting paper of five squares to a centimeter as Douglass originally used. When two samples of wood are compared, they may be growing at different rates which would prevent a productive comparison of these two cores. Time can be put on a standard scale by using graph paper where each vertical line represents one calendar year and the cores can be compared against each other. This can also be thought of as a two dimensional plot with time on the x-axis going from old on the left to the present on the right and an inverse scale of the narrowness of the ring on the y-axis and ranging from 0 (for average) to 10 (for an absent ring). This also reduces the bulky sample to a concise record of the narrow marker rings that can be compared between samples, stored for future reference, and compiled into a master chronology. A **marker ring** is a ring that is consistently narrow or has identifiable characteristics and is consistent between different trees. Graph paper is used as the standard scale for comparisons between trees where each line represents one year.

A line is drawn for the years representing narrow rings that are responding to a limiting environmental factor. Extraordinarily big rings can be marked with a “b” on the skeleton plot and may be as reliable for crossdating as narrow rings. Dating by use of skeleton plots and other methods to be mentioned later are much more efficient and quicker than measuring the rings and relying on statistics to find the match. Visual dating allows the dendrochronologist to use all aspects of the wood, such as color, latewood thickness, and marker rings, to determine the dating of the sample of wood. The computer program COFECHA (discussed more in Chapter 6) was created by Richard Holmes as a second check of the dating developed by a dendrochronologist. Historically (up until the 1980s), most dates were independently checked by a second dendrochronologist before they were assumed to be accurate and published. Today, the only second check that we generally use is the COFECHA program as long as visual dating is done independently of this statistical tool.

When preparing a skeleton plot, cut a sheet of 8 ½ X 11 inch graph paper on the long axis into, thin strips that are 15 squares high (Figure 5.16). We try to use the same graph paper that Douglass did in the early 1900s so that all of our plots can be compared to each other. This graph paper has five lines per centimeter. One hundred ten years can be marked on this sheet and additional sheets can be glued on to accommodate longer cores. The empty white margin of the paper on your left should be used to write the sample ID, your name, and current date. The top third (5 lines) of the paper should be marked with a regular count, either starting at year zero on the left and marking every tenth year, or starting with the outside date on the right and marking every decade going back in time. Either way, time is progressing from left to right. A flag is used to designate the inside date and outside date of the core. These flags are important

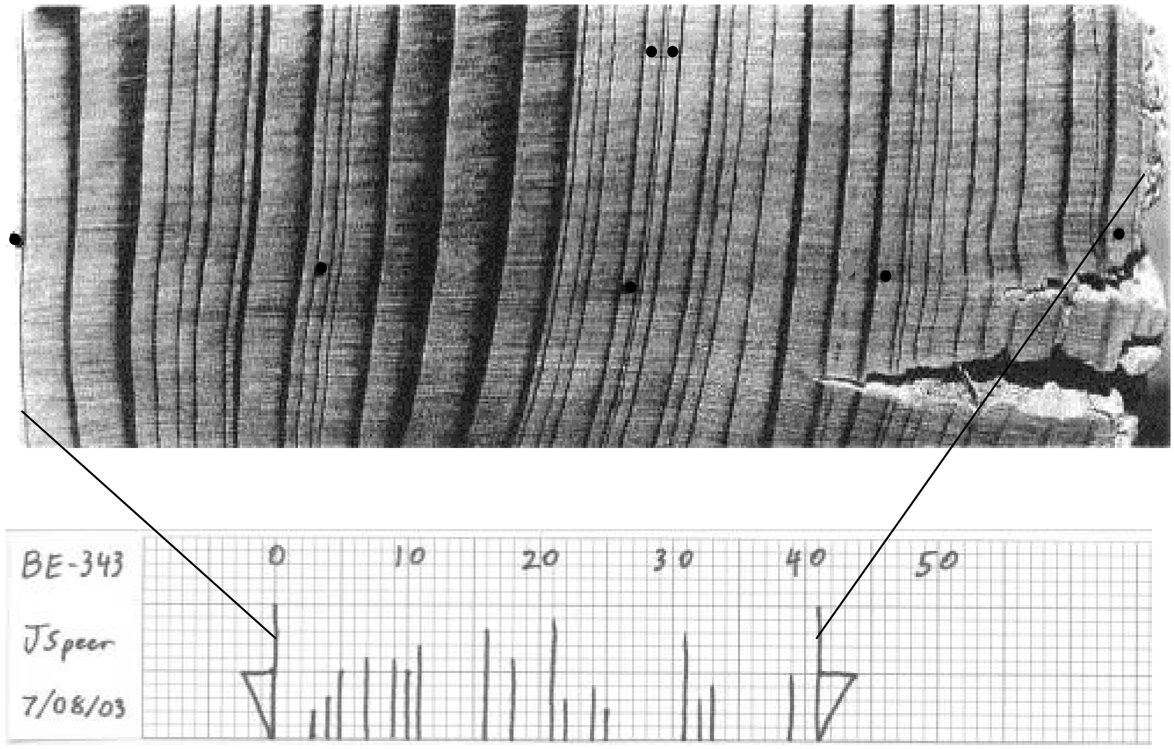

Figure 5. 16 Making a skeleton plot from a sample of wood. The plot illustrates time on a standard scale of each line representing one year. The more significant smaller marker rings are represented by longer lines on the plot. Beginning and end flags are drawn to show the inside and outside dates on the sample. Calendar years or a relative dating scale is marked along the top of the paper with every 10th ring marked with a date. Begin plotting from left to right, pith to bark. The sample ID, your name, and the date that the plot was created should be written in the blank space on the left of the plot (From Stokes and Smiley 1968).

because they provide the establishment date (or inside most date) and death date (or sampling date) respectively.

Because of the age-related growth trend discussed in chapter 2, some standardization process must take place while making a skeleton plot. Otherwise, all plots would start off with no narrow marker rings at the beginning and the length of the line (designating more narrow marker rings) will gradually get longer towards the outside of the plot paper. While this is an accurate representation of the growth curve of the tree, it does not provide useful interannual variability for dating. To remove this trend and any possible suppression and release events from forest dynamics, you should use a mental standardization process. Compare the ring that you are dating to three rings on either side of it. If the ring on which you are focused is relatively narrow compared to surrounding rings, it receives a vertical mark on the skeleton plot paper. Another technique compares the ring in question only to the rings before it, i.e. those closer to the pith, because this prior growth may affect the current year's growth making them a more accurate comparative pool. This also allows for autocorrelation as mentioned in Chapter 2.

The bottom 10 lines of the skeleton plot paper are used for representing the marker rings with a line that is 10 boxes tall representing the narrowest possible ring in the core and a line that is one box tall representing a ring that is only marginally narrower than average. Any ring that is of average width or wider gets no mark on the plot. Rings that are significantly wide, however, can be marked with a "b" on the plot designating them as a big ring. These wider rings can also be used as marker rings in dating samples. Dendrochronologists usually concentrate on narrower rings because wider rings are less noteworthy. The narrower the ring, the more significant that ring is as a marker, resulting in a longer line on the skeleton plot. Many students making their first skeleton plots are concerned about an absolute scale for the length of the line on the plots. The length of the line is really an arbitrary designation that has to be determined by the person making the plots. But after some experience with the range of possible ring widths, most plots converge to a similar pattern. Cropper (1979) made a computer program that could use the information from skeleton plots to date cores demonstrating that this is a repeatable process that can be quantified. More recently, Tom Harlan has commissioned a new crossdating program called Crossdate that makes electronic skeleton plots just as we do on graph paper and will compare plots to a master chronology and provide statistics on the best matches. This program was written for and is particularly useful when working on bristlecone pine samples that are dated against a 10,000 year master chronology that is over 15 meters long when marked out on graph paper.

Much of the inter-annual pattern used for dating is in the marker rings, but the spaces between those rings also represent much of the pattern. It is important (because of the mental standardization and for the precision of the dating pattern) that there are not any areas that have four or more rings marked as small in a row. If more than four rings in an area are small, that area is considered suppressed and only the smallest ring(s) in that area should be used as marker rings. With four marker rings in a row, shifting the plot back and forth will match up marker rings in four separate positions, removing the annual resolution needed for crossdating. On the other hand, double and sometimes triple small years can be important dating markers.

When I work on a new site, I usually skeleton plot at least ten cores from that site. I compare these plots to each other and determine if all of the rings are represented on each core by matching up the marker rings. I start off by matching the two plots from within the same tree. We expect dating within trees (from the two cores from the same tree) to be stronger than dating between trees. If one or more of the plots do not match the others, I go back to the wood to find where the problem in dating lies in that particular core. Every place where two plots disagree (for example only one plot shows a narrow ring) I go back to the wood to check both plots. This variation in plots may not be a dating error, but could be due to the individual ecological response of the tree or even differences (such as compression wood) on the side of the tree that you are examining. If many decades of marker rings are consistently off in one direction, however, it is likely to be a dating error. The quality of the match is difficult to determine and is something of an arbitrary determination, but repeated attempts to date a sample from trained dendrochronologists produces the same results. The date of an unknown sample should be checked through the length of the entire master chronology (the master plot for the site containing the average widths for the narrow rings). An analyst will recognize some locations where the marker rings match up better than others. I will often mark these dates on the plot as possible dates, then go back to them at the end and determine which represents the strongest match.

The result of these checks is a correctly dated set of cores from which a master chronology can be built. As a first step in developing a master chronology, I overlap the individual plots, one on top of the other so that they are very precisely aligned with all of the yearly line marks corresponding to one another. The master chronology plot is made in a mirror image of the other plots (Figure 2.3b). The blank space on the left side of the plot paper still contains information about the site and master plot status. The dates, however, are real calendar dates that are listed along the bottom of the plot paper. The lines representing the narrow marker rings now run from the top of the plot paper down to a maximum of 10 boxes on the graph paper. The mirror-image characteristic of the master chronology enables regular skeleton plots to be easily compared with it in order to identify matching dates. A line is drawn on the master plot each time the ring in question is represented on at least 50 percent of the individual tree plots. For example, if 1974 appears as a narrow ring in 5 out of 10 plots, that ring should be marked on the master chronology. The length of the line on the master is calculated by taking the average length of the lines represented on the individual tree plots. I do not count the cores not showing a narrow ring for those years in the average, but I will make a slightly longer line if that ring is represented on nearly every skeleton plot.

The master chronology, then, is a continuous time series containing all marker rings that agree between trees for the length of the chronology. This is the best tool that you can use to date your remaining samples.

List Method

The list method is another way to determine marker rings, if the outside date of the sample is known. The analyst can count back the rings from the bark to the pith, marking calendar years on the core according to the previously mentioned dot notation. Each time a narrow ring is noted, the date is written in a vertical list under the sample ID (Figure 2.4). Once the researcher has done this for five to ten cores, he or she can go back to the lists and determine which rings are consistently narrow between samples. At this early stage, as with skeleton plots, one should be careful that none of the samples are consistently off from the others which would represent an initial dating error. Once a list of marker rings is developed, the analyst can use these marker rings to quickly date the rest of the samples.

Memorization Method

The memorization method starts with known marker rings that may have been developed from the skeleton plot or list method (Douglass 1941). The narrow marker rings can be memorized or written down as a list. Newly surfaced cores should be counted back from the known outside date, and the calendar years should be marked on the core using the dot notation. Every time a narrow ring is seen, one should check it against the marker rings. If the ring should be narrow, then the dating is still accurate. Continue this to the inside of the sample. If the dating of the wood is off by a year or more from the marker rings, then the analyst checks other marker rings in the sample. If these rings are consistently off in one direction from the master chronology, a dating error has been located. The time period when the marker rings started to become different from the master should be examined for possible micro, false, or locally absent rings.

I usually build my master chronology from ten cores using the skeleton plot method, and then date the remaining cores using the memorization method. When building the master, I start with the oldest cores in the collection so that I develop the longest possible master chronology representing the entire length of the chronology. Skeleton plotting takes some time, but it is the best technique for building a strong working master chronology, permanently recording that master, and providing a basis for dating. The memorization method allows for quick dating of the subsequent cores but relies on a valid master chronology. After measuring the tree-ring widths, I second check all of my dates using COFECHA (see Chapter 6). The final check on a master chronology is to check its dating against other master chronologies from the surrounding area. The remote possibility exists that every tree in your chronology is missing a ring or that you assigned the outside date off by a year. Comparison to another master chronology might also help demonstrate crossdating in sections of your chronology with low sample depth. This second check of the whole chronology against another master can confirm your dating. At that point I am confident that my dates have no error and are accurate and precise with annual resolution.

Measuring Methods

Most dendrochronology projects require ring width measurement for a quantitative analysis for comparison with climate data or some other calibration data set. Other projects, such as archaeological dating or fire history, simply require crossdating and do not need the samples to be measured. One of the benefits of measuring all samples is that the program COFECHA can provide the validation on the visual crossdating. These measured ring widths can also be contributed to the International Tree-Ring Databank (see appendix E for web addresses) which is a worldwide repository of tree-ring chronologies. This is also the location where you can find other master chronologies to which you can compare your dating.

Measuring Systems: Many measuring systems exist that can be used to obtain accurate measurements of tree rings. Most of these systems have a moving stage whose location is determine by rotation of a lead screw or by an optical linear encoder. These systems include the

Bannister Measuring Stage, the Measurechron, the Henson Measuring Stage, the Zahn Measuring Stage, the LinTab Measuring System, and the Velmex Measuring System. All of these systems are used in conjunction with a stereozoom microscope supported by a boom stand (Figure 5.17). The Bannister, Measurechron, Henson, and Zahn measuring stages all count the number of rotations of the lead screw to determine the width of each ring. One drawback from this type of system is that the screw can wear over time so that if the technician measuring a core measures past the end of a ring, error can be incorporated in the measurement by turning the screw back. This can be avoided by backing off from the ring boundary and measuring back up to it. The Bannister, Henson, and Zahn systems are no longer made and it is hard to find replacement parts for them. The Velmex Measuring System and the LinTab Measuring System have a movable stage that is advanced by a lead screw connected to a handle but an optical linear encoder actually determines the exact location of the stage and measures its position to an accuracy of 0.01 mm, 0.002 mm, or 0.001 mm depending upon the precision of the instrument. The microscope should have a crosshair reticle in one of the eye pieces and this crosshair should be lined up with a ring boundary so that the vertical hair is tangent to the curve of the ring boundary. Measurements should be made along a core or cross section perpendicular to the ring boundary or along a radial file (a row of cells that are produced from the same cambial initials). The average width of the ring should be measured based on the observable ring area. For example, if a ring pinches across the field of view, the average width of that ring should be measured. Because it is necessary to measure perpendicular to the ring boundary, the core must be repositioned to take the curvature of the ring near the pith of a core into consideration (Figure 5.18).

Figure 5. 17 The Velmex Measuring System.
The Velmex Measuring System is the standard instrument for measuring ring width. It is a movable stage, rigged with an optical encoder, and working in conjunction with a stereozoom microscope that has a crosshair reticle in one eye piece. The print button is depressed each time the crosshair lines up with a ring boundary, sending the measurement from the QuickCheck device to the computer file. These measurements are retained in the virtual memory of the computer until the file is saved to the hard disk (photo by Jim Speer).

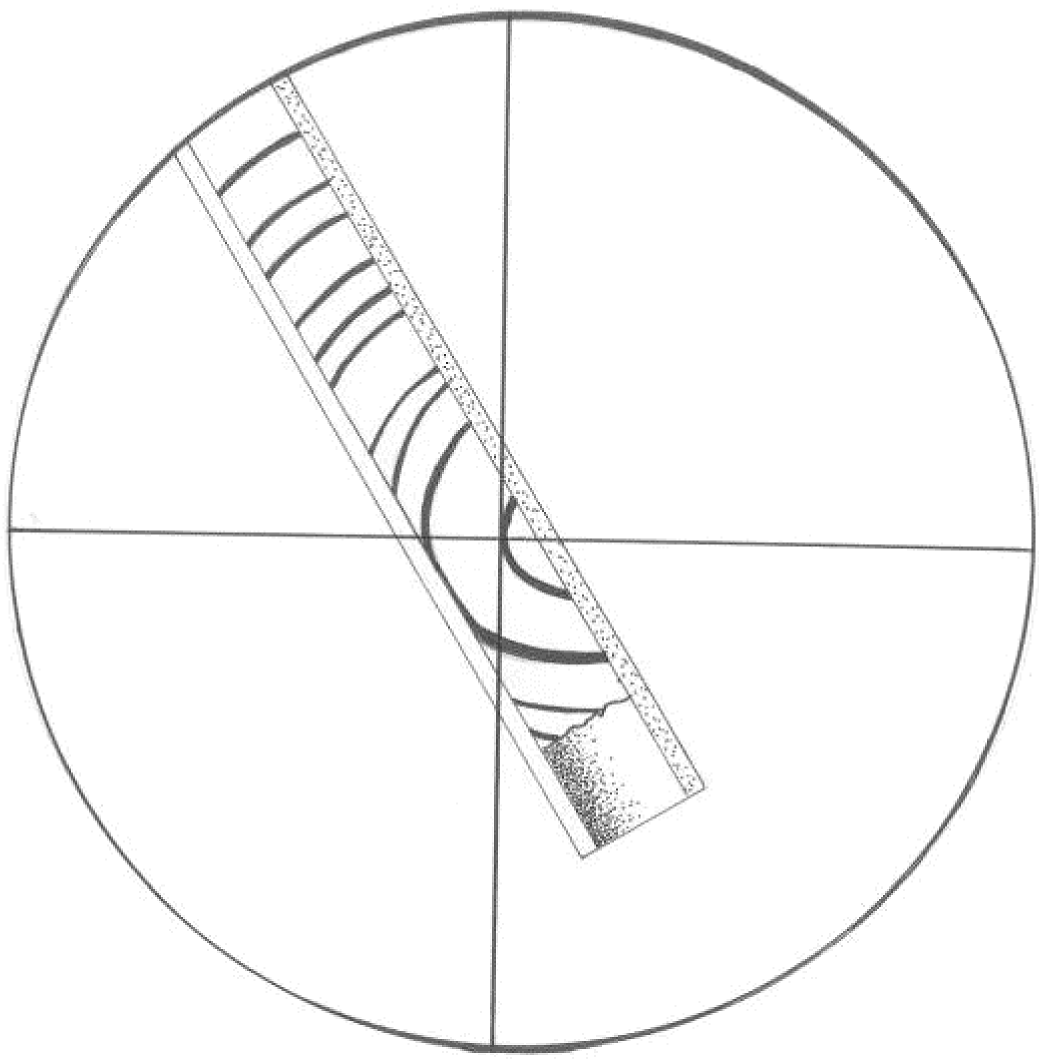

Figure 5. 18 Measuring rings near the pith of a core.

Rings should be measured perpendicular to the current ring boundary at an area of average ring width for that year. The core needs to be repositioned at the end of each measurement while you measure rings near the pith that exhibit a distinct curvature (drawing by Karla Hansen-Speer).

Other measuring systems use digital images that are produced by scanning the sample on a flat-bed scanner. WindDendro and LignoVision are two such programs. They both provide automated measuring options that can speed the time it takes to measure samples. The draw back for these systems is that the accuracy of the program depends upon the resolution of the scanned image. Close supervision by the operator is needed to make sure that all of the rings are accurately measured. Micro rings can easily be missed by these automated processes. Wood samples that do not have very distinct ring boundaries such as diffuse porous woods are not very well recognized by these system and the cost of the programs can be prohibitive.

*Measuring rings***.** The best technique for measuring rings is to measure perpendicular to each ring boundary. As a core approaches the pith, it often shows much curvature at the center, and the core will have to be adjusted in between each measurement to stay perpendicular to the previous ring boundary (Figure 5.18). The microscope that is connected to the measuring machine must have a crosshair reticle in one of its eye pieces. This crosshair is the target that is used to mark the ring boundary. The vertical crosshair should be tangent to the previous ring boundary, and the horizontal crosshair should reach the next ring boundary without going off of the wood sample.

Many researchers prefer to use a video capture system on a trinocular microscope to send the image from the microscope to a monitor. Crosshairs can be attached to the video monitor by using fishing line that has been colored black with a permanent marker. The image moves across the monitor in real time so that measurements can be made on the video screen. This arrangement reduces the eye strain of continually looking through the microscope for hours at a time. Some resolution is lost between the microscope and the video monitor so this system is not the best for very narrow rings. Also there can be some parallax between the crosshairs and the image on the monitor so the technician has to remain still while measuring each ring.

Work Time Distribution

Each step of a project, from collection to analysis, takes a certain amount of time, and it can be useful when planning a project to have an idea about the time one can reasonably expect to spend on each part. The data collection process takes much less time than the laboratory procedures (not counting travel time to the site). Crossdating takes the most amount of time, including the check of the dating that can be done with the COFECHA program. Measuring the cores also takes considerable time, but the analysis can progress relatively quickly once these steps are completed. Table 5.2 lists the amount of person hours that it takes for each stage of a standard project that is completed by a skilled dendrochronologist with relatively straightforward wood.

Table 5. 2 Average work time in hours to collect, process, and build a chronology that is from 200-400 years in length from 20 trees (modified from Fritts 1976).

Task	**Mean Minimum**	**Mean**	**Mean Maximum**	**Mean Percentage**
1. Collection	11	15	23	9
2. Specimen preparation	7	12	17	7
3. Dating	51	72	120	42
4. Measuring	30	39	53	23
5. Dating Check with COFECHA	10	17	28	10
6. Basic climate response analysis	3	5	8	3
7. Project Supervision	8	11	15	6
Totals	120	171	264	100 %

Chapter 6: Computer Programs and Statistical Methods

Introduction

Dendrochronology uses a suite of custom computer programs that incorporates both standard and complex statistical routines and tools that facilitates crossdating, climate analysis and reconstruction, biological response modeling, and tree-ring data editing. Many of these programs were written beginning in the 1960s and 1970s and are, therefore, DOS-based programs that run in a DOS shell in the Windows operating environment. Richard Holmes rewrote these programs or wrote many new programs for the Macintosh operating system and created the Mac-compatible Dendro Program Library (DPL), a set of routines that helps dendrochronologists explore tree-ring data. Some programs have also migrated the other direction. ARSTAN (a program that conducts autoregressive time series standardization of tree-ring data) was initially written for the Mac by Edward R. Cook of Columbia University and then ported to the PC in the late 1980s and early 1990s. Currently, the most up-to-date versions of ARSTAN are made available to run on Macintosh computers first. Many other programs have been developed for Macintosh computers, Unix systems, or the SAS statistical package, but I will not describe those programs in this chapter. More information about these programs and applications can be obtained through the International Tree-Ring Data Bank (ITRDB) computer forum archives. Most of the programs mentioned below are free and can be downloaded from Henri Grissino-Mayer's Ultimate Tree Ring Web Pages (see appendix E for web addresses).

In the following sections, I describe some useful statistics followed by descriptions of the main dendrochronology programs in the approximate order of their use. I explain the purpose of the program and, in some cases, provide a keystroke tutorial that walks you through the execution of the main programs. I also provide some basic interpretations that explain the output for the main programs. Some of this information is published elsewhere in a different format and by different authors. I cite these references at the beginning of each section so that the reader can also examine those publications.

My intent in this chapter is to provide the basic tools needed to conduct analysis, not an exhaustive description of the programs and their output. See the cited references for more detailed description of the programs. Many of these programs can run as a black box using the program's default settings, where the user does not need to understand the internal (often statistically complex) operations executed by the program. Please try to educate yourself as much as possible about how each program functions and the proper parameters for the specific project in mind. Also, look to some of the classic literature published on dendrochronological methods, such as Fritts (1976) and Cook and Kairiukstis (1990), for further reading.

Statistics in Dendrochronology

Series Intercorrelation

In the case of dendrochronology a tree-ring series from one core might be correlated against the master chronology or two cores can be compared to each other. The series intercorrelation can be the average of every series back to the master chronology and in this case will represent the common stand-level signal recorded for a site (Equation I) . It is calculated between two series, such as a core (x) and the master chronology (y) using

$$r_{xy} = \frac{\sum_{t=1}^{t=n} (x_t - m_x)(y_t - m_y)}{(n-1)s_x s_y} \qquad [I]$$

where, x_t is the index value for a core at year t, y_t is the index value for the master chronology at year t, m_x is the mean index value for the core, and m_y is the mean index value for the master, s_x is the standard deviation for the core, s_y is the standard deviation for the master, and n is the number of years being compared. This equation adjusts for the variance between the core and the master chronology as well as simply comparing the size of the rings in each year.

Mean Sensitivity

Mean sensitivity is a measurement of the year-to-year variability in tree-ring width ranging from 0 to 1 (Equation II). If every ring were the same width, the series would have a mean sensitivity of 0 and if every other ring were absent then the mean sensitivity would approach 1. For dating tree rings, it is possible to have series that are too complacent and other series that are too sensitive to date accurately. From personal experience, a series with a mean sensitivity around 0.1 is so complacent that it is difficult to date and a mean sensitivity of greater than 0.4 is so sensitive that it becomes extremely tricky to date due to frequent micro or absent rings next to very wide rings. Mean sensitivity around 0.2 is generally accepted as series that are sensitive enough for climate reconstruction. The equation to calculate average mean sensitivity for a series is

$$ms_x = \frac{1}{n-1}\sum_{t=1}^{t=n-1}\left|\frac{2(X_{t+1} - X_t)}{X_{t+1} + X_t}\right| \qquad [II]$$

where, X_t is ring width in year t, X_{t+1} is ring width in the following year, and n is the number of years being compared.

Gleichläufigkeit – Sign Test

The **Gleichläufigkeit** (G) is a measure of similarity between two chronologies based on the first difference between successive tree rings (Eckstein and Bauch 1969, Schweingruber 1988). In other words, it tests to see if two chronologies are increasing in growth at the same time or decreasing in growth at the same time. This examination of annual trends enables the researcher to compare the trend of cores for dating as well as comparing the ring widths (Equation III and IV). G-scores have been incorporated into the programs CDendro, CATRAS, and TSAP or they may be calculated by hand.

$$\Delta_i = (x_{i+1} - x_i) \qquad [III]$$

$$\textbf{when} \quad \begin{array}{l} \Delta_i > 0 : G_{ix} = +\frac{1}{2} \\ \Delta_i = 0 : G_{ix} = 0 \\ \Delta_i < 0 : G_{ix} = -\frac{1}{2} \end{array}$$

$$\text{then } G_{(x,y)} = \frac{1}{n-1}\sum_{i=1}^{n-1}\left|G_{ix} + G_{iy}\right| \qquad [IV]$$

Figure 6.1 shows an example that compares two cores to calculate the G-values. Each core's increase or decrease is calculated for every year-to-year change, and then these G-values are added together for each year-to-year change. This sum on an annual basis is then added up for the entire length of the core and the result is the G-value between those two cores. For example, if one tree is increasing in growth in the first year and the second core is also increasing in growth for that year, the chronologies score a 1 for that year. If one tree is decreasing in annual trend while the other core is increasing, then those chronologies score a 0 for that year. In the end all of these annual scores are summed and in the case of the figure 7 out of 10 intervals are trending in the same direction so the chronologies score a G = 70%.

Rbar

The **running rbar** is one statistic that can be used to examine the signal strength throughout the chronology. It is calculated by taking the average correlation between all series in a 100-year window with 50 years overlap, throughout the entire chronology. Because it is a running correlation between series, it is a good measure of the common signal strength through time and is dependent upon the sample depth (Cook *et al*. 2000).

Expressed Population Signal (EPS)

The **Expressed Population Signal** (EPS) is a measure of the common variability in a chronology which is dependent upon sample depth (Equation V; Wigley *et al.* 1984, Briffa and Jones 1990). Its formula is

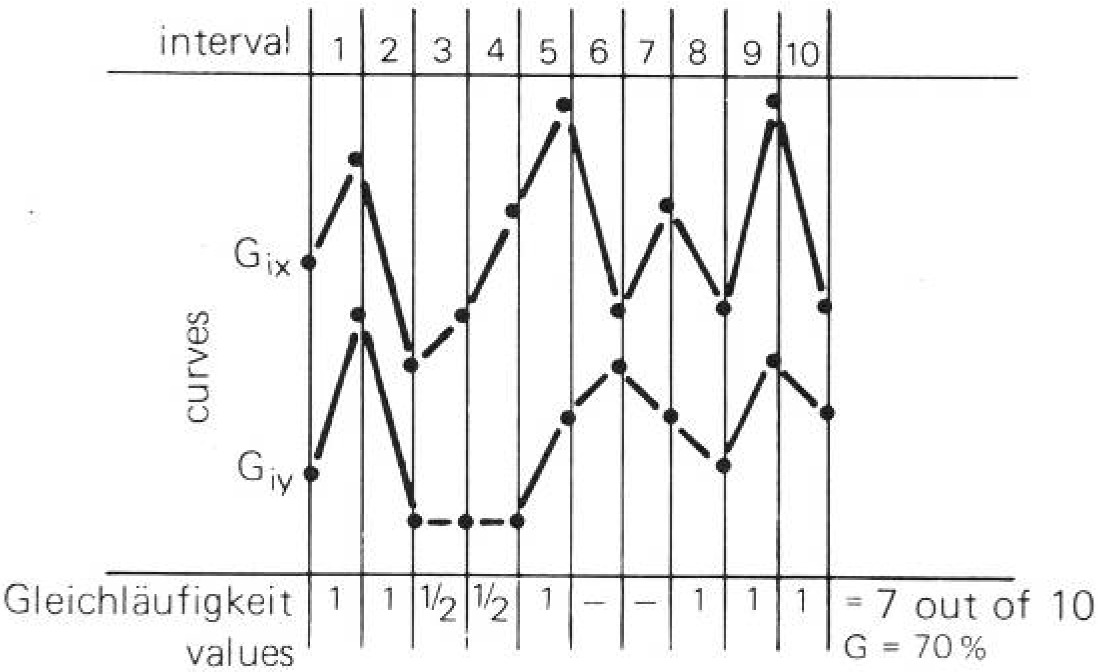

Figure 6. 1 An example of calculating the Gleichläufigkeit value (from Schweingruber 1988). If an interval increases for one core it receives a +1/2 value and if the same interval increases on the second core it also receives a +1/2 value giving a total G-value for that one interval of 1. The calculation is conducted for each interval with a constant value being equal to 0 and a decreasing interval is scored as -1/2. All of these intervals are summed over time throughout the chronology resulting in the overall G-value (from Schweingruber 1988).

$$EPS_t = \frac{t * r_{bt}}{t * r_{bt} + (1 - r_{bt})} \quad [V]$$

where, t is the average number of tree series using one core per tree and r_{bt} is the mean between-tree correlation. When the EPS value drops below a predetermined level, the chronology is starting to be dominated by individual tree-level signal rather than a coherent stand-level signal (Figure 6.2). The chronology can still be well dated and useful for dating studies such as in archaeological research, but may produce large confidence limits in a climate reconstruction. A value of 0.85 has frequently been used as an appropriate cut-off point. This chronology measure is frequently used by European dendrochronologists and has recently come into use by American dendrochronologists.

Subsample Signal Strength (SSS)

The **subsample signal strength (SSS)** is a measure of the amount of signal captured by a subsample of cores out of some master chronology (Equation VI; Wigley *et al*. 1984, Briffa and Jones 1990). This calculation enables the researcher to quantify the variance in common between a subset of samples and the master chronology, which is particularly important as sample depth decreases in a climate reconstruction further back in time. It is calculated by

$$SSS = \frac{t'[1 + (t - 1)\bar{r}]}{t[1 + (t' - 1)\bar{r}]} \quad [VI]$$

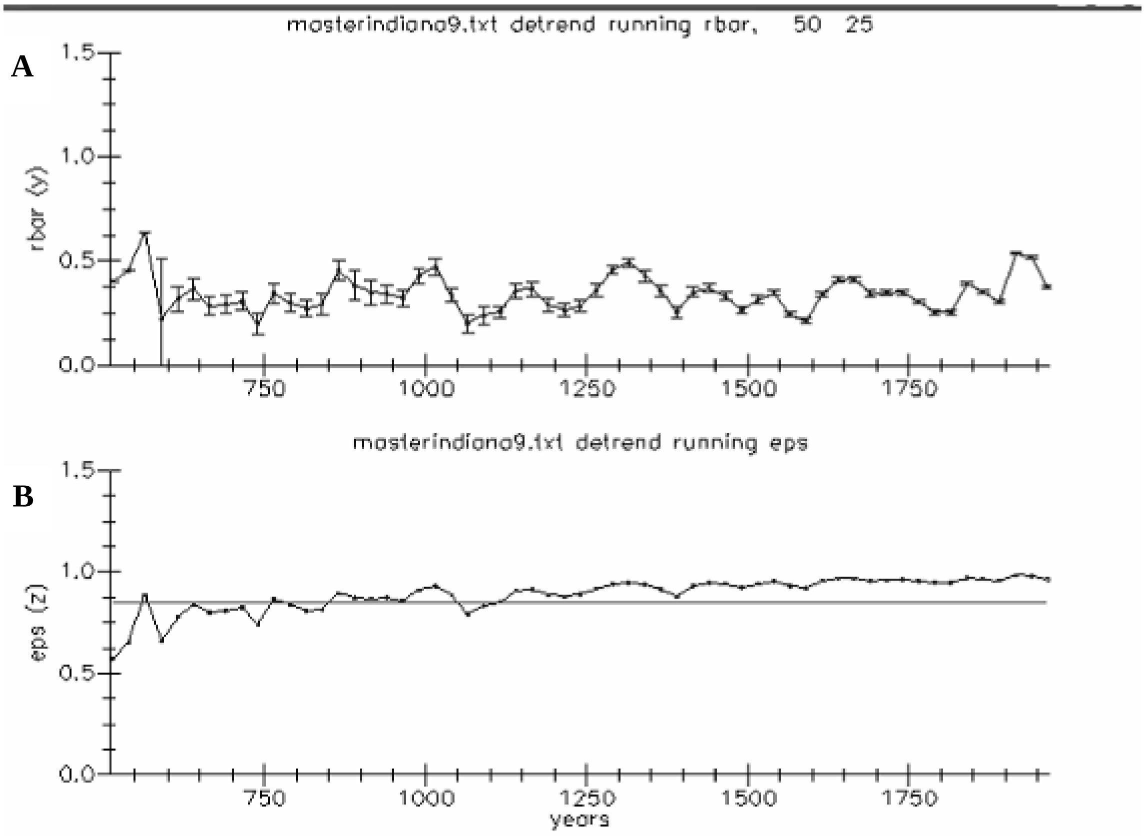

Figure 6. 2 A) Running rbar and B) Running EPS analysis for the Newberry Crater Lava Flow Ponderosa Pine Chronology (from Clark and Speer unpublished data).

where t′ is the number of cores (if one core per tree) or trees (if two cores per tree) in a subset of the whole population, t is the number of cores or trees in the full set, and $\bar{r}$ is the mean interseries correlation for the chronology.

Measuring Programs

Many programs have been developed to measure tree rings, such as TRIMS, MEDIR, PJK, and MeasureJ2X. These programs take tree-ring width data that are fed to the computer through a data recording box such as Accurite or QuikCheck. Each program has some good features and many have some bothersome quirks, just like all computer programs. TRIMS, MEDIR, and PJK have been used for decades and do an excellent job as an interface to record tree-ring widths. They also have some minor data editing features that enable the user to correct measuring mistakes while still at the measuring system. Currently, MeasureJ2X is the measuring program that is recommended when buying a new Velmex measuring system, so I will explain its use in greater detail below.

Measure J2X

MeasureJ2X is written in JAVA language and can, therefore, be used on Mac or PC. It is one of the few programs that was written professionally so it does have a cost. It has a graphical user interface (GUI) which presents a program that functions like most of the Microsoft package of programs. One can open files, save them, start new ones, see statistics on cores already measured, and do some editing of measurement files. It still has some limitations, such as the inability to rename folders, so it is best to prepare that space before you start to measure (see the MeasureJ2X User Guide which is available online through the Voortech website).

Keystroke Tutorial for MeasureJ2X. Set the core up on the measuring stage as described in Chapter 5 under the section labeled "measuring rings." MeasureJ2X has menu options of File, Series, Options, Setup, or Help (Figure 6.3). To start a new series, go to the Series menu and choose New. Figure 6.3 will then appear on the screen and request the series ID and start year for that core. When entering series IDs, always enter the same length site and tree characters so that later programs can differentiate between cores from the same tree. For example, it is standard to have a three character site designation and a two digit tree number followed by an "a" or "b" for two cores taken from the same tree. The program ARSTAN can then average these core-level measurements together resulting in a tree-level chronology, but for that to happen the standard site and tree mask (or code) must be adhered to. Once these data are entered, click OK and go to the initialization of measurements.

The next window that comes up is the measuring window (Figure 6.4). The sample ID shows up at the top of that internal window (in this case TES01) and the first year to be measured is displayed on the screen as well (in this case 1895). The program needs to be initialized at this time, which entails sending a beginning measurement from which all other measurements will be calculated. This enables the user to reset the stage at any time and not need to zero out the measurements. Click on the *Measure* button. A new window will pop up asking for an initial measurement. It is good to reset the measurement to zero at this stage and click *OK*. A new box will pop up saying what the initial measurement was and click *OK* on that as well. Now the

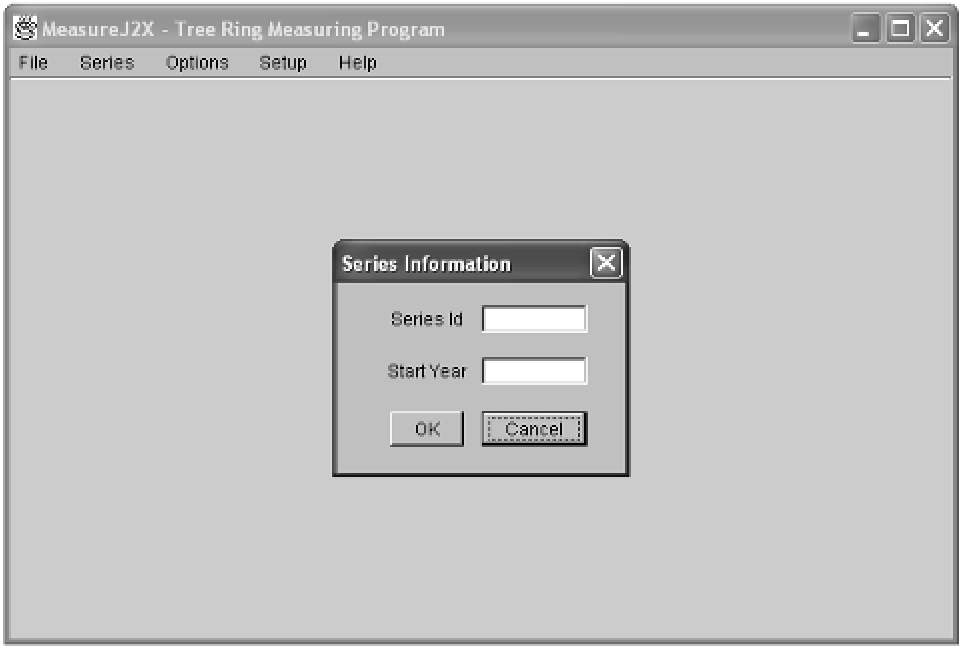

Figure 6. 3 Initializing a new series in MeasureJ2X.

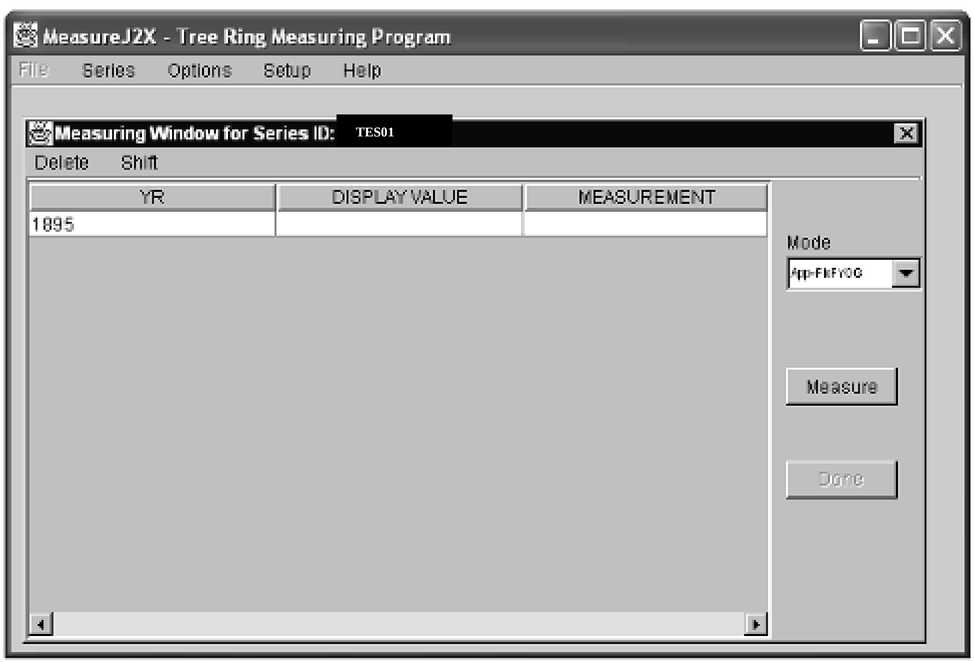

Figure 6. 4 Measuring view in MeasureJ2X.

program is initialized and waiting for measurements. Turn the dial on the measuring machine, which moves the stage and the sample, until the crosshair is at the next ring boundary. Push the Print button on the remote, which sends the measurement to the computer screen. The display on the computer screen of the Display Value will show the cumulative measurement for that core and the measurement which is the width of the individual ring (usually in millimeters but can be changed to inches). This procedure is repeated for each ring on the core. All of the measurements will be displayed on the screen along with the year of each ring. The computer will beep each time a measurement is entered and a second beep should be heard for each decade year that is measured. It is important to pay attention to this second beep and to use the decade years as landmarks so that a mistake in measuring can be identified within the decade being measured.

Once all measurements are completed, it is important to note that the data are in the computer memory and have not been saved permanently to the hard drive. The user should click the *Done* button on the screen and then close out the measuring window by clicking the small x in the top-right hand corner of the screen. Be very careful that the measuring window is being closed and not the entire program window. If the program is closed the measurements are lost. Once the measuring window is closed, the user can save the file by going to the drop-down menu in *File* and clicking *Save*. At this point another series can be initialized by clicking *Series* and *New* (as above) and when this file is saved, it will append these new measurements to the bottom of the last file measured.

It is possible to Delete or Shift the series in the Measuring Window if a mistake occurs. To delete one or more rings, highlight the ring width measurements in the Measurement column. Click *Delete* and choose to leave the first year or the last year fixed in time. Any other edits should be conducted in the EDRM or EDT programs (discussed below).

DPL

The Dendrochronology Program Library (DPL) is a compilation of DOS programs that have been developed by multiple users and provides useful tools for dendrochronology. This program library has also been ported to the Macintosh operating system. Historically it was a package of 31 programs, some of which have been so useful that they have been taken out and now stand alone, including COFECHA, EDT (now called EDRM), FMT, and YUX (Figure 6.5). Many old versions of DPL are being used in research labs today. The modern version of DPL contains 20 programs (Figure 6.6), many of which are useful for filling gaps in data, converting and displaying meteorological data, or generating a climate reconstruction.

FMT

The FMT program enables the researcher to change the file format as well as do some basic file reorganization such as putting the series in alphanumeric order. The first set of menus gives options to change the format of the file between any standard dendrochronological format such as compact, measurement (in 0.01 or 0.001mm precision), index, one column, or two column (Figure 6.7). The compact format was developed when the computers that we used to measure tree rings had very limited hard drive space. This format removes all of the spaces between ring-

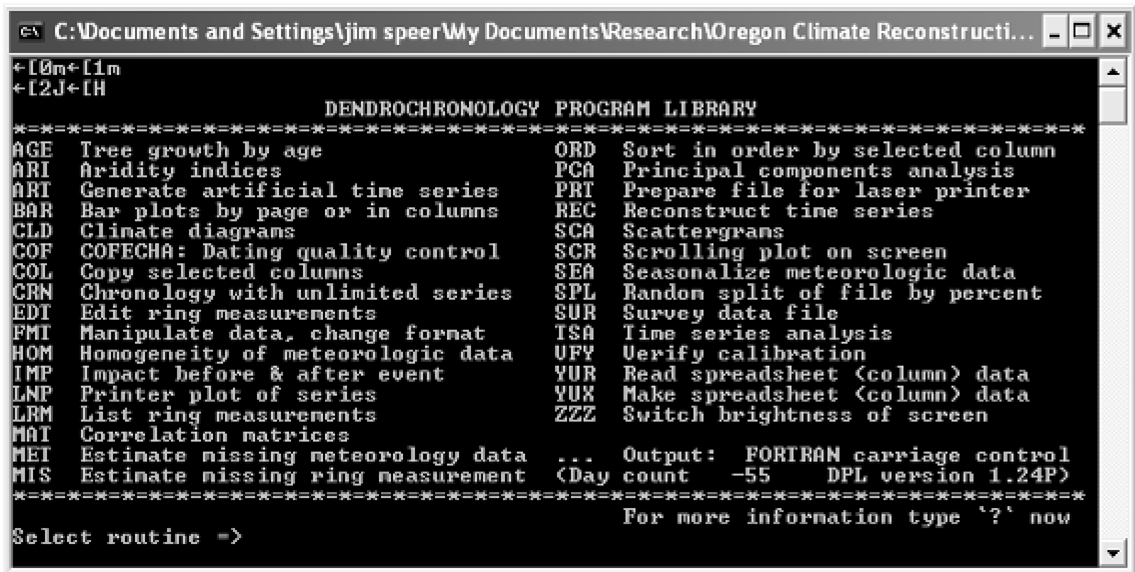

Figure 6. 5 The Dendrochronology Program Library (DPL) version 1.24p contains 31 Fortran programs that can be accessed by their three letter designation in this command line driven DOS window. Many of the more commonly used programs have been extracted as stand alone programs such as EDRM, COFECHA, YUX, and FMT.

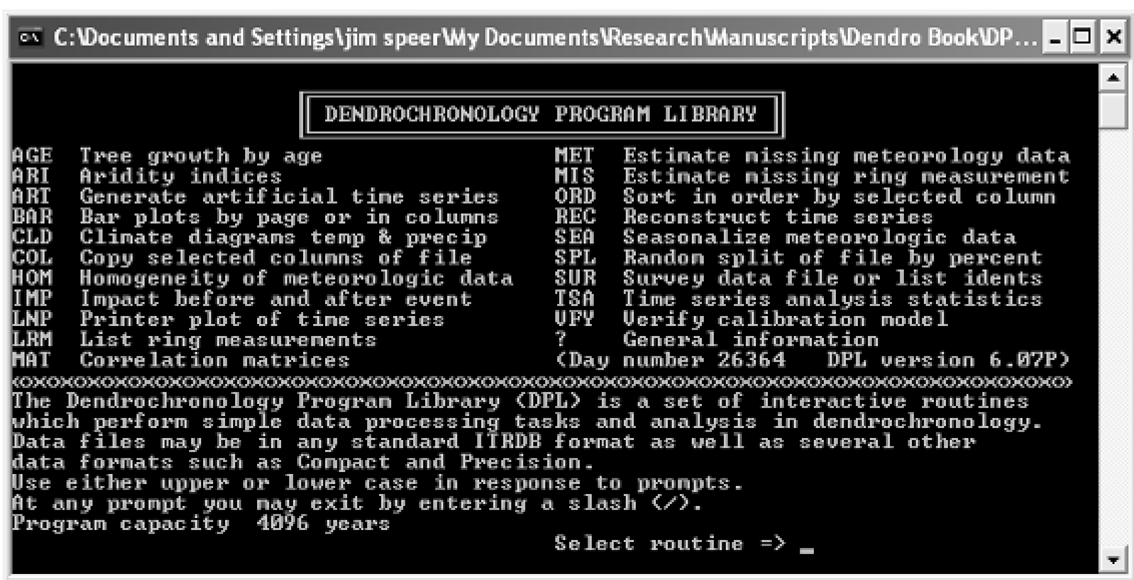

Figure 6. 6 The Dendrochronology Program Library (DPL) version 6.07p contains 20 Fortran programs that can be accessed by their three letter designation in this command line driven DOS window.

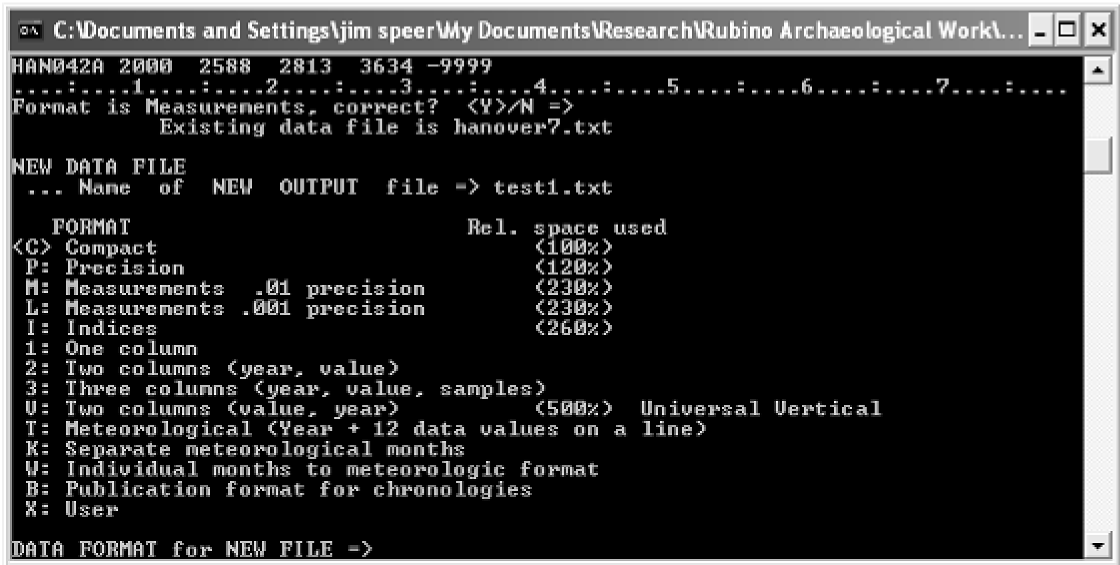

Figure 6. 7 Formatting options in FMT.

width measurements. The computer can read the file based on space delimitation but the operator cannot read the measurements in the file because they all run together. The measurement format has also been called decadal or Tucson format. The file is presented with each line representing a decade and the first column holds the ring width for that decade year. The second column is the first year in the decade and this continues through the ninth year of the decade in the last column. This format is easy for the use to read and determine the ring widths, however, the decimal places have been removed to conserve space and the end of file marker designates where the decimal should occur. A -9999 marker means the file has 0.001 mm precision and the decimal place should be three spaces for the furthest right reported value. An end of file marker of -999 means that the file has 0.01 mm precision and the decimal place should be two characters from the right. The index format includes the ring-width index and the sample depth that went into that calculation. It is also more compact than the measurement or decadal format and is difficult to read. The second set of menus provides 23 options for procedures that can be conducted on the series (Figure 6.8). I find option 17 for reordering the series to be the most useful tool in this package.

COFECHA

Historically, dendrochronologists at the University of Arizona would date a sample of wood with skeleton plots, remove their marks on the wood, and have a second dendrochronologist skeleton plot the wood to check the dates. If their two dates differed, they would confer and find the problem. This quality control and second check on all dates produced from the University of Arizona helped to establish the reliability of dendrochronology as a dating technique. In today's research climate with expectations of high productivity, researchers don't have the time to

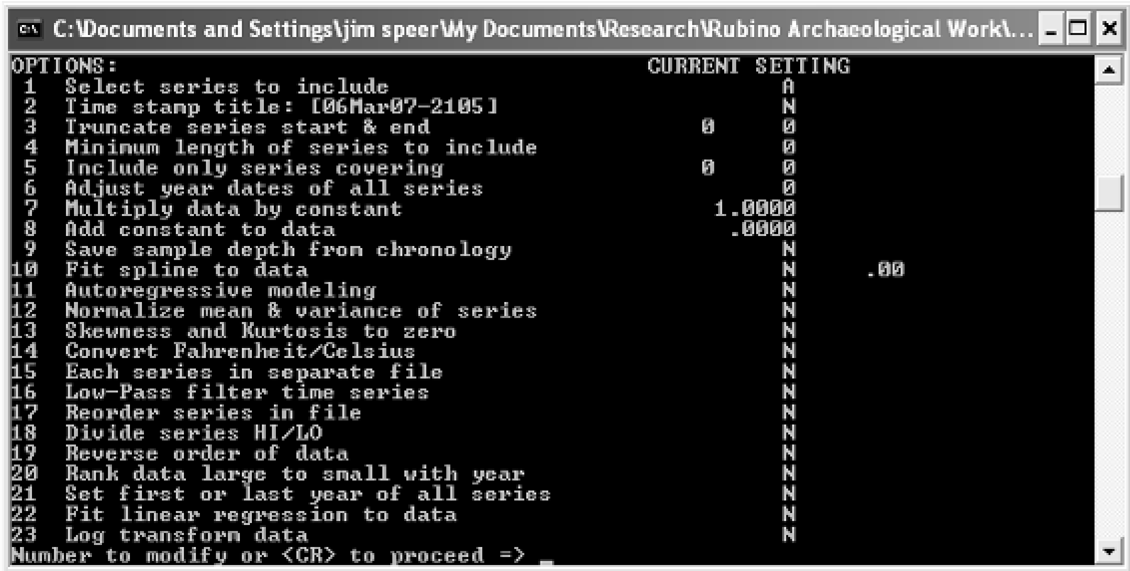

Figure 6. 8 Twenty three separate functions that can be performed on data in the FMT program. Option 17 allows you to reorder the series based on alphanumeric sequence of the core identifications.

completely check each other’s dates, therefore, Richard Holmes developed the quality control computer program called COFECHA (Holmes 1983).

COFECHA took the place of the second dendrochronologist as a quality control check on dating of samples but it was never intended to be the only attempt to date a sample of wood or to replace crossdating. COFECHA provides a statistical match between segments of each core and the master chronology which is made out of the measurements that are entered into the program. However, if half of the cores going into the program are not properly dated prior to statistical analysis, the master chronology will be worthless; therefore it is essential that the researcher crossdates the wood samples before using COFECHA. The worst part about using COFECHA as the sole method of dating is that an operator will not know what good dating for that tree species and site type looks like and will not even discern that there is a problem. The operator of the program can manipulate the data and produce a chronology with acceptable statistics but the resulting chronology is not necessarily well dated. The result will be inaccurate dates and poor correlations with calibration data, such as temperature and precipitation records.

I attended a professional presentation where a researcher claimed that trees in a hardwood forest did not have any relationship with climate. When asked about his dating, the person replied that he had not yet checked the quality of dating with COFECHA and gave no indication that the samples were dated by any other means. Because of this lack of time spent dating the samples, the research made an inaccurate conclusion, and extrapolated it to the hardwood forest. *Dating of wood samples is the heart of dendrochronology*, and as such, dendrochronologists should do everything in their power to properly date samples and check their dating quality. Two attempts at dating are necessary to provide the quality control that has been the hallmark of good dendrochronological research. The first attempt should include a visual dating method during which the researcher learns the wood; visual dating can include skeleton plots, the list method, or the memorization method from a known chronology. The second check on the dating can be done by another research using visual dating or by a statistical check such as with COFECHA. See Chapter 5 for detailed descriptions of skeleton plots, the list method, and the memorization method for primary dating of samples.

COFECHA is a DOS program with all of its simplicity and quirks (Holmes 1983, Grissino-Mayer 2001). It has also been ported to the Macintosh operating system. For those that have not used DOS programs frequently, that means input file names can be no longer than eight characters and cannot have spaces or non-alphanumeric characters in a file title, and the program is command line driven (meaning you have to type your responses). It is best if the program COFECHA is placed in the same directory as the files to be analyzed so that you do not have to type in the directory chain each time the program is run. COFECHA leads the operator through default options with most of the command steps. On the command line, COFECHA will often provide answer options such as "<Yes>/No". The option that is in brackets is the default option and pressing enter will choose that answer. Proper use of these default responses can facilitate efficient use of this program.

COFECHA works by statistically creating a master chronology with the cores that the operator enters into the program. This means that if undated series are entered into the program then the master chronology will be useless. COFECHA takes the ring width measurements that were obtained from a measuring stage and, by default, fits a 32-year cubic smoothing spline to the cores for standardization. Next, it averages all of the index series for all of the cores together to create the master chronology. It then removes the core that is about to be analyzed, cuts it into 50-year segments with 25 years of overlap, and statistically correlates each segment against the master chronology. If the correlation is below the specified confidence level, which is set at 99% by default, then COFECHA checks from -10 to +10 lag years for a better match. If it finds a better match it reports a B flag in the output; if it does not find a better match it reports an A flag for that segment, simply meaning that it has a low correlation. This is the basic concept of how COFECHA works and I will go through the specific key strokes in running the program in the following section.

Keystroke Tutorial of COFECHA

To start the program, double-click on COFECHA.EXE in your directory (see Holmes (1983) or Grissino-Mayer (2001) for more information on COFECHA). A DOS command box for the program will open (Figure 6.9). The first entry that the program asks for is a five digit identifier for your program run. This identifier will be tacked on as a prefix on any subsequent file created by this program and should enable you to later (10 years down the road) understand what the file contains. I usually use a three letter site designation with possibly one letter for species if I have sampled multiple species on a site, and then a number at the end that can progress each time a new run is started (such as MORQ1 for Mogan Ridge Quercus first run). You will find that you will sometimes run COFECHA many times per site before you are done with the chronology. The next question will ask you to enter the existing input file name. Remember that the file name must be eight digits or less and not include any spaces or odd characters. COFECHA can

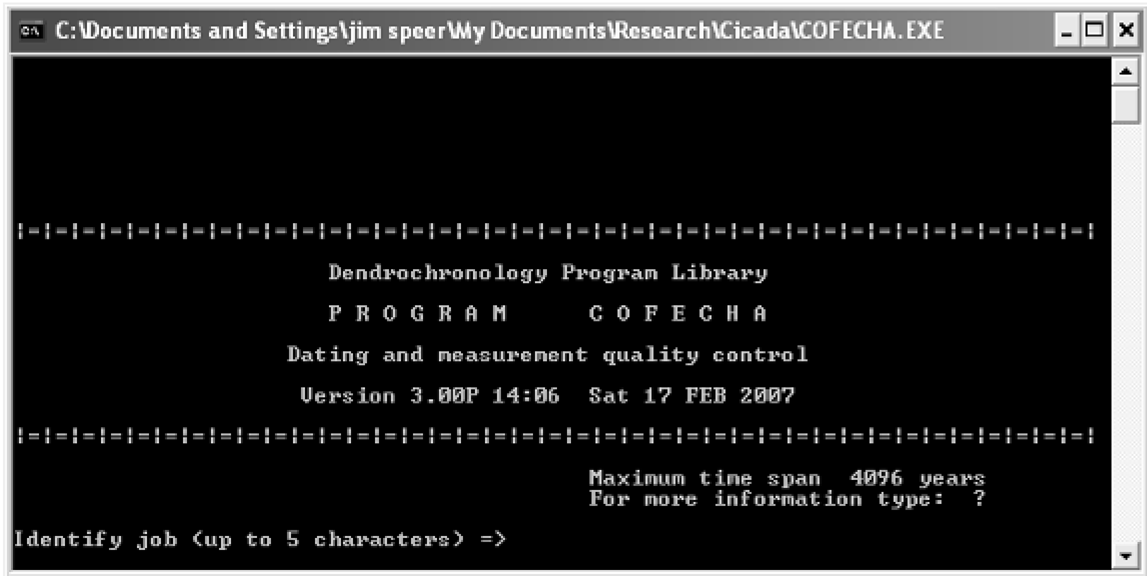

Figure 6. 9 Introductory screen of COFECHA in a DOS command line box.

read files in many different formats: compact, measurement, indices, Accurite measurements, meteorological, spreadsheet, single column of values, two columns of values, or a user defined protocol. COFECHA will automatically recognize most of these formats and ask you if it has identified the correct format. Next it will ask for the file name containing samples to run as undated tree-ring series. COFECHA can attempt to date undated series by breaking the series into 50-year segments and statistically testing each segment against the master chronology but not include it in the master chronology. The output from this option will show up as Part 8 in the COFECHA output near the bottom of the .OUT file. Assuming that you do not want to enter undated series into COFECHA, simply hit enter. The next option is a title for this run which can be 36 characters including spaces and odd characters. The title should be an informative description for each run. It is useful to type out the site name, species, and any other notes for this run in the title. Remember that you might be looking back at these files in 10 years and not have any idea what the very short file names mean. This is your chance to mark the file with needed information to remind you of this research project at a later date. When you are done entering the title for this run, hit enter to get to the next stage of the program.

The heart of COFECHA is the table that allows you to change the spline length for creation of the master chronology, change the segment length and overlap, run an autoregressive model, change the critical level of correlation (which will be based on your segment length or N), decide whether to save the master dating series, list the ring width measurements in the output, list the parts of the output to include, and decide whether to calculate absent rings in the master series (Figure 6.10). The default options in this program are listed on the right side of the screen and are usually applicable to most purposes. Richard Holmes tested a series of spline lengths in

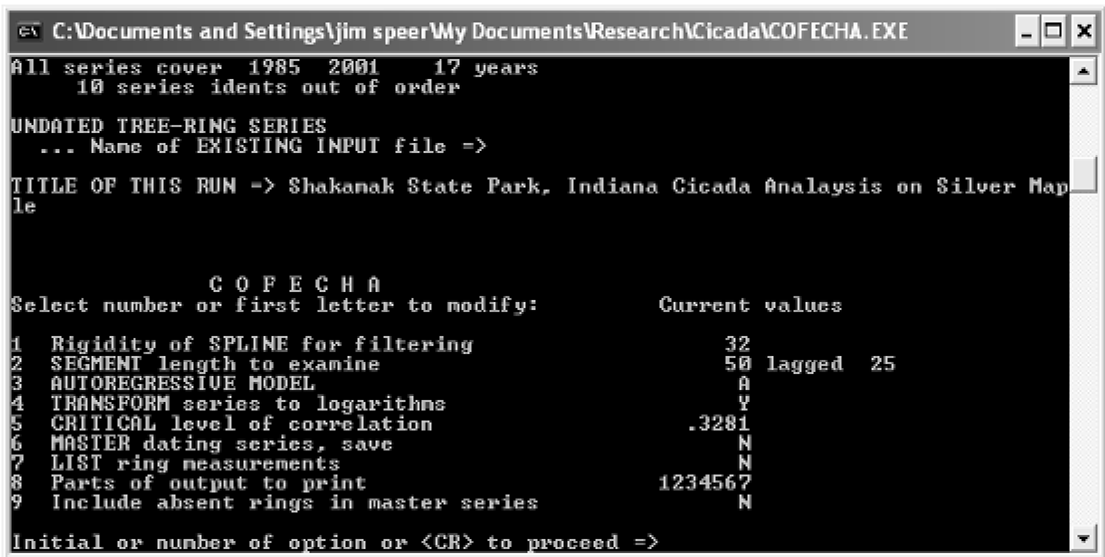

Figure 6. 10 Command line driven DOS box for COFECHA showing the series summary at the top of the screen, the line for Undated tree-ring series input file, the Title of this run line with data entered, and the table that offers options to control the analysis.

creating the master chronology and found that the 32-year cubic smoothing spline is the most appropriate spline length for enhancing the interannual variability that leads to strong dating. The segment length is optimal for providing a high N for statistical tests and providing the flexibility to pin-point where missing or false rings may occur in the chronology. These segments are lagged, by default, at 25 years, again making it possible to pin-point dating problems.

To make changes in the main table in COFECHA, use the program submenus that are keyed by the number associated with the function. To adjust any of the values in this table, simply type the number on the left side of the screen that correlates to that object. For example, to make a change from a 50 years segment with a 25 year overlap to a 30 year segment with a 10 year overlap, type "2" and hit enter. A submenu then opens and asks for the length of the segment. Type "30" and hit enter. A prompt comes up asking for the lag between segments. Type "10" and hit enter. Because the N has been reduced from 50 years to 30 years of comparison, the critical level automatically adjusts from 0.3281 to 0.4226.

As I mentioned before, the default options in this table work well for most analyses. To run the program, hit Enter once you have made any changes that you want in the table. The program will then execute and very quickly display on the screen the progress of the program and finally the correlation of each core with the master, as shown by a series of brackets where each bracket represents a 0.05 overall correlation (Figure 6.11). This will flash by on the screen and the program will exit itself. An output file with the result of the run is placed in the directory where

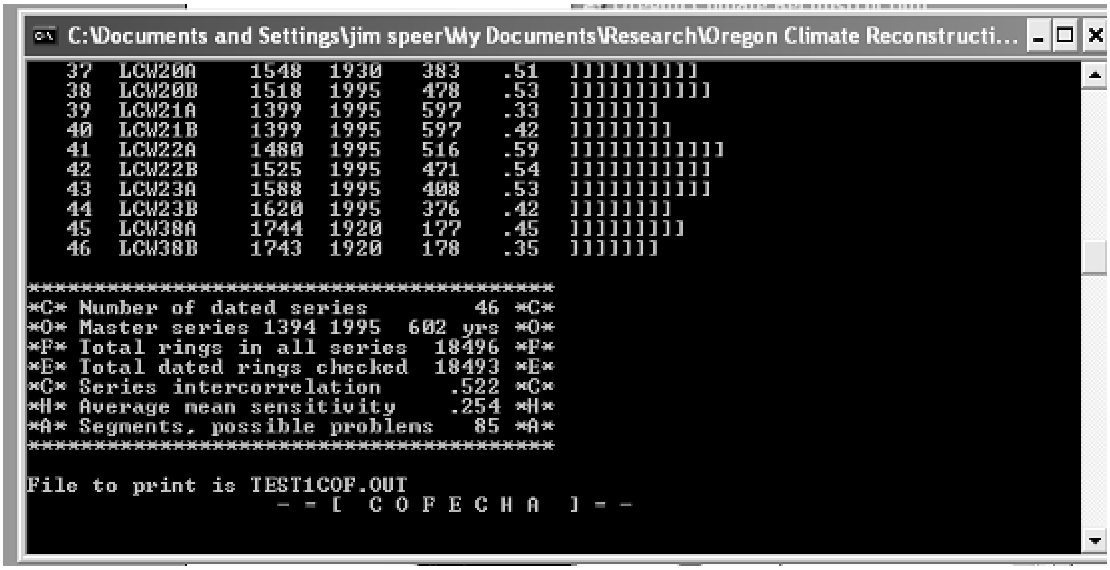

Figure 6. 11 The end of the information that flashes on the screen while COFECHA runs. In the top half of the screen is the summary of how each core correlated with the master chronology and the graphical representation is in the right column. The box in stars contains the summary statistics for the chronology that will also be reported on the first page of the COFECHA output.

you ran the program. The file will begin with the prefix that you entered at the beginning of this run, the three letters COF to designate this as a COFECHA file, and the suffix .out.

Reading the Output of COFECHA

The output file contains all of the summary statistics about the master chronology, the correlation of each core with that master, and some descriptive statistics for each core. The first page of the output provides the program name and version, the date of the run, the title that was entered, as well as the file name used in the analysis, the parts included in the output, and the control options that were selected during the run (Figure 6.12). The bottom half of the page contains the summary statistics for the chronology, starting with the time span of the master chronology, the entire continuous time span for the chronology, and the portion of the chronology with a sample depth of two or more series. Next, COFECHA provides a warning of any rings that are inserted as absent on only one series.

The table bracketed by stars in Part 1 is the most important summary of the COFECHA run, much of which should be reported in a research paper. The table presents the number of dated series, the master chronology length, the total number of rings in all series, and the total number of dated rings (as in those that overlap with at least one other chronology), the series intercorrelation, the mean sensitivity, and the segments with possible problems. The series intercorrelation is a measure of the stand-level signal and mean sensitivity is a measure of the year-to-year variability in the master chronology. These two statistics should be reported in any publication as they are the most comparable measure of site-level signal and sensitivity between

```
[]  DENDROCHRONOLOGY PROGRAM LIBRARY                                           Run LCWEX  Program COF  22:29  Thu 22 FEB 2007  Page   1
[]
[]  P R O G R A M      C O F E C H A                                                                      Version 3.00P    26352
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QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

Title of run:           Sample Cofecha Run for the Lava Cast For

File of DATED series:   lcwexample.rwl

CONTENTS:

   Part 1:  Title page, options selected, summary, absent rings by series
   Part 2:  Histogram of time spans
   Part 3:  Master series with sample depth and absent rings by year
   Part 4:  Bar plot of Master Dating Series
   Part 5:  Correlation by segment of each series with Master
   Part 6:  Potential problems: low correlation, divergent year-to-year changes, absent rings, outliers
   Part 7:  Descriptive statistics

RUN CONTROL OPTIONS SELECTED                             VALUE

        1  Cubic smoothing spline 50% wavelength cutoff for filtering
                                                           32 years
        2  Segments examined are                           50 years lagged successively by  25 years
        3  Autoregressive model applied                     A  Residuals are used in master dating series and testing
        4  Series transformed to logarithms                 Y  Each series log-transformed for master dating series and testing
        5  Critical correlation, 99% confidence level   .3281
        6  Master dating series saved                       N
        7  Ring measurements listed                         N
        8  Parts printed                              1234567
        9  Absent rings included in master series           N

Time span of Master dating series is  1394 to  1995   602 years
Continuous time span is               1394 to  1995   602 years
Portion with two or more series is    1397 to  1995   599 years

  >> WARNING:  Year  1850 absent in    1 of   45 series; Master Series value  -.011
  >> WARNING:  Year  1980 absent in    1 of   39 series; Master Series value   .490

                                       ****************************************
                                       *C* Number of dated series        46 *C*
                                       *O* Master series 1394 1995  602 yrs *O*
                                       *F* Total rings in all series  18495 *F*
                                       *E* Total dated rings checked  18492 *E*
                                       *C* Series intercorrelation     .520 *C*
                                       *H* Average mean sensitivity    .254 *H*
                                       *A* Segments, possible problems   88 *A*
                                       ****************************************

ABSENT RINGS listed by SERIES:            (See Master Dating Series for absent rings listed by year)

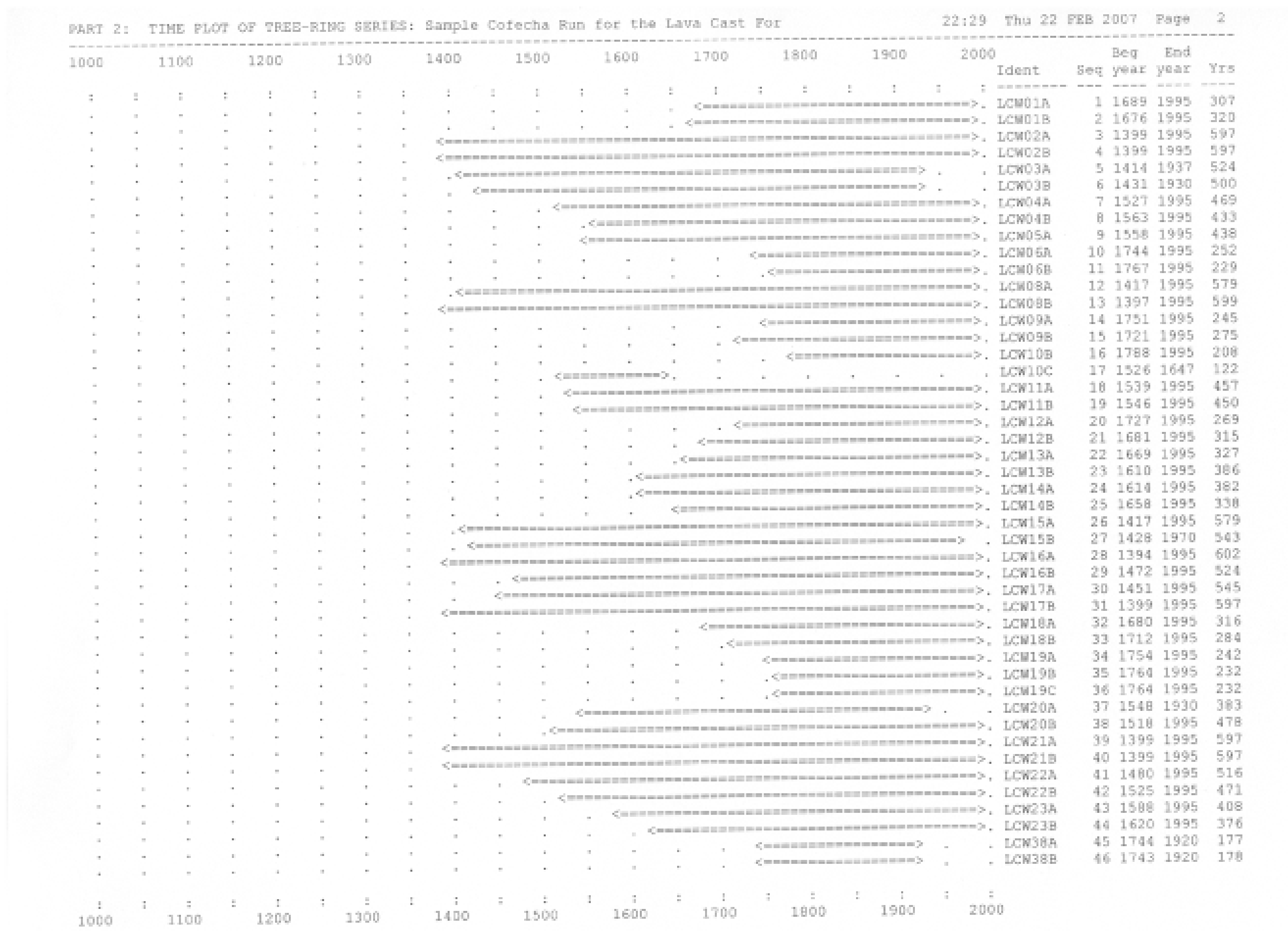
LCW04A      1 absent rings:   1804
LCW06A      2 absent rings:   1935  1980
LCW06B      1 absent rings:   1935
LCW08B      2 absent rings:   1930  1936
LCW11A      1 absent rings:   1899
LCW13A      1 absent rings:   1935
```

Figure 6. 12 COFECHA output page 1.

sites. These statistics are described in greater detail in the sections below. Finally, a complete list of any absent rings is listed by core.

Part 2 of the COFECHA output is a graphic representation of the length of the chronology (Figure 6.13). It also summarizes the sequence number (which can provide an easy way to navigate the COFECHA output), the beginning and end years of each series, and the total number of years in each series.

Part 3 contains the master chronology in a three column format, including the year, the index value, and the sample depth (Figure 6.14). Remember that COFECHA standardizes the series with a cubic smoothing spline of your choice or the default 32-year spline. Each core is standardized and then the master chronology is created by averaging together the index series for each core. Because the master chronology in Part 3 records the index value for each year, it can be used to identify extremely small rings that may be missing in other cores. I find the sample depth to be the most useful column in this part of the output because it is the only place where it is recorded for the master chronology. This information can be used to determine where your master chronology has enough samples included in the chronology to provide an accurate stand-level signal. A general rule is to have a minimum sample depth of 10 cores for a well-replicated stand-level signal, although 20 is more robust and chronologies have been used with fewer cores. A site's sensitivity to climate will determine how many cores are necessary to average out the individual tree-level noise and to reinforce the stand-level signal. Earlier in this chapter I described the Expressed Population Signal (EPS) which is a statistical measure of adequate replication. In order to maintain sufficient sample depth, many years often have to be cut out of



PART 2: TIME PLOT OF TREE-RING SERIES: Sample Cofecha Run for the Lava Cast For 22:29 Thu 22 FEB 2007 Page 2

Ident	Seq	Beg year	End year	Yrs
LCW01A	1	1689	1995	307
LCW01B	2	1676	1995	320
LCW02A	3	1399	1995	597
LCW02B	4	1399	1995	597
LCW03A	5	1414	1937	524
LCW03B	6	1431	1930	500
LCW04A	7	1527	1995	469
LCW04B	8	1563	1995	433
LCW05A	9	1558	1995	438
LCW06A	10	1744	1995	252
LCW06B	11	1767	1995	229
LCW08A	12	1417	1995	579
LCW08B	13	1397	1995	599
LCW09A	14	1751	1995	245
LCW09B	15	1721	1995	275
LCW10B	16	1788	1995	208
LCW10C	17	1526	1647	122
LCW11A	18	1539	1995	457
LCW11B	19	1546	1995	450
LCW12A	20	1727	1995	269
LCW12B	21	1681	1995	315
LCW13A	22	1669	1995	327
LCW13B	23	1610	1995	386
LCW14A	24	1614	1995	382
LCW14B	25	1658	1995	338
LCW15A	26	1417	1995	579
LCW15B	27	1428	1970	543
LCW16A	28	1394	1995	602
LCW16B	29	1472	1995	524
LCW17A	30	1451	1995	545
LCW17B	31	1399	1995	597
LCW18A	32	1680	1995	316
LCW18B	33	1712	1995	284
LCW19A	34	1754	1995	242
LCW19B	35	1764	1995	232
LCW19C	36	1764	1995	232
LCW20A	37	1548	1930	383
LCW20B	38	1518	1995	478
LCW21A	39	1399	1995	597
LCW21B	40	1399	1995	597
LCW22A	41	1480	1995	516
LCW22B	42	1525	1995	471
LCW23A	43	1588	1995	408
LCW23B	44	1620	1995	376
LCW38A	45	1744	1920	177
LCW38B	46	1743	1920	178

Figure 6. 13 Part 2 of COFECHA lists and graphically depicts the length of each core.

PART 3: Master Dating Series: Sample Cofecha Run for the Lava Cast For 22:29 Thu 22 FEB 2007 Page 4

Year	Value	No	Ab
1400	-1.519	7	
1401	.100	7	
1402	1.662	7	
1403	.514	7	
1404	1.597	7	
1405	2.050	7	
1406	.816	7	
1407	-.745	7	
1408	-.384	7	
1409	.233	7	
1410	-2.045	7	
1411	-.891	7	
1412	.201	7	
1413	-1.246	7	
1414	-.957	8	
1415	.345	8	
1416	-.668	8	
1417	-.168	10	
1418	.312	10	
1419	.945	10	
1420	1.020	10	
1421	1.633	10	
1422	.806	10	
1423	1.951	10	
1424	.505	10	
1425	-.958	10	
1426	-.197	10	
1427	-.217	10	
1428	-3.401	11	
1429	.802	11	
1430	.164	11	
1431	-.149	12	
1432	-1.410	12	
1433	-1.331	12	
1434	-.033	12	
1435	.395	12	
1436	-2.388	12	
1437	.296	12	
1438	.519	12	
1439	-.068	12	
1440	-.206	12	
1441	.404	12	
1442	1.002	12	
1443	-.034	12	
1444	.028	12	
1445	.185	12	
1446	-.140	12	
1447	1.923	12	
1448	.197	12	
1449	.473	12	
1450	-.824	12	
1451	-.385	13	
1452	-.589	13	
1453	.729	13	
1454	.894	13	
1455	.231	13	
1456	.726	13	
1457	-.338	13	
1458	-.284	13	
1459	-.043	13	
1460	-.498	13	
1461	-.576	13	
1462	.708	13	
1463	-.164	13	
1464	-.602	13	
1465	.096	13	
1466	-.639	13	
1467	.738	13	
1468	-.017	13	
1469	1.385	13	
1470	.426	13	
1471	.260	13	
1472	-.324	14	
1473	.220	14	
1474	.142	14	
1475	.730	14	
1476	.198	14	
1477	-.044	14	
1478	.619	14	
1479	-.818	14	
1480	-.584	15	
1481	-2.285	15	
1482	-1.997	15	
1483	-1.373	15	
1484	-.575	15	
1485	1.130	15	
1486	.265	15	
1487	-.414	15	
1488	-.010	15	
1489	-1.251	15	
1490	1.477	15	
1491	.776	15	
1492	.871	15	
1493	.516	15	
1494	.354	15	
1495	-.002	15	
1496	2.205	15	
1497	.317	15	
1498	-.095	15	
1499	-1.360	15	
1500	-.225	15	
1501	-.003	15	
1502	-.164	15	
1503	.982	15	
1504	.120	15	
1505	-2.055	15	
1506	.599	15	
1507	1.177	15	
1508	.148	15	
1509	1.365	15	
1510	-.402	15	
1511	.909	15	
1512	.172	15	
1513	-.888	15	
1514	.746	15	
1515	-1.150	15	
1516	-.982	15	
1517	.270	15	
1518	-.322	16	
1519	-.421	16	
1520	-1.213	16	
1521	-1.660	16	
1522	-1.397	16	
1523	-.095	16	
1524	1.555	16	
1525	2.111	17	
1526	.104	18	
1527	-.069	19	
1528	1.711	19	
1529	-3.536	19	2
1530	1.308	19	
1531	.801	19	
1532	-.286	19	
1533	.274	19	
1534	.063	19	
1535	.374	19	
1536	1.608	19	
1537	-1.245	19	
1538	-.091	19	
1539	.917	20	
1540	-1.059	20	
1541	-.800	20	
1542	-.084	20	
1543	.828	20	
1544	.793	20	
1545	-.055	20	
1546	-.162	21	
1547	1.688	21	
1548	.011	22	
1549	.222	22	
1550	-3.514	22	
1551	-.168	22	
1552	-.900	22	
1553	.162	22	
1554	-.876	22	
1555	.214	22	
1556	-.774	22	
1557	.214	22	
1558	.600	23	
1559	1.048	23	
1560	1.782	23	
1561	.296	23	
1562	.643	23	
1563	.524	24	
1564	1.345	24	
1565	-1.035	24	
1566	-.271	24	
1567	-1.219	24	
1568	-.802	24	
1569	-.729	24	
1570	-.179	24	
1571	-1.003	24	
1572	.213	24	
1573	-.322	24	
1574	.631	24	
1575	1.385	24	
1576	-.097	24	
1577	.898	24	
1578	.974	24	
1579	.379	24	
1580	.726	24	
1581	-2.729	24	
1582	.046	24	
1583	-.705	24	
1584	.196	24	
1585	.110	24	
1586	-1.293	24	
1587	-.483	24	
1588	1.463	25	
1589	.826	25	
1590	.791	25	
1591	-.219	25	
1592	.908	25	
1593	.699	25	
1594	-.994	25	
1595	.476	25	
1596	-.090	25	
1597	.457	25	
1598	-1.530	25	
1599	-.538	25	
1600	-1.684	25	
1601	-.177	25	
1602	.611	25	
1603	-1.670	25	
1604	-.212	25	
1605	.326	25	
1606	.587	25	
1607	-.247	25	
1608	.263	25	
1609	-.222	25	
1610	1.255	26	
1611	.847	26	
1612	-.043	26	
1613	1.277	26	
1614	.829	27	
1615	-.144	27	
1616	.190	27	
1617	1.670	27	
1618	1.848	27	
1619	-.871	27	
1620	.295	28	
1621	-.655	28	
1622	-1.624	28	
1623	-2.211	28	
1624	-.382	28	
1625	.318	28	
1626	.061	28	
1627	.815	28	
1628	.748	28	
1629	-2.133	28	
1630	-.078	28	
1631	-1.552	28	
1632	-1.684	28	
1633	-.480	28	
1634	-.532	28	
1635	-.692	28	
1636	.172	28	
1637	.516	28	
1638	.265	28	
1639	-.578	28	
1640	.967	28	
1641	2.530	28	
1642	1.391	28	
1643	.334	28	
1644	-.348	28	
1645	.843	28	
1646	-.141	28	
1647	.341	28	
1648	1.328	27	
1649	1.213	27	
1650	.539	27	
1651	-.568	27	
1652	-4.794	27	2
1653	-.761	27	
1654	-.018	27	
1655	.131	27	
1656	.499	27	
1657	-.570	27	
1658	.846	28	
1659	.336	28	
1660	.592	28	
1661	-1.211	28	
1662	-1.301	28	
1663	-.635	28	
1664	-.890	28	
1665	-1.476	28	
1666	-.333	28	
1667	.101	28	
1668	.153	28	
1669	.479	29	
1670	.784	29	
1671	.558	29	
1672	1.416	29	
1673	1.776	29	
1674	1.327	29	
1675	1.103	29	
1676	1.259	30	
1677	-1.005	30	2
1678	.012	30	
1679	-.188	30	
1680	-.742	31	
1681	-.062	32	
1682	-1.640	32	
1683	-1.511	32	
1684	-.574	32	
1685	-.839	32	
1686	-.217	32	
1687	.160	32	
1688	-.453	32	
1689	.538	33	
1690	1.565	33	
1691	.507	33	
1692	1.131	33	
1693	.094	33	
1694	1.325	33	
1695	-3.277	33	
1696	.656	33	
1697	.903	33	
1698	.006	33	
1699	.174	33	

Figure 6. 14 COFECHA Part 3 shows the index values and sample depth for the master chronology.

the final analysis because there are not enough overlapping series to demonstrate a stand-level signal. It is important to note, however, that as long as there is agreement of dates between series (at least two cores for a time period) then it may be possible to record events at the tree level for those cores and have some confidence that the dating is accurate.

Part 4 is a graphical representation of the master chronology and is a good way for quickly observing the dates of narrow rings and determining how small the rings are compared to the rest of the chronology (Figure 6.15). An @ symbol indicates an average ring, upper case letters are wider than average rings, and lower case letters are smaller than average rings. The further up the alphabet, the larger or smaller the ring is. In the example given in Figure 6.15, a lower case "s" for 1652 means that this ring is extremely small and is actually one of the smallest rings in the chronology. An uppercase "C" at 1670 means that the ring is larger than, but not much different than the mean.

Part 5 summarizes the correlation of each segment against the master chronology (Figure 6.16). Remember that to date the core, COFECHA took all of the measured series and, by default, broke them into 50 year segments with 25 years of overlap. Then it statistically correlated each segment to the master chronology, minus the core being analyzed, at the date those rings were assigned. This section of the output reports the correlation of each 50 year segment to the master for each core with 25 years of overlap in the segments. COFECHA also marks poor correlations with either an "A" or a "B" flag. An "A" flag next to a segment correlation means that segment correlated below the critical level designated in this COFECHA run. A "B" flag means that COFECHA found a better correlation for that segment in a 20 year window of -10 to + 10 years

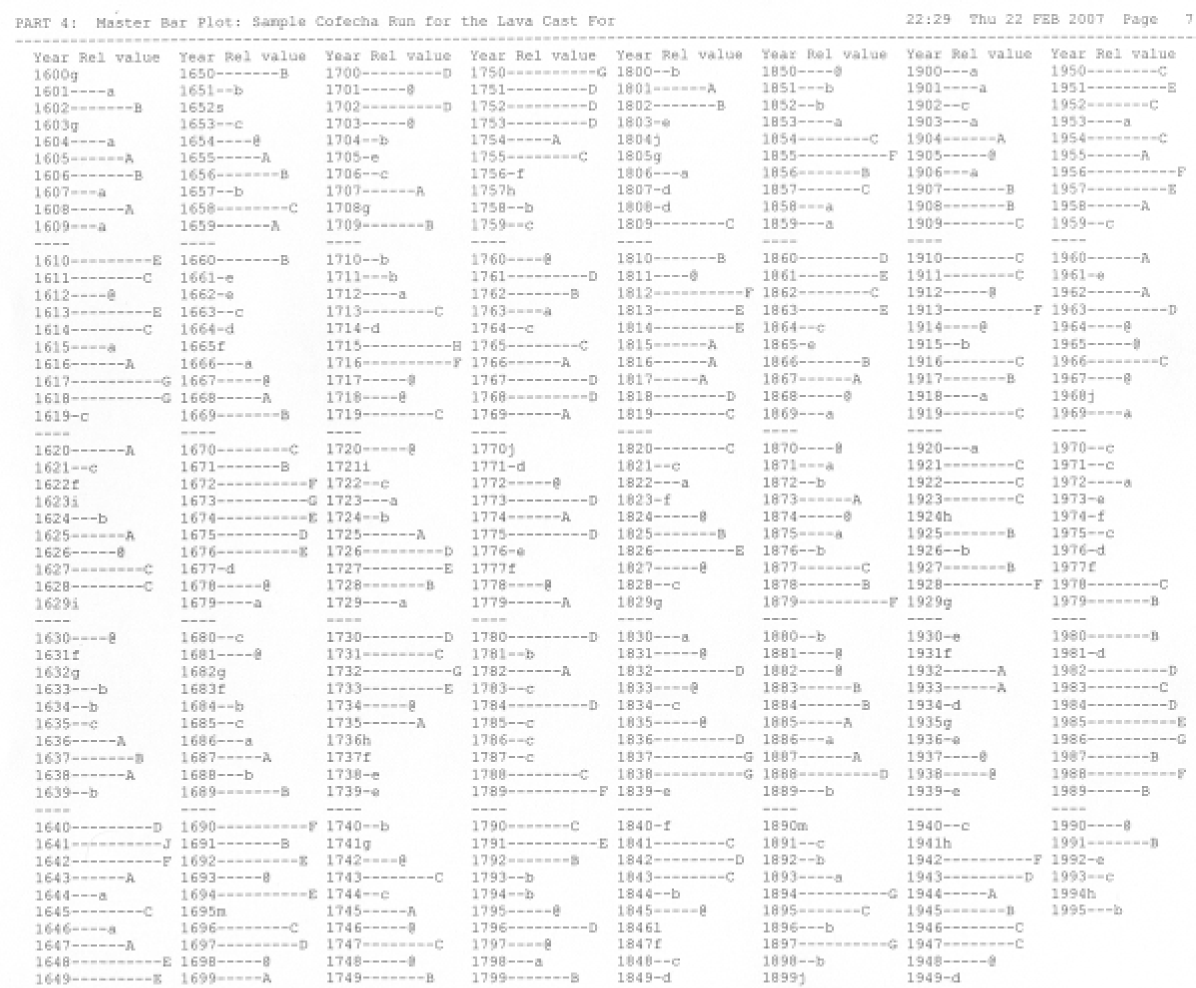


Figure 6. 15 COFECHA Part 4 provides a graphical representation of the master chronology. The @ symbol is an average ring, uppercase letters are larger than average rings, and lower case letters are smaller than average rings. The further up the alphabet, the larger or smaller the ring.

PART 5: CORRELATION OF SERIES BY SEGMENTS: Sample Cofecha Run for the Lava Cast 22:29 Thu 22 FEB 2007 Page 5

Correlations of 50-year dated segments, lagged 25 years
Flags: A = correlation under .3281 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1375 1424	1400 1449	1425 1474	1450 1499	1475 1524	1500 1549	1525 1574	1550 1599	1575 1624	1600 1649	1625 1674	1650 1699	1675 1724	1700 1749	1725 1774	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899
1	LCW01A	1689 1995													.52	.52	.55	.51	.51	.79	.72	.60
2	LCW01B	1676 1995													.58	.70	.68	.46	.43	.69	.73	.43
3	LCW02A	1399 1995	.65	.65	.48	.29A	.53	.60	.64	.73	.71	.53	.57	.55	.58	.80	.52	.48	.57	.60	.64	.61
4	LCW02B	1399 1995	.56	.55	.39	.30A	.46	.60	.72	.71	.61	.51	.61	.63	.46	.35	.36	.56	.35	.16B	.21B	.25B
5	LCW03A	1414 1937		.47	.48	.36B	.32B	.34	.52	.44	.50	.65	.75	.72	.63	.49	.39	.51	.66	.46	.23B	.38
6	LCW03B	1431 1930			.49	.53	.48	.47	.57	.47	.43	.58	.79	.70	.46	.49	.45	.39	.55	.63	.53	.56
7	LCW04A	1527 1995							.55	.52	.59	.78	.68	.64	.63	.53	.60	.51	.41B	.51	.37	.47
8	LCW04B	1563 1995								.65	.69	.72	.77	.83	.81	.66	.68	.55	.46	.64	.54	.59
9	LCW05A	1558 1995								.41	.50	.58	.68	.81	.81	.66	.44	.32A	.53	.76	.66	.49
10	LCW06A	1744 1995															.36	.40	.32B	.43	.62	.53
11	LCW06B	1767 1995																.39	.26A	.43	.48	.44
12	LCW08A	1417 1995		.47	.44	.40	.62	.71	.69	.48	.32A	.37B	.70	.81	.57	.30A	.39B	.50	.50	.57	.53	.59
13	LCW08B	1397 1995	.59	.61	.50	.47	.61	.65	.75	.60	.46	.58	.62	.59	.52	.39	.56	.42	.27A	.50	.55	.65
14	LCW09A	1751 1995																.47	.59	.64	.53	.50
15	LCW09B	1721 1995														.44	.50	.39	.53	.69	.66	.60
16	LCW10B	1788 1995																	.16B	.25B	.15B	.41
17	LCW10C	1526 1647							.50	.37	.43	.45										
18	LCW11A	1539 1995							.41	.42	.56	.62	.82	.73	.66	.69	.67	.61	.54	.65	.59	.67
19	LCW11B	1546 1995							.43	.40	.52	.58	.74	.63	.47	.56	.75	.70	.61	.67	.56	.56
20	LCW12A	1727 1995															.70	.53	.56	.74	.68	.66
21	LCW12B	1681 1995													.71	.59	.75	.68	.63	.71	.62	.64
22	LCW13A	1669 1995												.68	.75	.65	.72	.70	.24B	.38	.40	.21B
23	LCW13B	1610 1995										.71	.68	.56	.55	.57	.66	.66	.41	.55	.68	.51
24	LCW14A	1614 1995										.61	.72	.67	.64	.52	.58	.62	.62	.57	.42	.53
25	LCW14B	1658 1995												.57	.55	.51	.46	.49	.53	.59	.43	.49
26	LCW15A	1417 1995		.30A	.25A	.40	.61	.62	.68	.68	.70	.59	.53	.60	.61	.68	.65	.48	.33B	.54	.59	.48
27	LCW15B	1428 1970			.25B	.28B	.49	.69	.82	.72	.56	.47	.63	.78	.59	.55	.68	.62	.47	.53	.56	.34
28	LCW16A	1394 1995	.60	.52	.19B	.25A	.58	.78	.73	.69	.74	.79	.59	.50	.60	.66	.66	.54	.22B	.44	.59	.27B
29	LCW16B	1472 1995				.61	.66	.85	.74	.57	.51	.58	.55	.49	.57	.48	.60	.67	.47	.65	.72	.33
30	LCW17A	1451 1995				.15B	.38	.56	.51	.51	.61	.39	.42B	.51	.41	.37	.42	.45	.57	.71	.62	.49
31	LCW17B	1399 1995	.52	.50	.30A	.23B	.42	.62	.45	.18B	.19B	.35	.60	.61	.54	.53	.23B	.18B	.49	.60	.43	.16B
32	LCW18A	1680 1995													.47	.59	.54	.42	.65	.69	.57	.57
33	LCW18B	1712 1995														.48	.40	.44	.71	.69	.57	.60
34	LCW19A	1754 1995																.50	.57	.34B	.29B	.60
35	LCW19B	1764 1995																.52	.48	.43	.36B	.46
36	LCW19C	1764 1995																.53	.54	.51	.47	.47
37	LCW20A	1548 1930							.61	.62	.55	.60	.58	.35	.43	.66	.54	.55	.61	.59	.53	.32B
38	LCW20B	1518 1995						.69	.73	.65	.51	.53	.68	.76	.51	.20B	.36	.42	.49	.61	.58	.46
39	LCW21A	1399 1995	.35	.36	.26B	.20B	.24B	.29B	.34	.10B	.07B	.35	.51	.38	.04B	.10B	.40B	.46	.56	.57	.42	.40
40	LCW21B	1399 1995	.37	.35	.27A	.34	.39	.54	.50	.28A	.31A	.53	.58	.53	.39	.40	.27A	.25A	.42	.51	.49	.39
41	LCW22A	1480 1995					.66	.74	.76	.67	.61	.55	.65	.64	.63	.63	.64	.64	.65	.56	.38	.32A
42	LCW22B	1525 1995							.73	.56	.58	.68	.72	.65	.37	.43	.59	.52	.51	.62	.49	.28A
43	LCW23A	1588 1995									.53	.50	.57	.65	.79	.65	.44	.39	.47	.54	.50	.52
44	LCW23B	1620 1995										.41	.46	.60	.48	.46	.30A	.25A	.38	.46	.40	.62
45	LCW38A	1744 1920															.57	.55	.40	.44	.39	.41
46	LCW38B	1743 1920															.52	.49	.33	.46	.35B	.18B

Figure 6. 16 COFECHA Part 5 shows the correlation of each 50-year segment to the master. An "A" flag means that the series dated best where it was, but the correlation was below the critical level defined on page 1, and a "B" flag means that segment correlates better within a 20 year window of where it is currently dated.

from the place where it is currently dated. This section is useful because it displays the correlation of each segment to the master and is the only place in COFECHA where all of the correlations for all of the segments are reported. Part 6 will report poorly correlated segments, but not the results of the highly correlated segments. One has to refer back to part 5 for that information.

Part 6 presents each core, one at a time, with a closer look at how well it correlates to the master and reports any measurements that are outliers (Figure 6.17). The core name is given in the top left corner and a series number is assigned to each core based on its order in the file. These series numbers can be used to find the cores more easily in COFECHA or other dendrochronological programs such as EDT (also called EDRM). Section A in Part 6 is printed only when segments have a low correlation (as shown by an “A” flag in Part 5) or a better date somewhere else in the 20 year window around the present date for the segment (as shown by a “B” flag in Part 5). Section B is always presented showing the five years that added the most weight to the correlation, labeled “higher”, and the five years that lowered the correlation the most, labeled “lower”. This section also provides the correlation of each series to the master. Section C presents any year-to-year differences (such as an acute increase or decrease in growth from one year to the next) that were unexpected based on the master chronology. Any absent rings in a core will be presented in section D, along with a comparison to what the master shows. Section E presents any ring width measurements that are more than three standard deviations from the mean. Because environmental effects on the trees are likely to cause rings that are larger or smaller than the mean, I am concerned mainly when rings are five or more standard deviations off of the mean; then the measurements should be rechecked for human error.

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PART 6:  POTENTIAL PROBLEMS: Sample Cofecha Run for the Lava Cast For                    22:29  Thu 22 FEB 2007  Page   6
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For each series with potential problems the following diagnostics may appear:

[A] Correlations with master dating series of flagged  50-year segments of series filtered with  32-year spline,
    at every point from ten years earlier (-10) to ten years later (+10) than dated

[B] Effect of those data values which most lower or raise correlation with master series

[C] Year-to-year changes very different from the mean change in other series

[D] Absent rings (zero values)

[E] Values which are statistical outliers from mean for the year
========================================================================================================================

LCW01A     1689 to  1995     307 years                                                                      Series   1

[B] Entire series, effect on correlation (  .622) is:
      Lower   1883  -.013   1731  -.007   1910  -.006   1738  -.006  Higher   1890   .017   1960   .013   1770   .012   1846   .010

========================================================================================================================

LCW01B     1676 to  1995     320 years                                                                      Series   2

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
  ---------   ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
  1875 1924    -1    .05 -.07  .10  .15 -.20 -.11  .07 -.23 -.12  .35* .32| .16  .11 -.28 -.13  .04 -.09 -.14  .22  .16  .09

[B] Entire series, effect on correlation (  .560) is:
      Lower   1897  -.010   1776  -.007   1767  -.007   1994  -.006  Higher   1968   .011   1770   .011   1721   .010   1839   .006
    1875 to 1924 segment:
      Lower   1897  -.057   1896  -.016   1906  -.015   1900  -.011  Higher   1890   .075   1879   .028   1880   .016   1913   .012

========================================================================================================================

LCW02A     1399 to  1995     597 years                                                                      Series   3

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
  ---------   ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
  1450 1499     0    .06  .14  .10 -.09  .01 -.15 -.07 -.19  .04 -.03  .29*-.01 -.03 -.08 -.30  .19  .14  .18  .12 -.16 -.11

[B] Entire series, effect on correlation (  .558) is:
      Lower   1452  -.009   1817  -.007   1762  -.007   1544  -.006  Higher   1652   .017   1529   .007   1581   .006   1428   .005
    1450 to 1499 segment:
      Lower   1452  -.052   1492  -.036   1482  -.033   1483  -.030  Higher   1496   .088   1481   .084   1485   .031   1499   .018

========================================================================================================================

LCW03B     1431 to  1930     500 years                                                                      Series   6

[B] Entire series, effect on correlation (  .524) is:
      Lower   1925  -.008   1711  -.005   1622  -.005   1463  -.005  Higher   1652   .018   1890   .014   1846   .007   1529   .006

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1829 -5.0 SD

========================================================================================================================
```

Figure 6. 17 COFECHA Part 6 provides core-level analysis of how well each core dates against the master, shows the 20 year window of possible other dates for problem segments, shows the effect of the best and worst segments on the overall correlation, and shows any outliers that are more than 3 standard deviations from the mean so that those measurements can be checked for accuracy.

The four cores presented in Figure 6.17 all date well, although the middle two (LCW01B and LCW02A) have been flagged with a “B” flag and “A” flag respectively in Part 5. Core LCW01B correlates better at a -1 shift for the 1875-1924 segment. If the outside (bark side) is the known date of coring and should not be shifted, then the segment to be shifted falls in the middle of the series and necessitates not only a missing ring near the modern part of the segment, but also a false ring near the older part of the segment. Although the occurrence of both missing and false rings in a 50 year segment is certainly possible, note that the correction would only lead to a 0.029 increase in correlation (from 0.321 to 0.350), a small increase for a lot of change in dating. This kind of flag obliges the researcher to go back to the wood. In this case after checking the sample, I ruled this a spurious correlation and left the core the way it was dated. Core LCW02A has an “A” flag because the segment from 1450 – 1499 correlated at 0.29 with the master which is below the critical level. Again, after checking the growth on the sample and seeing nothing anomalous, I left this core alone with no correction. The four cores shown on this page of Part 6 correlated with the master at 0.622, 0.560, 0.558, and 0.524, which are good correlations for this site. It is important to realize that there is no specific threshold that will guarantee that a core is well dated or not. The correlation depends upon the species being analyzed and the site characteristics. Once a researcher has worked in a region and with a tree species for some time, one can learn what a good score is and use that for a benchmark.

In contrast to the case of LCW01B in figure 6.17, LCW10B in figure 6.18 has three segments in a row that suggest a clear -1 shift: they are at one end of the core and the correlation of each overlapping segment increases dramatically with the shift (for example from 0.16 to 0.70 for 1788-1837. This type of pattern clearly designates that there is a missing ring in the series and

```
LCW09A    1751 to  1995     245 years                                                                              Series  14

[B] Entire series, effect on correlation (  .562) is:
      Lower   1838  -.017   1869  -.011   1947  -.011   1864  -.007  Higher   1924   .015   1804   .014   1846   .012   1929   .009
=================================================================================================================================

LCW09B    1721 to  1995     275 years                                                                              Series  15

[B] Entire series, effect on correlation (  .530) is:
      Lower   1972  -.012   1721  -.010   1757  -.009   1755  -.009  Higher   1968   .020   1890   .019   1924   .013   1770   .013

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1939 -4.8 SD
=================================================================================================================================

LCW10B    1788 to  1995     208 years                                                                              Series  16

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1788 1837   -1   -.12 -.15 -.11 -.08 -.17 -.07 -.13  .16  .24  .70* .16| .01 -.05  .03  .05  .17 -.06 -.16 -.34 -.07  .05
    1800 1849   -1   -.21 -.22 -.04  .00 -.17 -.04 -.16 -.08  .18  .73* .25| .01 -.02  .04 -.04  .27  .00 -.12 -.35 -.14  .06
    1825 1874   -1   -.33 -.18 -.03 -.03 -.07 -.06 -.11 -.26  .17  .65* .15| .08 -.01 -.22 -.03  .37  .00  .00 -.14 -.07 -.01

[B] Entire series, effect on correlation (  .428) is:
      Lower   1846  -.018   1818  -.015   1841  -.014   1860  -.014  Higher   1890   .028   1929   .019   1924   .017   1804   .009
    1788 to 1837 segment:
      Lower   1818  -.051   1788  -.032   1823  -.031   1824  -.028  Higher   1804   .081   1805   .079   1837   .032   1812   .026
    1800 to 1849 segment:
      Lower   1818  -.051   1846  -.050   1841  -.047   1824  -.035  Higher   1804   .046   1805   .042   1837   .028   1838   .025
    1825 to 1874 segment:
      Lower   1841  -.052   1860  -.051   1863  -.043   1846  -.041  Higher   1847   .044   1837   .034   1861   .031   1838   .030
=================================================================================================================================

LCW10C    1526 to  1647     122 years                                                                              Series  17

[B] Entire series, effect on correlation (  .430) is:
      Lower   1596  -.023   1540  -.023   1631  -.013   1628  -.011  Higher   1600   .015   1622   .013   1530   .012   1550   .012

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1540 +3.3 SD
=================================================================================================================================

LCW11A    1539 to  1995     457 years                                                                              Series  18

[B] Entire series, effect on correlation (  .620) is:
      Lower   1550  -.010   1610  -.008   1865  -.007   1828  -.005  Higher   1652   .013   1846   .008   1770   .005   1890   .005

[D]    1 Absent rings:  Year    Master  N series Absent
                        1899    -2.592     45       1

[E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
      1865 -5.3 SD;    1899 -4.8 SD
=================================================================================================================================

LCW11B    1546 to  1995     450 years                                                                              Series  19
```

Figure 6. 18 A second page from COFECHA Part 6 showing when a core has a missing ring. Note that LCW10B, also called series 16 by COFECHA, has three inside segments that correlate better if they are shifted back 1 year in time. If we assume that the outsides of the core is anchored in time by the coring date, a negative shift usually means that a missing ring needs to be inserted and a positive shift means that a false ring needs to be removed.

that ring will be in the area around 1825-1850 because the 1850-1899 segment dated without any problems (check Part 5 to see this correlation). The other series on this page date well with the master chronology.

Part 7 summarizes all of the descriptive statistics for each core including its correlation with the master chronology and its mean sensitivity (Figure 6.19). At the bottom of the chart, we see again the average of all of the series intercorrelations (0.520) and the average of the mean sensitivities (0.254) that were reported in Part 1.

Conclusions from COFECHA

COFECHA is one of the most useful programs in dendrochronology and it can provide standard statistics which enable researchers to compare between sites and species. It is often misused as the sole dating method for samples and care should be taken to mainly use it as a quality control check on previously dated samples. The COFECHA program is designed to assist in dating and to develop individual series that are well dated. In a later section, I will describe ARSTAN which is a much more powerful program that is used for chronology building. The tree-ring series that are vetted in COFECHA will be input into ARSTAN for final chronology development. On the way to chronology development COFECHA is used iteratively with EDRM (meaning Edit Ring Measurements) to make corrections of problem segments that are identified in COFECHA and confirmed on the wood.

PART 7: DESCRIPTIVE STATISTICS: Sample Cofecha Run for the Lava Cast For 22:29 Thu 22 FEB 2007 Page 9

Seq	Series	Interval	No. Years	No. Segmt	No. Flags	Corr with Master	Unfiltered Mean msmt	Unfiltered Max msmt	Unfiltered Std dev	Unfiltered Auto corr	Unfiltered Mean sens	Filtered Max value	Filtered Std dev	Filtered Auto corr	Filtered AR ()
1	LCW01A	1689 1995	307	12	0	.622	.82	3.18	.547	.918	.184	1.91	.314	-.036	1
2	LCW01B	1676 1995	320	12	1	.560	1.13	4.96	.856	.884	.230	2.00	.347	.015	2
3	LCW02A	1399 1995	597	24	1	.558	.46	1.02	.159	.632	.231	2.08	.295	-.012	1
4	LCW02B	1399 1995	597	24	7	.452	.40	1.06	.175	.715	.264	2.21	.336	-.019	1
5	LCW03A	1414 1937	524	21	3	.485	.83	5.78	.677	.898	.274	1.91	.322	.005	1
6	LCW03B	1431 1930	500	20	0	.524	.83	2.77	.427	.810	.249	1.87	.253	-.016	1
7	LCW04A	1527 1995	469	18	1	.544	.60	2.26	.362	.821	.290	1.95	.342	.014	2
8	LCW04B	1563 1995	433	17	0	.646	.73	2.26	.383	.833	.253	2.02	.284	-.009	1
9	LCW05A	1558 1995	438	17	2	.573	.39	.96	.158	.743	.228	2.10	.325	-.022	1
10	LCW06A	1744 1995	252	10	1	.428	.30	.73	.129	.516	.368	1.99	.353	-.001	1
11	LCW06B	1767 1995	229	9	3	.407	.34	.82	.135	.499	.356	2.01	.358	-.031	1
12	LCW08A	1417 1995	579	23	4	.534	.34	1.54	.221	.870	.275	1.93	.234	-.019	1
13	LCW08B	1397 1995	599	24	2	.522	.41	2.28	.373	.927	.259	1.93	.215	-.014	1
14	LCW09A	1751 1995	245	9	0	.562	.51	.95	.147	.522	.234	1.97	.366	-.017	1
15	LCW09B	1721 1995	275	11	0	.530	.54	1.13	.212	.753	.232	1.79	.262	-.001	1
16	LCW10B	1788 1995	208	8	3	.428	.56	1.27	.177	.569	.240	2.01	.412	.022	1
17	LCW10C	1526 1647	122	4	0	.430	.23	.39	.069	.693	.190	2.03	.378	-.007	2
18	LCW11A	1539 1995	457	18	0	.620	.71	1.67	.318	.772	.245	1.86	.244	-.013	1
19	LCW11B	1546 1995	450	18	1	.555	.75	2.20	.329	.766	.239	1.96	.299	.006	1
20	LCW12A	1727 1995	269	10	0	.667	.95	2.85	.611	.917	.187	2.04	.366	-.010	2
21	LCW12B	1681 1995	315	12	0	.686	.88	2.26	.419	.890	.179	1.91	.292	-.023	1
22	LCW13A	1669 1995	327	13	2	.515	.82	2.57	.525	.852	.279	2.15	.309	-.020	2
23	LCW13B	1610 1995	386	15	0	.557	.72	1.95	.335	.763	.276	2.17	.307	-.020	1
24	LCW14A	1614 1995	382	15	0	.588	.32	.85	.130	.622	.267	1.97	.269	-.010	1
25	LCW14B	1658 1995	338	13	0	.536	.41	1.01	.166	.596	.311	2.08	.338	-.009	1
26	LCW15A	1417 1995	579	23	3	.538	.60	1.58	.211	.504	.295	1.85	.253	-.004	1
27	LCW15B	1428 1970	543	21	3	.533	.47	1.53	.228	.738	.279	1.95	.298	-.018	1
28	LCW16A	1394 1995	602	24	5	.539	.39	1.33	.166	.739	.268	1.84	.217	-.011	2
29	LCW16B	1472 1995	524	21	1	.584	.43	1.96	.246	.793	.319	1.92	.266	-.025	1
30	LCW17A	1451 1995	545	21	3	.458	.40	2.55	.244	.813	.299	1.92	.252	-.011	1
31	LCW17B	1399 1995	597	24	8	.412	.42	1.46	.223	.824	.234	1.89	.248	.000	1
32	LCW18A	1680 1995	316	12	0	.569	.97	2.57	.490	.819	.226	1.83	.231	-.045	1
33	LCW18B	1712 1995	284	11	0	.575	.94	2.32	.462	.788	.247	1.91	.280	-.020	2
34	LCW19A	1754 1995	242	9	3	.462	.44	.76	.140	.642	.225	2.04	.304	.005	2
35	LCW19B	1764 1995	232	9	3	.456	.44	1.14	.177	.579	.311	2.04	.362	-.011	1
36	LCW19C	1764 1995	232	9	1	.480	.63	1.36	.226	.650	.241	1.95	.319	-.011	2
37	LCW20A	1548 1930	383	16	1	.515	.56	1.38	.259	.826	.226	1.80	.227	-.003	1
38	LCW20B	1518 1995	478	19	1	.529	.57	1.64	.278	.873	.204	1.86	.265	-.013	2
39	LCW21A	1399 1995	597	24	11	.333	.35	1.01	.146	.696	.252	1.85	.232	-.007	1
40	LCW21B	1399 1995	597	24	5	.416	.30	.93	.132	.750	.248	2.02	.309	-.027	1
41	LCW22A	1480 1995	516	20	1	.592	.76	2.83	.391	.795	.243	1.91	.277	-.019	1
42	LCW22B	1525 1995	471	18	2	.539	.75	1.92	.269	.494	.271	1.93	.267	.002	2
43	LCW23A	1588 1995	408	16	1	.529	.48	1.31	.223	.834	.207	2.03	.325	-.002	2
44	LCW23B	1620 1995	376	15	2	.420	.53	1.09	.177	.723	.199	1.94	.281	-.011	1
45	LCW38A	1744 1920	177	7	0	.449	.33	.59	.082	.413	.210	2.03	.328	.045	1
46	LCW38B	1743 1920	178	7	3	.353	.43	.75	.100	.599	.181	1.91	.321	-.003	1
Total or mean:			18495	727	88	.520	.56	5.78	.283	.748	.254	2.21	.287	-.010	

- = [COFECHA LCWEXCOF] = -

Figure 6. 19 COFECHA Part 7 provides a table of the descriptive statistics for each core including the sequence number, sample ID, start and end dates, number of years, number of segments, number of segments with flags, and then statistics on each core for the ring width series before and after filtering. This last part shows the autocorrelation and how it was removed from the series.

EDRM

EDRM (used to be called EDT) enables you to edit ring width measurements (Figure 6.20) and is most often used after COFECHA has identified some sections of a core that need to be corrected or eliminated. EDRM and COFECHA are often run many times to correct a series. EDRM takes an input file name and accepts the standard dendrochronological file formats such as compact, measurement (with 0.01 or 0.001 mm precision), indices, Accurite measurements, meteorological data, spreadsheet data, or one or two column data. It asks for an output file name so that a new file is always created instead of overwriting old data. This is a good safety procedure so that original data files are not accidentally corrupted. The output file can be in compact, measurement at 0.01mm precision, or measurement at 0.001mm precision. The program asks if you want to use the first line of data as a header or title for the file. As with all of the DOS programs, the option in <brackets> is the default response. The program then takes one core at a time and allows the user to conduct various procedures on that core such as copy as is, insert a value, eliminate a value, change the first year of the core, cut the core from the beginning or end, omit a series, or change the core ID.

ARSTAN

ARSTAN is one of the main programs in dendrochronology that is used to build the final stand-level chronologies. ARSTAN differs from COFECHA in that it has a broader range of standardization techniques that can be used on individual series before a master chronology is compiled. This should not be confused with the master chronology that is developed in COFECHA. COFECHA also uses standardization (usually a 32-year cubic smoothing spline) to

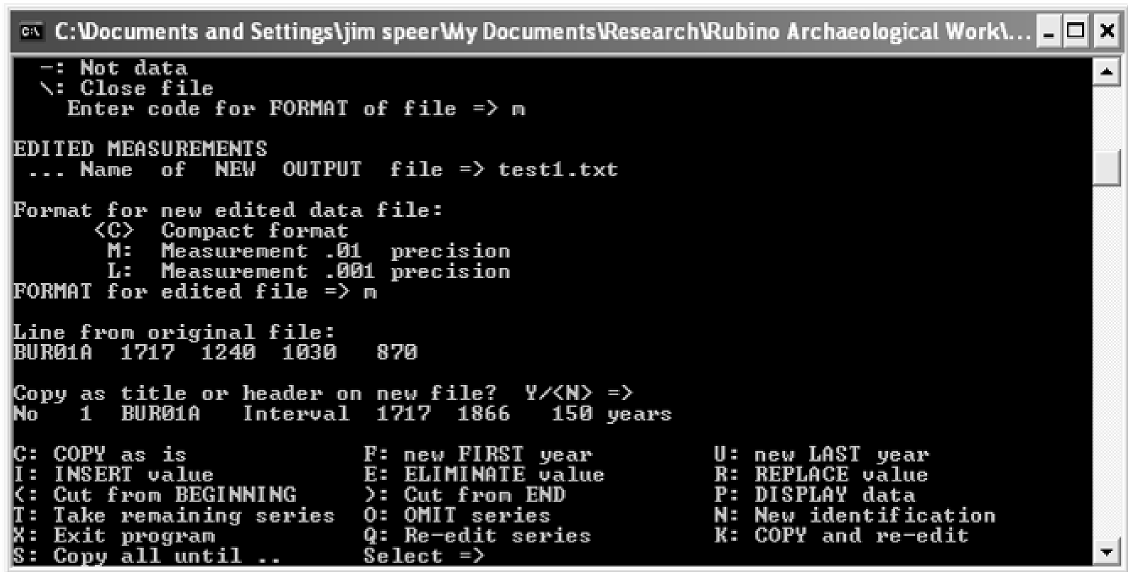


Figure 6. 20 EDRM showing the options for editing a file.

create a master chronology for the dating of other cores. This master chronology though was created specifically for dating purposes and is not the master chronology that should be used for the final analysis. In ARSTAN, I will describe how different standardization techniques can be used to maximize the signal of interest and remove noise from the final chronology. It was developed to be able to mathematically standardize tree-ring series and to remove or control the autocorrelation component in the time series (Cook 1985, Cook and Holmes 1986). The program fits a curve to the measurements from each core, divides the ring width by the modeled curve value, averages together the resultant index for each core to create a tree-level index, then averages together the tree indices to develop a stand-level chronology (Figure 6.21; Fritts and Swetnam 1989).

Historically, a negative exponential curve was considered a conservative standardization technique because it removed a known age-related geometric curve from the ring width series. A negative exponential curve describes the decreasing thickness of rings from pith to bark that can develop in open grown pine trees putting the same volume of wood each year on an ever increasing cylinder. More recently dendrochronologists have come to realize that this curve works best where the trees are open grown and do not experience many disturbance events. Cook (1985) demonstrated the need for more complex standardization techniques in closed-canopy forests that have more stand dynamic signal than open grown forests. Cubic smoothing splines take into consideration autocorrelation (the effect of previous growth or climate on the current year's growth) and Cook (1985) suggested the use of cubic smoothing splines as an empirical fit to the growth of the trees (Figure 6.22). Today these spline fits are commonly used, but too often they are applied with little rigor; it is essential that the researcher know what signal

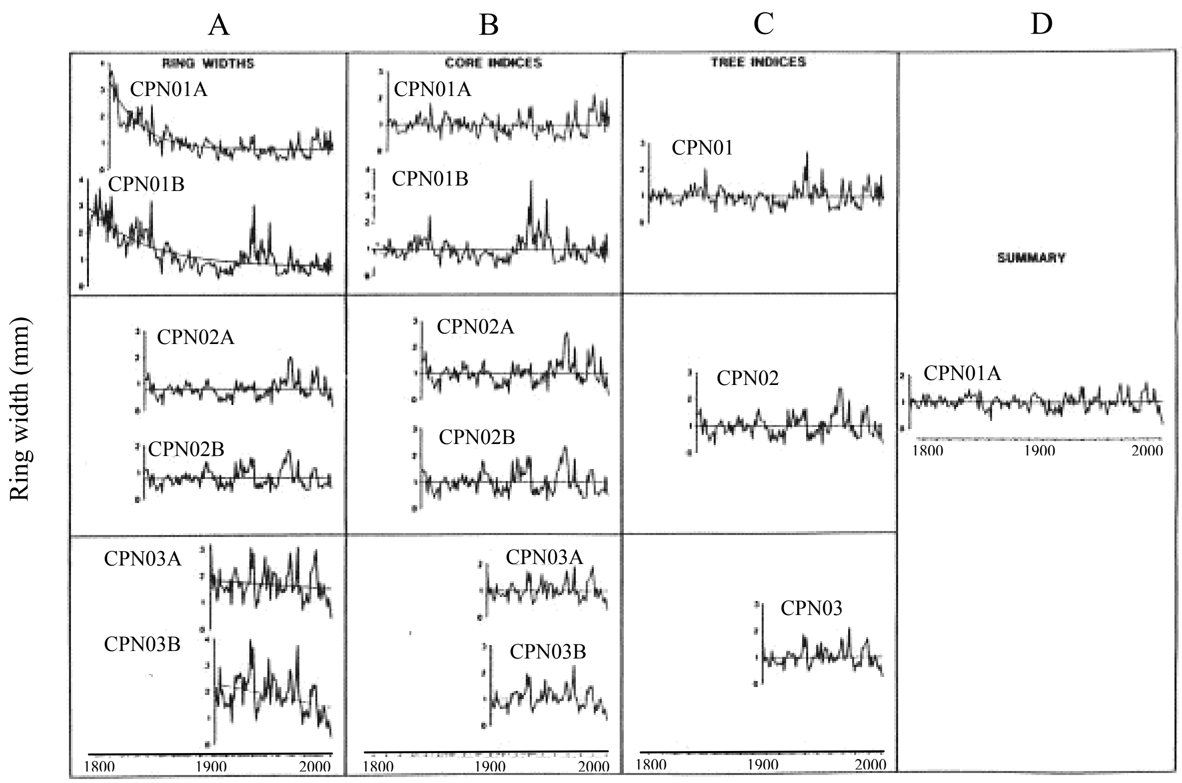


Figure 6. 21 Standardization and tree-level index series. ARSTAN matches a curve to the individual series, as seen in column A, with a negative exponential curve used for cores CPN01A and CPN01B, a straight line fit for cores CPN02A and CPN02B, and a decreasing trend for cores CPN03A and CPN03B. Note that in this case the site ID is CPN the tree ID is tree number 01, 02, and 03 respectively, and the last digit (A or B) stands for the first and second core from the same tree. ARSTAN then takes the ring width and divides it by the model fit (from column A) and the resultant series is plotted in this column as a dimensionless index value with the average of the series drawn as a straight line of value 1. ARSTAN then averages the index series from the two cores from each tree together to create a tree-level index series in column C. Finally, the tree-level series are averaged together to produce the stand-level master chronology in column D. The intermediate step of the development of a tree-level series avoids the circumstance of overrepresentation of one tree in the master chronology from which multiple cores may have been taken (modified from Fritts and Swetnam 1989 p126).

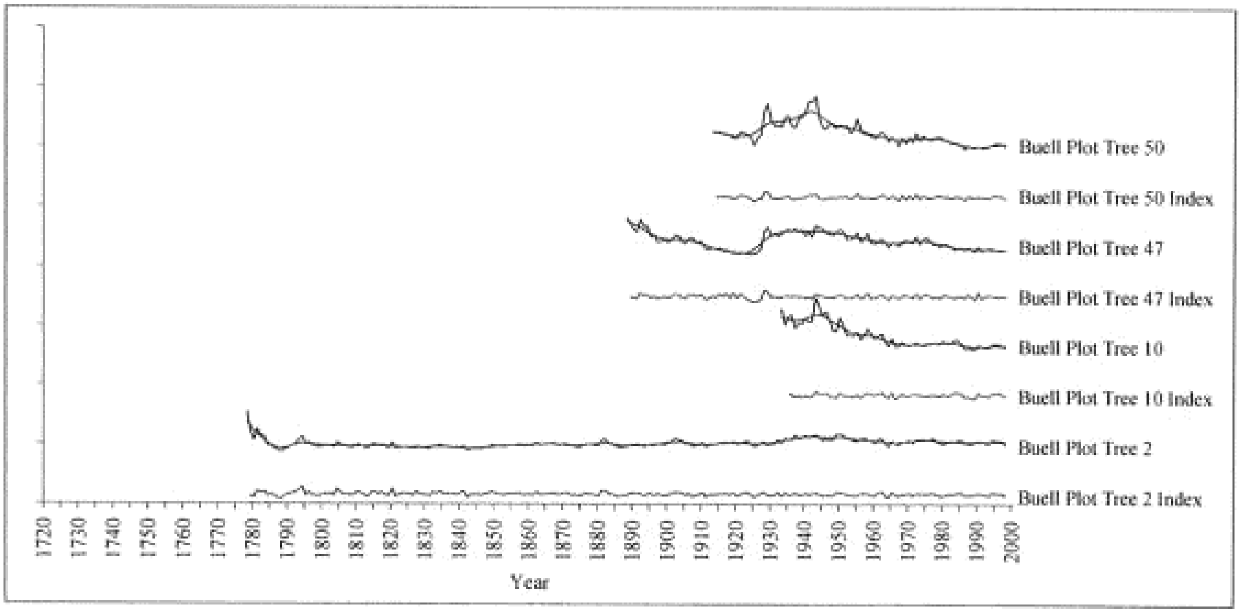


Figure 6. 22 Examples of four tree ring chronologies that have been standardized using a 15-year cubic smoothing spline. This was a very flexible spline that was used to remove as much climate as possible to enhance a mast (synchronous fruiting) signal in oak trees from the southeastern United States. This graph shows the original ring width chronology, with the model fit on top of that chronology, followed by the resultant index chronology for four trees (Buell Plot Tree 50, 47, 10, and 2) (From Speer 2001).

is being removed and what signal is being kept in the resultant chronology (see Chapter 2 for more description about standardization and spline length choice).

ARSTAN was first developed for the Macintosh operating system and continues to have the most features. It has been made available in two different formats for the PC. A DOS version of ARSTAN exists that is a black box where the researcher chooses the standardization procedure which is then applied to all cores. This technique assumes that the researchers know what they are doing in their choice of standardization and are manually plotting out the ring-width chronologies, standardization curve fits, and the resultant index series to make sure they are choosing the correct standardization technique for keeping the signal that they are pursuing. A version of ARSTAN for Windows was recently developed that enables researchers to interactively detrend their series, showing the curve fit and the resultant index series for each core. Users can choose to fit different standardization curves to the data and see how well the curve fits (Figure 6.23). This procedure is a good way to visualize the data and to see how standardization affects the process.

Keystroke Tutorial for ARSTAN for Windows

To begin, the ring-width file (from a measuring program, checked with COFECHA, and edited in EDRM) should be placed in the ARSTAN directory and the ARS37win_5f.exe file should be executed. Enlarge the windows so that they fill the whole screen. Next, hit "enter" twice to get past the introduction to the program. At this point the user is prompted for the name of the data file. Following that, the user can identify a second file to include in this run or hit enter to use only the first file. The user should then enter a descriptive title for the run that will allow for the

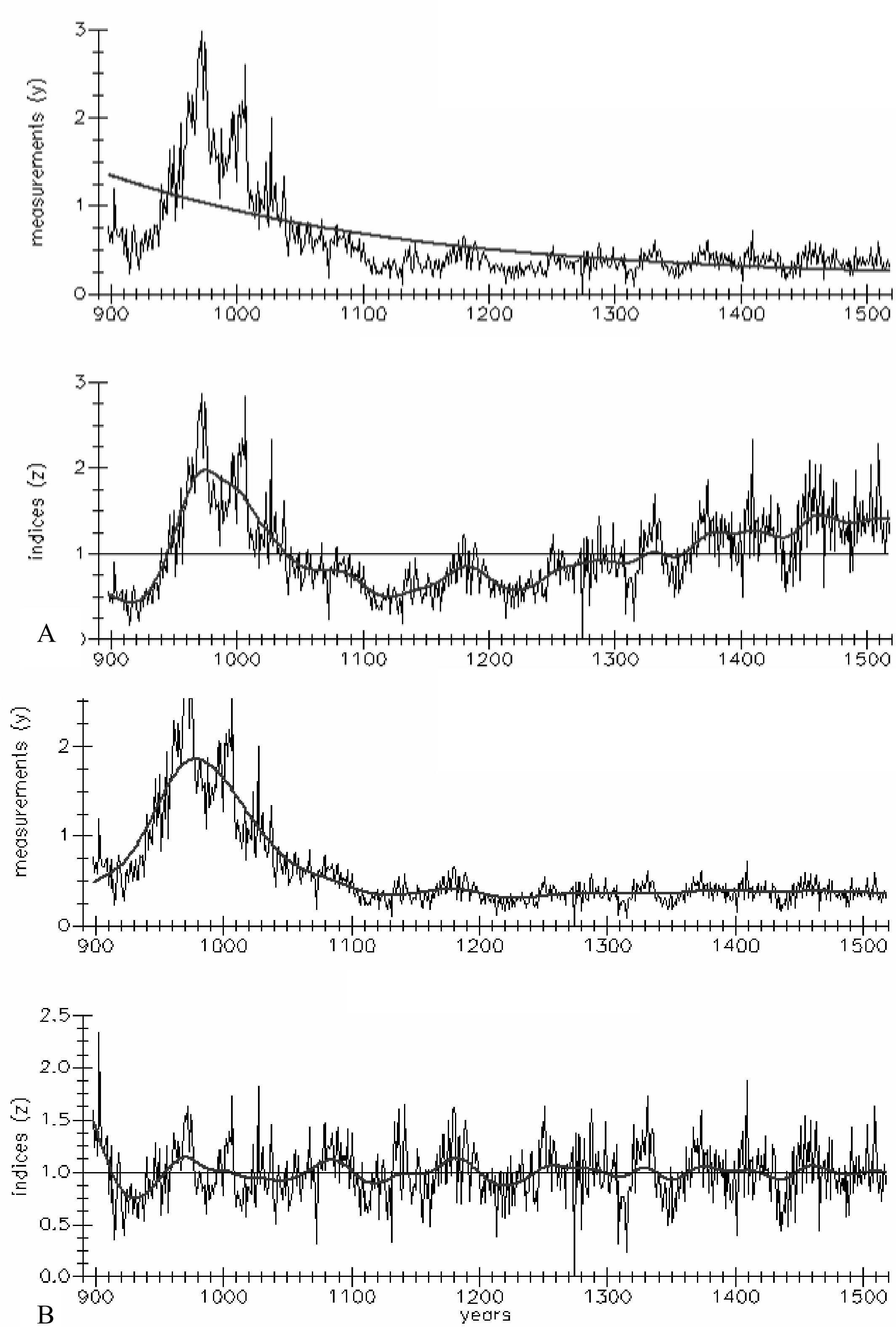

measurements (y)
indices (z)
A
measurements (y)
indices (z)
B
years
900 1000 1100 1200 1300 1400 1500
0 1 2 3
0.0 0.5 1.0 1.5 2.0 2.5

Figure 6. 23 Comparison of standardization with a negative exponential curve (A) versus a 100 year cubic smoothing spline (B) on a 600-year chronology. Notice the greater flexibility of the 100 year cubic smoothing spline for removing the slow growth when the tree is establishing followed by the spurt of juvenile growth and then the age-related growth trend (from Clark and Speer unpublished data).

identification of this run at a later date. The next option allows the user to run ARSTAN in batch mode, enabling the user to run ARSTAN on many file sets. The default response is no.

The main menu in ARSTAN that controls the whole program appears next (Figure 6.24). There are more than 20 options one can access at this point in the program. The options that I find most useful are [4] first detrending, [7] interactive detrending, [15] site-tree-core mask, and [19] summary plots. ARSTAN provides the most powerful standardization options out of any of the dendrochronological programs. With option [4], the user can choose to fit a negative exponential, linear trend, or various cubic smoothing splines. Option [5] allows for a second detrending, but I am personally opposed to manipulating the data more than necessary, and a second detrending is rarely warranted. Some researchers will use second detrending when a deterministic model such as a negative exponential or regression line is used first to remove noise from a known cause, i.e. age-related growth trend. Many of the standard detrending methods, for example most cubic smoothing splines, will remove noise such as a negative exponential curve so that two runs at detrending the series are not necessary. Also, two separate detrending curves will move the data farther from the raw ring widths that were observed and measured on the actual the wood. I suggest using the interactive detrending option [7] in ARSTAN because this is the best way to visualize the data, as seen in figure 6.24. Option [15] allows the site, tree, and core mask to be changed to fit your identification tags, but your tags have to be consistent with the same number of characters for the site ID and tree number. The mask fits the tree identification code so that the program can differentiate separate cores from the same tree. In Figure 6.24 option [15] the site-tree-core mask is “sssttcc” where “sss” allows three letters for the site ID, “tt” allows two numbers for the tree ID, and “cc” allows two letters

```
File  Edit  Format  Window
                         ***                              ***
                         **********************************
                         **********************************

                      maximum tree-ring chronology length:  5000
                      maximum number of tree-ring series:   1500

 <ret> to run, / to exit, h for more info:

 open the file listing the data file names
 type h for help or <ret> to enter them     ==>

 okay, so enter your data file name(s)
 which will be stored in the new file: arstan.files
 when done, hit <ret> to process the data file(s).

 file name # 1: hanover15.txt
 file name # 2:

 number of files to be processed:     1

 okay, enter your overall run title:
 ==>

 run in batch mode from log file? y/<n>/h   ==>

 |*************** arstan run time menu and current options settings ***************|

                            opt          plt
  [1] tree-ring data type    1                !tucson ring-width format
  [2] missing data in gap   -9            0   !missing values estimated (no plots)
  [3] data transformation    0            0   !no data transformation (no plots)
  [4] first detrending       1            0   !1st-neg expon curve (k>0), no = opt 4
  [5] second detrending      0            0   !2nd-no detrending performed
  [6] robust detrending      1                !non-robust detrending methods used
  [7] interactive detrend    0                !no interactive detrending
  [8] index calculation      1                !tree-ring indices or ratios (rt/gt)
  [9] ar modeling method     1            0   !non-robust autoregressive modeling
 [10] pooled ar order        0            0   !minimum aic pooled ar model order fit
 [11] series ar order        0                !pooled ar order fit to all series
 [12] mean chronology        2   0    0   0   !robust chronology (w/ biweight plots)
 [13] stabilize variance     0                !no variance stabilization performed
 [14] common period years        0    0       !no common period analysis performed
 [15] site-tree-core mask       sssttcc       !site-tree-core separation mask
 [16] running rbar              50   25   0   !running rbar window/overlap (no plots)
 [17] printout option        2                !summary & series statistics printed
 [18] core series save       0                !no individual core series saved
 [19] summary plots          0                !no spaghetti and mean chronology plots
 [20] stand dynamics stuff   0            0   !no stand dynamics analyses done
      running mean window    0                !running mean window width
      percent growth change  0                !percent growth change threshold
      std error threshold    0                !standard error limit threshold

 enter the option to change (<ret> = go)    ==>
```

Figure 6. 24 Main menu for ARSTAN.

or numbers for the core ID. Option [19] provides summary plots so that you can visualize your final chronologies. Option [20] is also useful for some disturbance quantification techniques.

Reading the Output of ARSTAN

When ARSTAN is run in interactive mode it plots the ring-width measurements, the curve fits, and the resultant indices so that the user can see how well each curve fits the data (Figure 6.25). These curves are not saved, so it is useful to do a screen capture (Ctrl + Prnt Scrn) of the plots and then paste them into another document such as Word or PowerPoint.

The output from ARSTAN summarizes all of the descriptive statistics for the raw ring widths and then goes through the same descriptive statistics for the standard, residual, and arstan chronologies (explained below). These statistics include the start and end dates of each core, the mean, standard deviation, skewness, kurtosis, mean sensitivity, and first order autocorrelation for each core. The ARSTAN output also lists the detrending curve for each core so that any changes that have been made in the interactive detrending part of the analysis are recorded for later reference.

Four chronologies are produced by ARSTAN. The raw chronology is a simple average of the raw ring widths, in other words, no standardization was done on these series. The standard chronology is an average of the index values from the standardization process chosen by the operator (see Chapter 2 for more details on standardization). This chronology still has all autocorrelation included in the final chronology, which may be an issue when conducting regression analyses later as one of the assumptions of regression analyses is that the series are

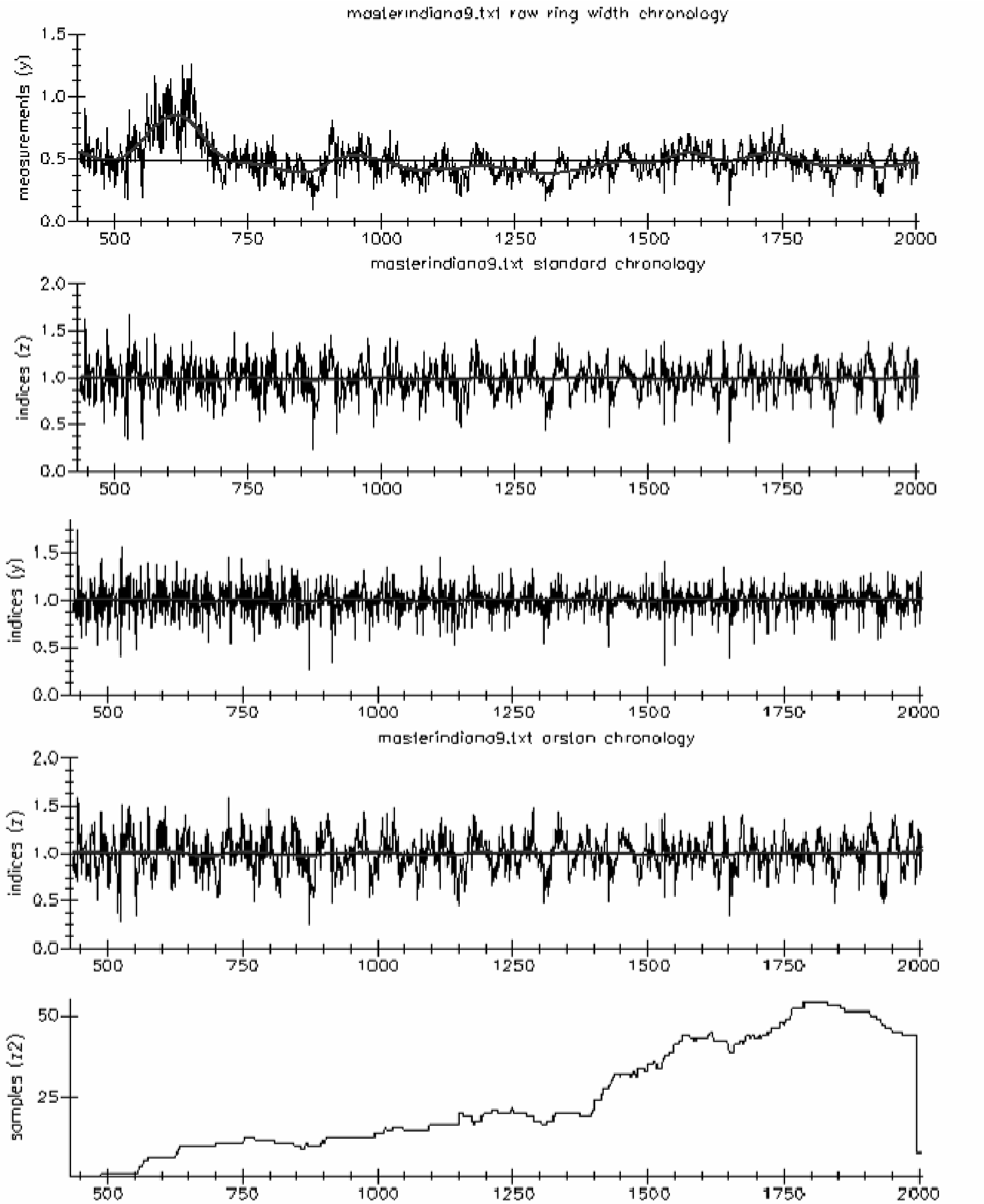


Figure 6. 25 Master chronologies for the Mokst Butte Lava Flow Ponderosa Pine Chronology. A) raw ring width chronology B) standard chronology C) residual chronology D) arstan chronology E) sample depth curve (from Clark and Speer unpublished data).

not autocorrelated. The residual chronology has had all autocorrelation stripped from the series making it a more suitable chronology for regression analysis, but not necessarily the most sensitive to the signal of interest. The arstan chronology has been calculated by removing the autocorrelation, modeling it, and reintroducing a stand-level autocorrelation back into the chronology. All three chronologies are output in the .crns file, meaning chronologies file. A benefit of interactive mode is that these chronologies are also plotted on the screen along with a sample depth curve for all of the chronologies (Figure 6.25). Chronology statistics such as the running rbar and EPS value (described above) are also graphically presented to help the researcher determine when the sample depth is so low that the that the stand-level signal is degraded (Figure 6.2).

Regional Curve Standardization (RCS)

The **Regional Curve Standardization** (RCS) technique was developed as an alternative standardization procedure that can maintain low-frequency variability in tree-ring chronologies while removing the age-related growth trend that is unique to each site (Cook *et al.* 1995, Esper *et al.* 2002, Esper *et al.* 2003). This is now a standardization option in ARSTAN. Low frequency signal in climate reconstructions would be useful to determine long-term trends in past climate. Short-term cubic smoothing splines remove this low frequency signal making the reconstruction of the Medieval Warm Period and Little Ice Age impossible in thousand year-long climate reconstructions (Cook *et al.* 1995). In the RCS method, the pith for each individual tree-ring series is set to zero, regardless of the actual calendar year (Figure 6.26). It is important to note that because this technique is based on the biological age of each ring, obtaining the pith is especially important. Esper *et al.* (2003) demonstrated that this method was relatively robust for differing pith offsets and sample depths, but was very sensitive to the calculation method used to obtain the RCS. The Regional Curve represents the average growth for that stand, which can be removed from each core by either calculating the difference from the mean growth curve (Figure 6.26) or as a ratio to the growth curve as is done in the classical method of standardization. Esper *et al.* (2003) indicated that a minimum sample depth of five series for any section of the curve is required and 40 series should be achieved at some point along the curve for the best results. This standardization technique has been programmed into ARSTAN for Windows which also presents the standardization curves so that its validity can be examined on a site-level basis.

YUX

YUX is a useful program that enables the user to convert a file with many chronologies to a spreadsheet where each chronology is in a subsequent column. This spreadsheet file can then be read into Excel as tab, comma, or space delimited, based on user specification in the program. It is the most efficient way to convert output chronology files from ARSTAN (such as the .crns file) or to convert raw ring width measurement files into a format that Excel can read.

Climate Analysis Packages

Two stand-alone programs have been developed to facilitate climate analysis called PRECON (Fritts and Dean 1992) and DENDROCLIM2002 (Biondi and Waikul 2004). Similar analyses can also be conducted in Excel or SAS but PRECON and DENDROCLIM2002 are written specifically for dendrochronological applications, making it easier to enter tree ring and meteorological data and incorporate more advanced principal component analyses (PCA) along

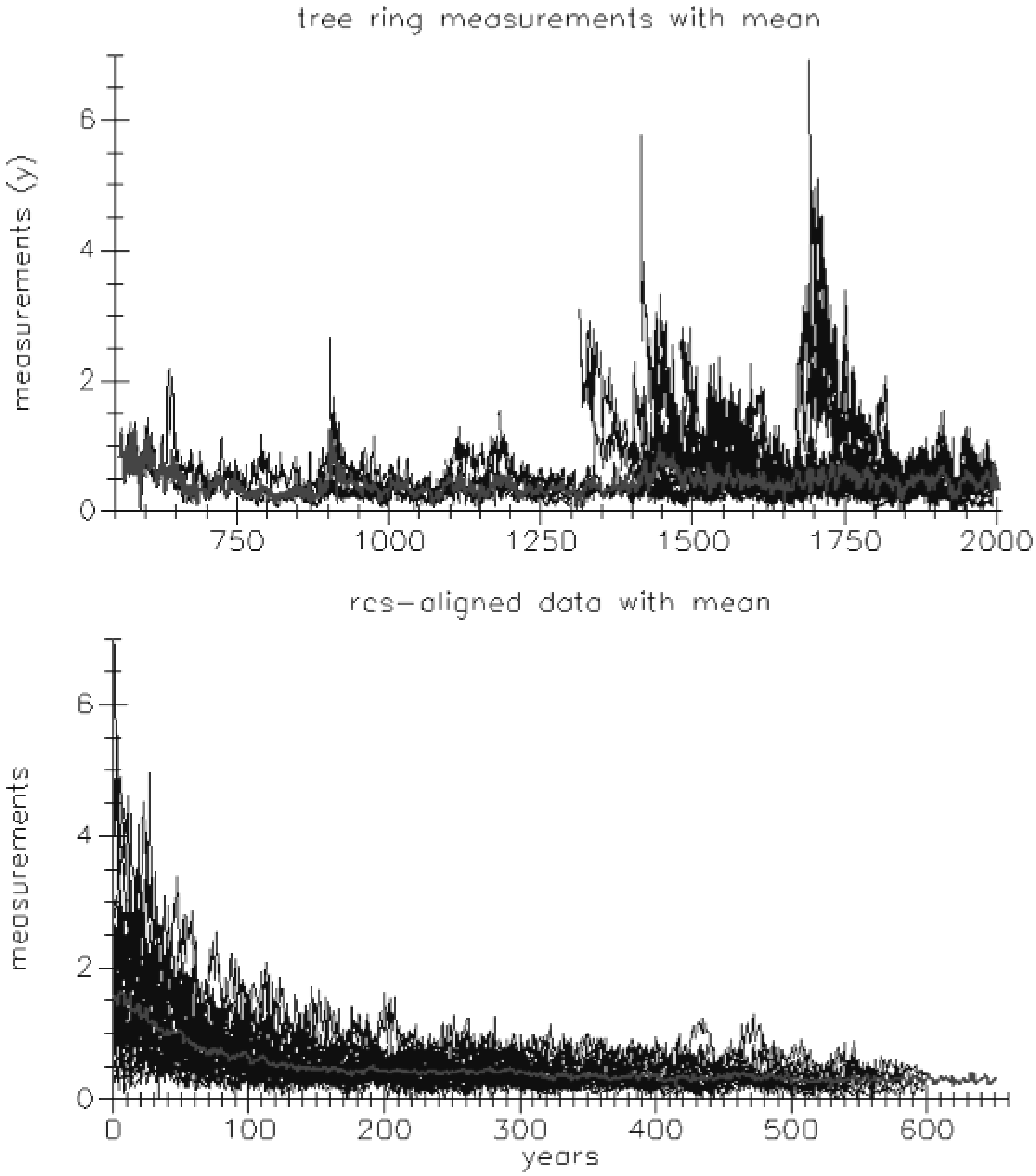


Figure 6. 26 Example of series lined up by a) pith date versus b) establishment time for the Regional Curve Standardization Method (from Clark and Speer unpublished data).

with bootstrap techniques (Guiot 1991). Bootstrapping is a statistical technique that can be used to determine the significance of any statistic of interest even when the data is autocorrelated, not normally distributed, or when the data set is small. This technique creates pseudo-data sets by randomly sampling the original data with replacement (which means that data point can be selected again) then calculating statistical parameters for this new data set that can then be compared to the actual data. The result is a set of confidence intervals for any regression or correlation analysis that enables tests of significance (Guiot 1990).

PRECON

PRECON is a program written by Harold Fritts that is "an empirical model of climatic and prior growth factors preconditioning annual ring growth in trees" (Figure 6.27; Fritts and Dean 1992). PRECON 5.17B is the latest version, written in April 1999, and is a DOS program that allows the user to read in a tree-ring chronology file and climatic data sets. The program runs correlation matrices and principal components analyses (PCA) resulting in response functions for each variable, which are then displayed in a graphical form. PRECON uses a bootstrapping method to determine significance of the response function analysis (Guiot 1991).

DENDROCLIM2002

DENDROCLIM2002 is a C++ computer program with a Graphical User Interface (GUI) that also conducts correlation and response function analysis, but uses a bootstrapping technique to determine significance levels for both types of analysis, whereas PRECON uses bootstrapping with only the response function analysis (Figure 6.28; Biondi and Waikul 2004). This program

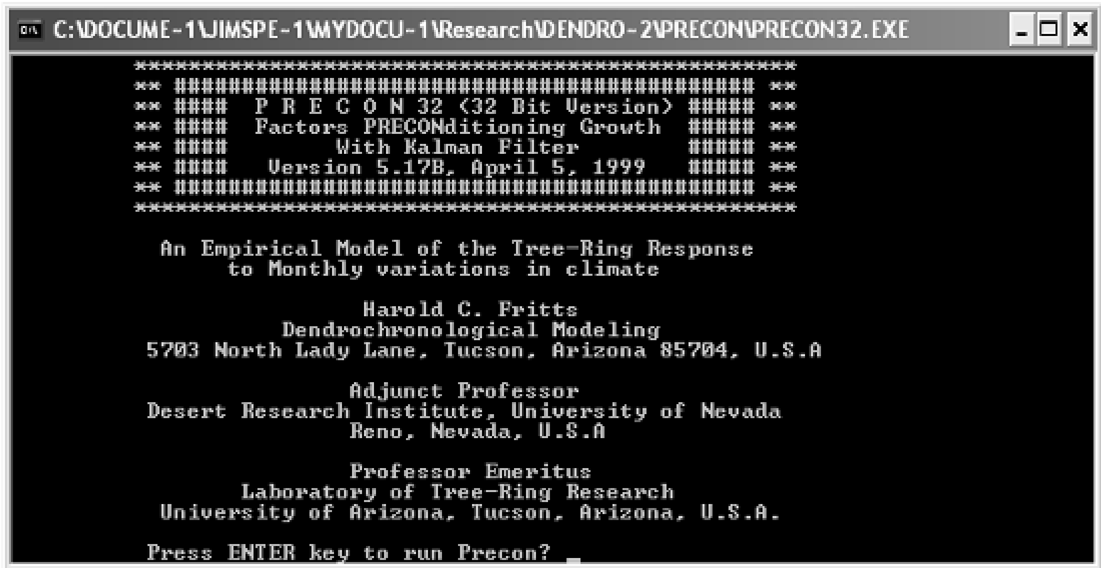


Figure 6. 27 The opening page to PRECON. This is a program used to determine the response function of how tree-ring chronologies respond to monthly climate data.

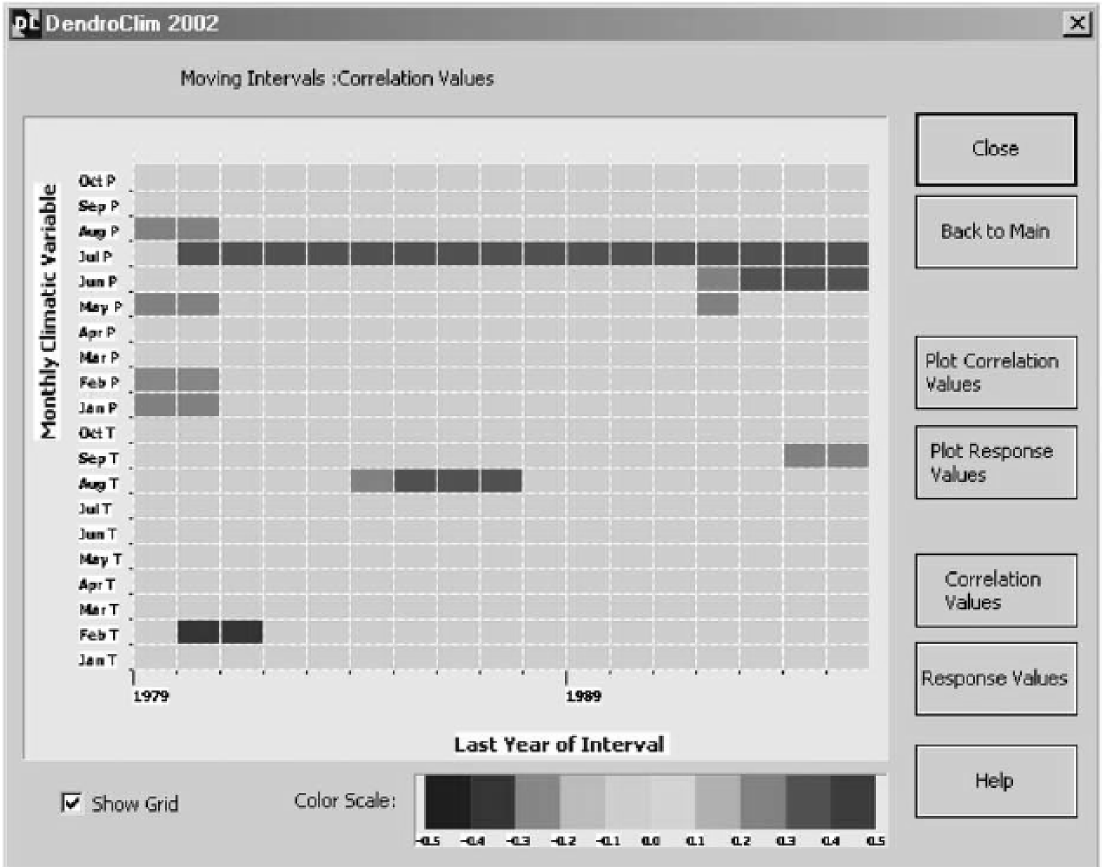


Figure 6. 28 Correlation results comparing tree rings to climate in DENDROCLIM2002 (from Biondi and Waikul 2004).

also calculates the correlation and response function analyses in moving intervals through time to determine if the climatic response is stable or if it changes through time.

OUTBREAK

The computer program OUTBREAK was written by Richard Holmes at the Laboratory of Tree Ring Research at the University of Arizona in consultation with Tom Swetnam (Holmes and Swetnam 1994a) for the purpose of quantifying and differentiating spruce budworm and tussock moth outbreaks as recorded in tree rings (Figure 6.29; also see the following authors for application of the program Swetnam *et al.* 1985, Swetnam and Lynch 1989, Swetnam and Lynch 1993, Swetnam *et al.* 1995, Speer *et al.* 2001, Ryerson *et al.* 2003). OUTBREAK allows for data from host trees to be entered into the program along with a non-host chronology to control for climate. The program runs on tree-level ring width indices that can be obtained from the DOS version of the ARSTAN program. Tree-level index chronologies are developed by averaging together the standardized “a” and “b” cores from the same tree and the results are output as the .tre file. The tree-level chronologies give a better representation for growth in the tree than a single core and assure that individual trees are not overrepresented in the final chronology in the case that more cores were taken from one tree than another. The non-host chronology is usually a master chronology from a site similar to the host sample site but of a different tree species that is not affected by the insect or pathogen that the researcher is studying. In 1996, this program was modified and calibrated for pandora moth outbreaks, which allowed for host chronologies to be entered, but did not require the non-host control (Speer *et al.* 2001). This modification was necessary in a ponderosa pine system where no long-lived non-host species were available growing in the same climate conditions. In a case such as this, other

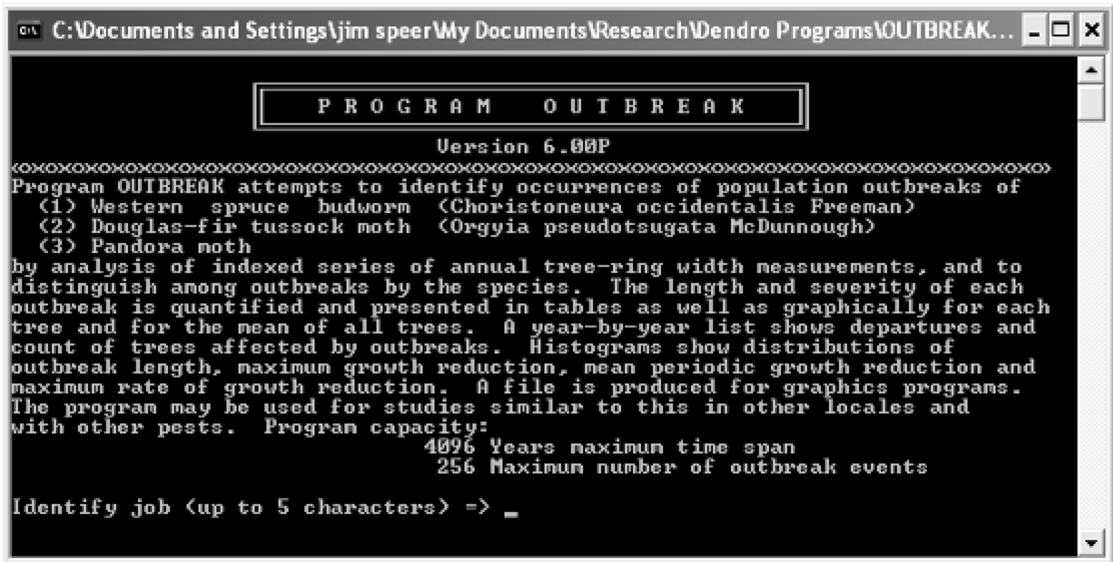


Figure 6. 29 The opening page of the program OUTBREAK.

efforts should be made to control for climate, such as determination of the climate response of the host trees using modern climate.

There are two difficult assumptions made with the host/non-host comparison. First, it is assumed that the non-host trees, usually of a different genus, have a similar climatic response to the host trees. The climate response can be tested for each species and the reliability of this assumption can be determined. The second assumption is that the non-host trees are not affected by the outbreak. Non-host trees that are growing in the same stand as the host trees may change growth due to a reduction in competition, nutrient cycling, or possibly by some damage to the trees associated with the outbreak. If a non-host species of a different genus is lacking, it may be tempting to use a host species for climate control that seems to be spatially separated from the outbreak. Spatial arguments are tenuous, however, because the spatial distribution of outbreaks is likely to have been different in the past. Therefore, a lack of modern outbreaks in a stand of host trees does not validate that stand as a long-term climate control site.

OUTBREAK should be calibrated in an iterative process on the specific site of interest in each new study. It was intended to quantify the effects of insect or pathogen outbreaks, and to automate the process of identifying past outbreaks. OUTBREAK is pre-programmed with three insect types (western spruce budworm, Douglas-fir tussock moth, or pandora moth) that have default values for outbreak duration, severity, and onset rate. This program can be used to quantify the growth reduction of any insect or pathogen, but it should be calibrated with known outbreak occurrences. Characteristics of the wood should be the primary indicator that an outbreak occurred. Once the signature of the outbreak has been identified in the wood, then the program OUTBREAK can be run in an iterative process until it records the start and end dates of historically known outbreaks. Once the program is accurately representing known outbreaks, then it can be used to infer outbreaks in the past and to quantify the outbreak characteristics.

Four main parameters control the ability of OUTBREAK to recognize events in ring-width measurement. These four parameters are the standard deviation of the maximum growth reduction, the shortest length of an outbreak, the longest length of an outbreak, and amount of the growth reduction at the beginning of the outbreak. The duration variables enable researchers to tease apart the effect of multiple insects in the same host tree, such as spruce budworm and tussock moth (Swetnam *et al.* 1995).

Spectral Analysis

Maximum entropy method (MEM; Burg 1978, Dettinger *et al.* 1995), singular spectrum analysis (SSA; Vautard and Ghil 1989), and wavelet analysis (Torrence and Compo 1998) are all types of spectral analysis that can be used to examine cyclicity in time series (Villalba *et al.* 1998, Speer *et al.* 2001). This is a common technique in insect outbreak studies to document the return interval of periodic outbreaks (Speer *et al.* 2001, Zhang and Alfaro 2002, Ryerson *et al.* 2003).

EVENT

The program EVENT runs a superposed epoch analysis (SEA) that overlays an event year (such as the occurrence of a fire or insect outbreak) every time it occurs in the chronology to examine previous and subsequent years of some variable such as climate or tree growth (Holmes and

Swetnam 1994b). The inputs for the program are either a time series of the comparison variable, such as a climate variable like PDSI to see the effect of climate on the event, or a tree-ring chronology to see the effect of the event on tree growth combined with a list of event dates. An event window in time is identified by the user to look at a number of years prior and subsequent to the event. Each event year is taken as year zero for that event, and then the lag years are taken from the chronology and averaged for all of the events. Subsequently a bootstrap technique is employed that uses a large number of random simulations (default of 1000) with randomly selected event years to produce confidence intervals to determine if any lag year has a significant response or correlation to the event. This analysis enables the researcher to determine if climate is forcing fire or insect outbreaks and can also be used to examine the effect of known repeated insect outbreak emergences (such as periodical cicadas (*Magiciada sp*.)) on tree growth (Figure 6.30).

Conclusion

Most of these programs and statistics are the basic tool set of dendrochronologists. There are other specialized programs and statistics used by researchers in the various sub-disciplines but they are more specialized and will either be described in subsequent chapters on the different applications of dendrochronology or in the references cited in each chapter. The rest of this book will expand on a different sub-discipline in each chapter and provide some of the specific methods that are involved in each application along with citation of many of the main works in that field of study.

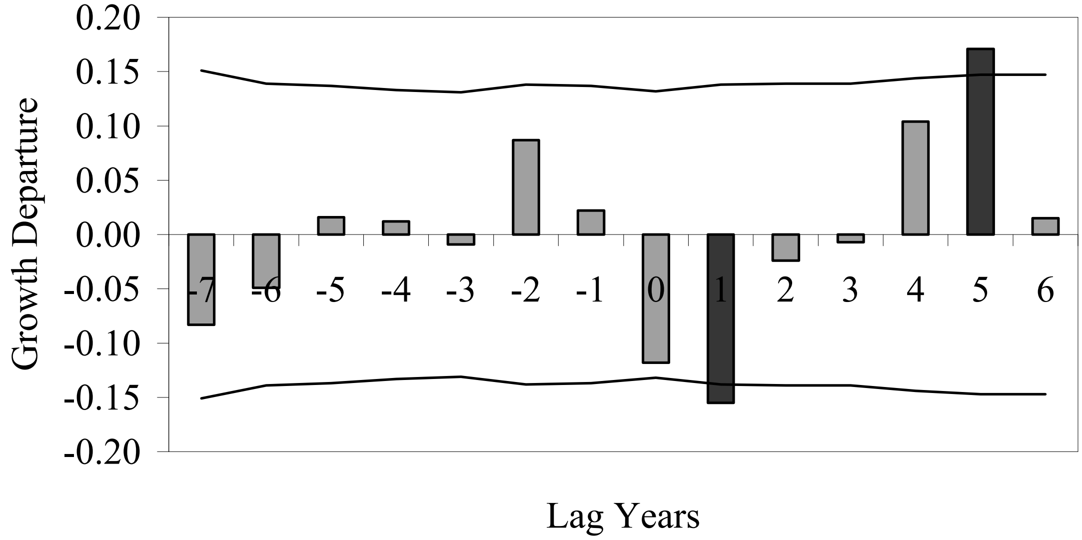


Figure 6. 30 A superposed epoch analysis showing the growth departure in pin oak (*Quercus palustris*) ring growth associated with periodical cicada emergences. Year zero is the overlay of four emergence events back through time (every 17 years) and the analysis shows growth before and after the emergence with the horizontal lines indicating 95% confidence intervals. This analysis shows a decrease in growth the year after emergence, presumably from damage to these trees from oviposition scarring. A significant increase in growth occurs five years after emergence, which could be related to nutrient cycling from the decay of dead cicadas at the base of the trees (Speer unpublished data).

Chapter 7: Dendroarchaeology

Introduction

Dendrochronology has gained recognition in archaeology as an accurate tool for chronological control. Dendrochronologists have used tree rings to date the construction of archaeological structures (Douglass 1929, Haury 1962, Dean 1978, Dean *et al.* 1985, Billamboz 1992, Cufar 2007), scars from Native American use of the inner bark of pine trees (Kaye and Swetnam 1999), and to verify the dating of historical works of art (Lavier and Lambert 1996, Jansma *et al.* 2004, Cufar 2007) such as the panels in paintings (Bauch and Eckstein 1970, Eckstein *et al.* 1986) or the wood in violins (Grissino-Mayer *et al.* 2002). Tree rings can also be used to **dendro-provenance** archaeological or historical wood (Eckstein and Wrobel 2007). This is a fast growing sub-field of dendrochronology that uses wood anatomy and correlation to regional master chronologies to determine the origin of and trade routes for wood that has been incorporated into artifacts.

The first contribution of dendrochronology to archaeology was made by A.E. Douglass, who determined the exact occupation dates of approximately 45 archaeological sites in the southwestern United States (Figure 7.1; Douglass 1929, Haury 1962, Nash 1999). This work started in 1914 when Clark Wissler (Figure 7.2), Curator of Anthropology with the American Museum of Natural History suggested that Douglass use tree rings to date the Native American structures in the American Southwest. Douglass began to examine samples that were submitted from archaeological sites in New Mexico. In 1921, Neil Judd (Figure 7.3) of the United States National Museum approached Douglass about continuing his dating efforts in the southwest and

Figure 7. 1 A.E. Douglass (1867-1962) coring a ponderosa pine. Douglass' first major project was to date some 45 archaeological ruins in the southwestern United States. Here he is coring a ponderosa pine tree in the Forestdale Valley in Arizona in 1928 (Laboratory of Tree-Ring Research, University of Arizona, from Webb 1983 and Nash 1999).

Figure 7. 2 Clark Wissler (1870-1947) and W. Sidney Stallings (1910-1989) with specimens from Pueblo Bonito and Aztec Ruins in 1932. Clark Wissler attended a Carnegie lecture by Douglass in 1914 on tree ring dating. Wissler realized the value of tree ring dating to obtaining dates on archaeological wood in the southwestern US and was the first to send Douglass archaeological samples to date. (Negative number 280306, by Clyde Fisher, Department of Library Services, American Museum of Natural History, reprinted in Nash 1999)

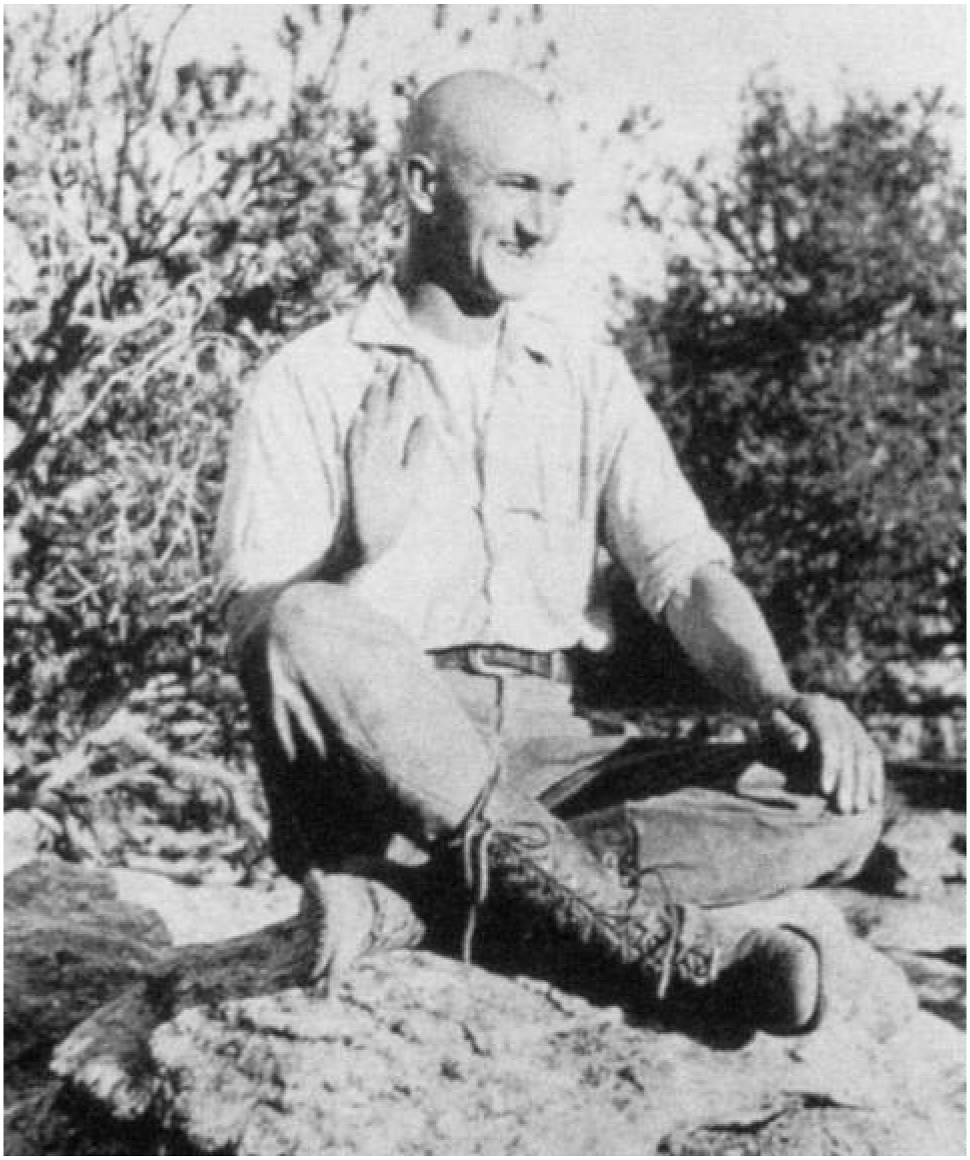


Figure 7. 3 Neil Merton Judd (1887-1976). Judd was enthusiastic about dendrochronological dating of dwellings and sent Douglass many samples. He also suggested that Douglass pursue funding from the National Geographic Society for his work in developing a long chronology in the southwest which started three major beam expeditions to complete the long master chronology for this region. This photograph was taken at Alkali Ridge, Utah in 1908. (Photograph from the Peabody Museum, Harvard University. Reprinted in Nash 1999).

suggested applying for funds from the National Geographic Society (NGS), which provided funds for Douglass' research from 1923-1930.

Douglass' efforts to build a long chronology in the southwestern U.S. to date the archaeological ruins and to build a climate chronology for himself is a classic story in dendrochronology and also demonstrates many of the basic principles of dendrochronology. The foundation for Douglass' chronology came from living trees that he sampled throughout the Flagstaff and Prescott area. Funding from the National Geographic Society for the first two "beam expeditions" in 1923 and 1928 resulted in a 700-year modern chronology that was anchored in time by living trees with known sampling dates and extended further back in time with archaeological wood that had been submitted by Clark Wissler, Neil Judd, and Earl Morris (Figure 7.4). Samples from the beam expeditions and from previous work enabled Douglass to build a 585-year floating chronology that provided relative dates for a number of the archaeological ruins in the southwestern U.S., but did not date against the modern chronology. Douglass acquired funding from the National Geographic Society to conduct a third beam expedition in 1929 to search for wood from archaeological sites that would bridge the gap between the modern and floating chronologies. This expedition was led by Lyndon Hargrave (Figure 7.5) and Emil Haury (Figure 7.6), with intermittent visits by Douglass himself. On June 22nd, 1929, Hargrave and Haury were leading an expedition at Whipple Ruin in Show Low, Arizona. With the help of the Whipple family, they excavated a sample which was labeled HH-39 (Figure 7.7). That same day, Douglass visited the ruin and spent the evening examining the sample in the local hotel. After his analysis, he was able to announce that sample HH-39 bridged the gap between his modern chronology and his floating chronology. In truth, there was no gap

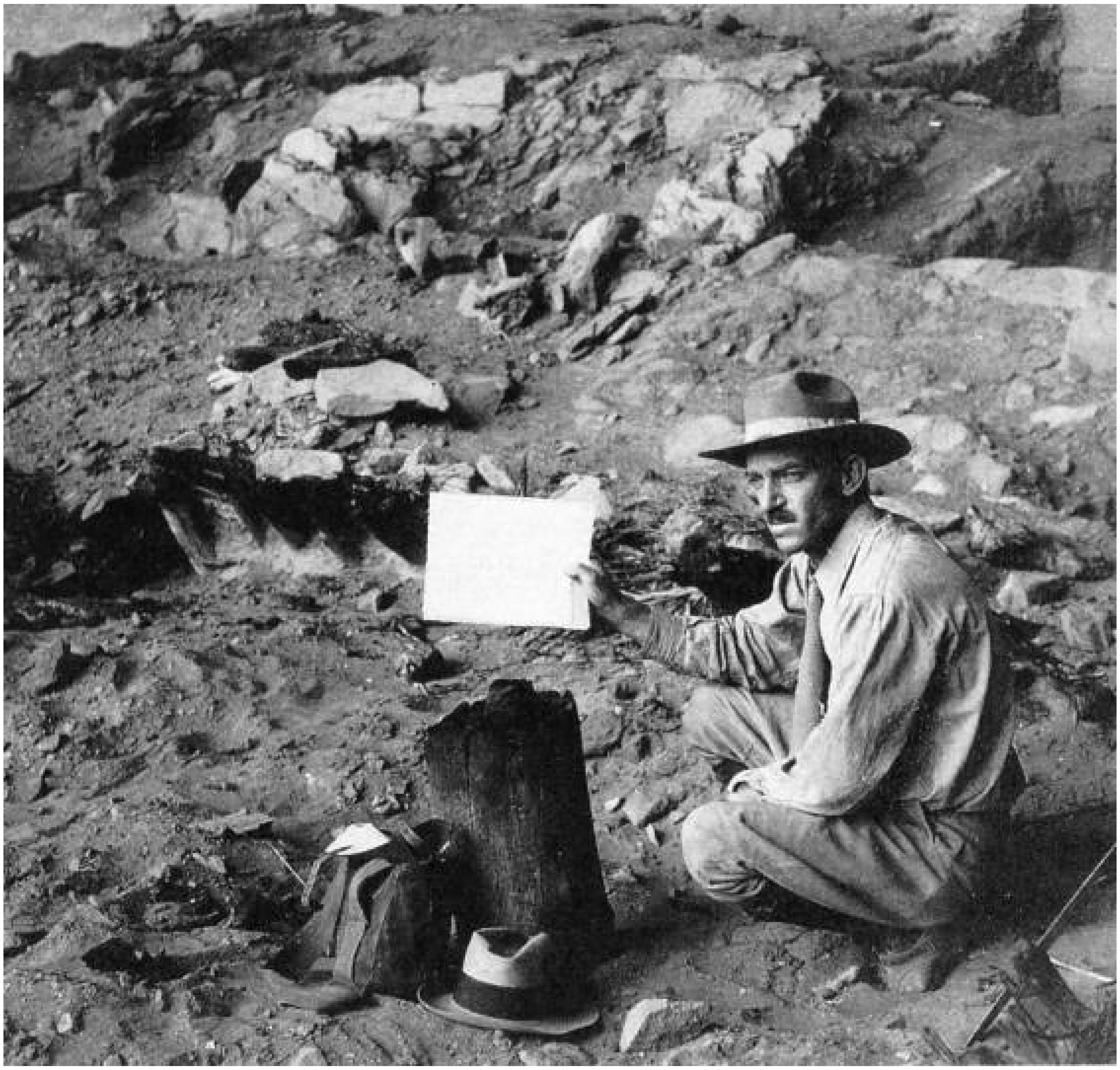


Figure 7. 4 Earl Halstead Morris (1889-1957). Earl Halstead Morris with a charred beam at Broken Flute Cave, Arizona in 1931 (from Nash 1999).

Figure 7. 5 Lyndon Lane Hargrave (1896-1978) examining a conifer cross section. Note the stone axe cut end of the beam to the right of the cross section that Hargrave is examining. (Photograph from the Museum of Northern Arizona and reprinted in Nash 1999).

Figure 7. 6 Emil W. Haury (1904-1992) examining a buried beam at Pinedale Ruin, Arizona during the Third Beam Expedition, 1929. Photograph from the Laboratory of Tree-Ring Research, Arizona and reprinted in Nash 1999.

Figure 7. 7 Sampling HH-39. This is Farmer Whipple removing sample HH-39 from an archaeological site in Show Low Arizona. This is the famous sample that bridged the gap between Douglass' modern chronology and his floating chronology, allowing Douglass to provide absolute dates to the archaeological ruins in the southwest (Courtesy of the Laboratory of Tree-Ring Research, University of Arizona, reprinted in Nash 1999).

at all, but the overlap was so small that it had not been noticed. HH-39 bridged the gap with enough rings covering the chronologies on either end that it made Douglass confident of the date of the floating chronology (Haury 1962, Nash 1999). The work of Douglass, Haury, and the beam expeditions resulted in the creation of a 1200-year long chronology that extended back to A.D. 700 (Douglass 1929, Nash 1999) and revolutionized southwestern archaeology by anchoring cultural traditions in time with great accuracy long before the advent of radiocarbon dating and other dating techniques.

Archaeological Methods

Many of the methods used in *Dendroarchaeology* are similar to those employed in basic dendrochronology, such as crossdating, sample preparation, and standardization. Other methods, such as site selection, cannot be employed, because the site is determined by the location of the archaeological dwelling, and the original locations of the trees are chosen by the residents of the dwelling. Dendroarchaeology also has some unique field methods of its own.

Sample Collection

Samples are often taken from structural beams in houses or wood that is in place and has been in position and drying for hundreds of years. To reduce the damage to the original structure and to be able to get a sample from dry wood, a special archaeological borer is used (Figure 7.8). A drill guide can be used to hold the drill bit steady as the researcher begins to core the beam. This drill guide is a metal plate with a hole in the center of it, just larger than the diameter of the drill bit. It is affixed to the beam with two short nails and is removed once the core is started. The

Figure 7. 8 An Archaeological borer. An archaeological drill can be used to cut a 12 mm core from dry wood. This archaeological borer uses a hollow bit that cuts away the wood around the core as the bit is drilled into the beam. A starter plate can be used to hold the bit in place while the core is taken. A long piece of metal is inserted along the side of the core, and then twisted to break the core off on the inside of the beam. This tool is being demonstrated by Dr. Darin Rubino (photo provided by Darin Rubino).

archaeological borer is driven by an electric drill and uses a specially made extra long hole-saw to cut the wood away from around a 10-12mm diameter core. The core is then removed from the hole with a bent wire which is inserted down the side of the hole and twisted to break the core off at the center of the beam. The most difficult part of this type of coring is the fact that the dust and wood chips from drilling can clog the borer. To remove this debris from the drill hole, one can frequently run the drill bit in and out of the hole, or core up into the beam so that the dust falls out with gravity; although the best surface of the beam is seldom in a convenient coring location. The dust and wood chips can also be removed by spraying a stream of air into the cut from a can of compressed air. The coring hole is often plugged with a cork to obscure the fact that core samples have been removed and to keep insects from making the core hole a home (Figure 7.9). Plugging the hole in archaeological samples differs from leaving the bore hole open in live samples because the live tree has mechanisms to defend itself, while the "dead" archaeological sample does not. The sample ID can then be written on the cork so that any dendroarchaeologist can refer back to a sample that was previously removed.

Archaeologists must collect the outer surface of a beam to be able to get the cutting date of a tree. That is the most important date for a dendroarchaeologist. This outer surface can be identified by bark, a smooth outer surface that may gain a patina with age, or by bark beetle galleries on the outer surface of the stem. The bark beetle will feed in the cambium layer while the tree is still alive and leave a small indentation in the xylem of the tree. Other wood boring insects, however, leave galleries in the xylem which should not be mistaken for an indication of the outer wood surface.

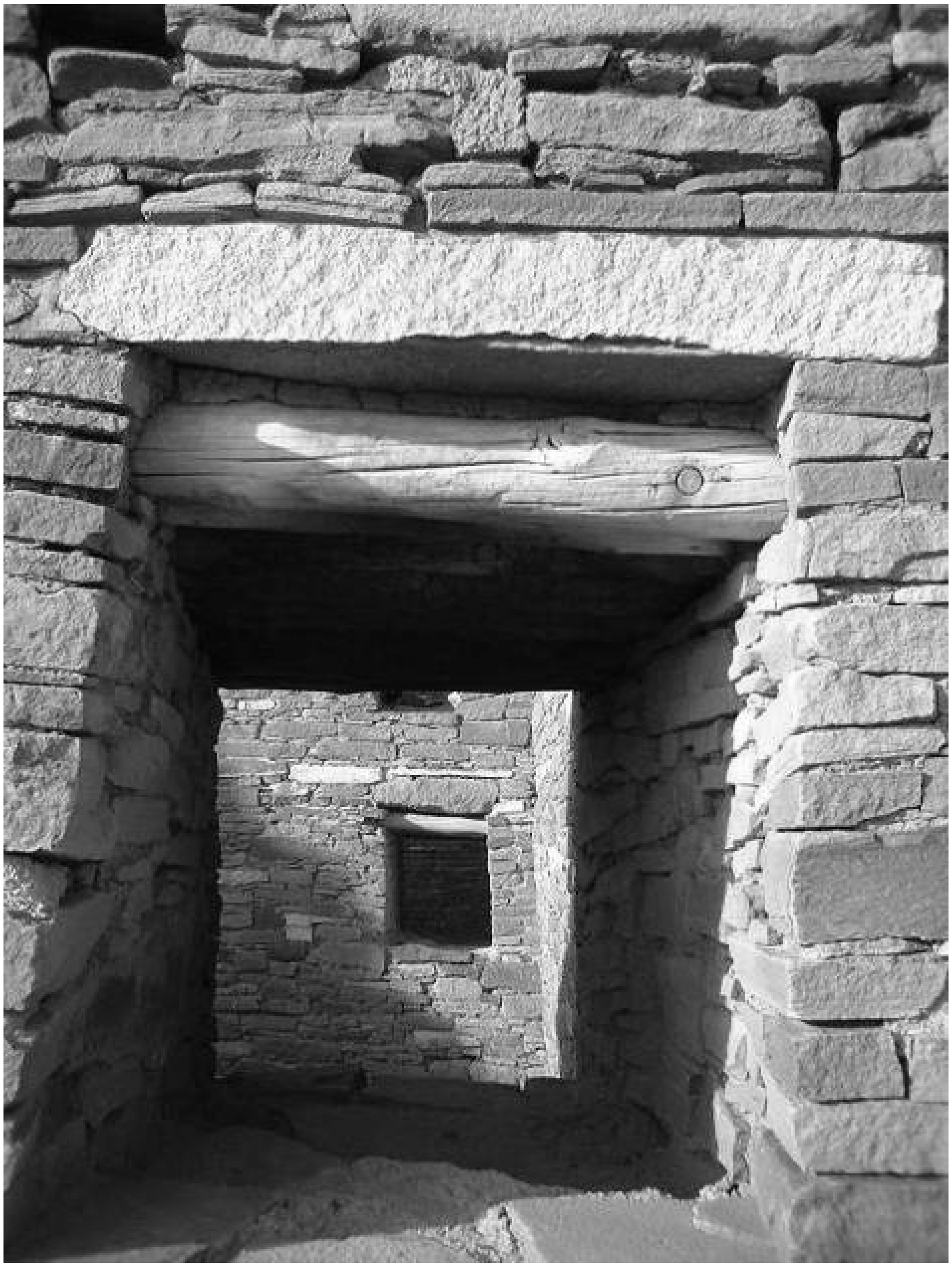


Figure 7. 9 Cores can be taken from window lintels. Although smaller than primary beams, window lintels can also be used for dendrochronological dating of structures as long as the cores have enough rings from bark to pith of the tree. The core holes in archaeological samples are often plugged with cork to protect the beams from insect invasion into these spaces and also for aesthetic reasons (note the cork plug on the right side of the front most lintel beam) (photo by Jim Speer).

Cross sections can also be obtained from wooden beams and artifacts. This process is more destructive, but it provides a larger amount of wood for analysis and when searching for micro or locally absent rings. Cross sections also give the researcher a greater chance to find more rings towards the outside of the tree, and thus get closer to a cutting date. One test for a cutting date on a tree sample is the continuity of the outer ring around the circumference of the section, so a full section can provide this data where a core cannot. Collecting a cross section from the end of a beam in a door frame or window frame can also reduce the visibility of sampling. The amount of wood available and the integrity of the artifact may constrain how much wood one is allowed to sample.

In the southwestern U.S., the Pueblo cultures used large primary beams and smaller crossing secondary beams to support multiple stories in their structures (Figures 7.10 and 7.11). These structures have provided extensive samples for the development of local chronologies from which cutting dates have been determined. Archaeological samples such as cross sections and cores taken from these beams can be surfaced with sandpaper using the methods discussed in Chapter 5.

Charcoal can also be used to date archaeological structures (Figure 7.12). Once the wood is carbonized, it is relatively inert and can last on a site for hundreds or even thousands of years without any biological decay. The cell structure is preserved in carbon, but it is extremely fragile, and may be mechanically broken down over time. The surface of carbonized wood cannot be prepared in the same way as other dendrochronological samples; instead of sanding, the wood must be snapped to produce a freshly broken surface along the cross sectional view or

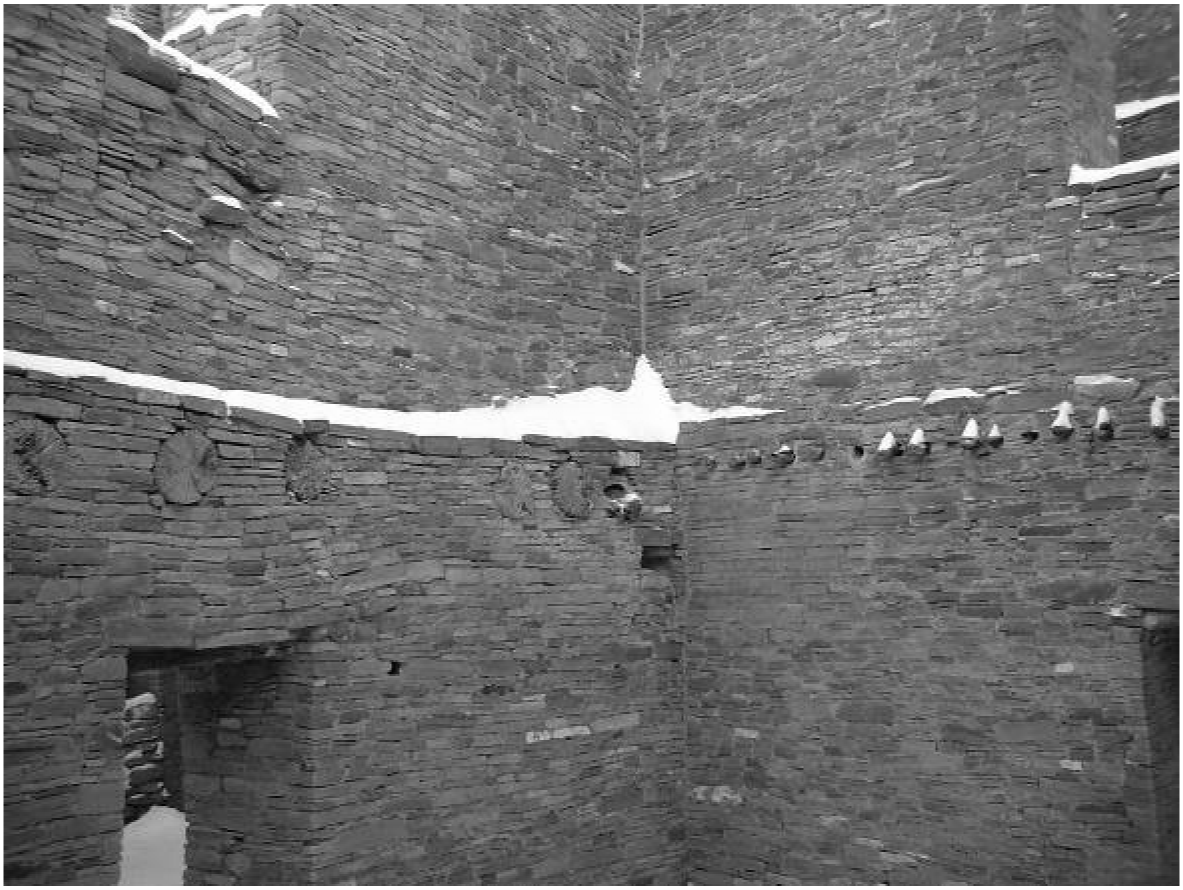


Figure 7. 10 Primary and secondary beams. Native Americans in the southwestern United States constructed complex above ground dwellings and incorporated large beams to support multiple stories. The major beams making up the support for the floor are called primary beams and the smaller poles making up the floor are called secondary beams (photo by Jim Speer).

Figure 7. 11 Cross section of a primary beam. Crosssections from the main support beams can be sampled to collect a complete series of years. Cutting dates can be obtained by cross dating the ring series of these dead trees against a master chronology of the area to assign exact felling dates, demonstrating when the trees were cut for incorporation into the architecture (photo by Jim Speer).

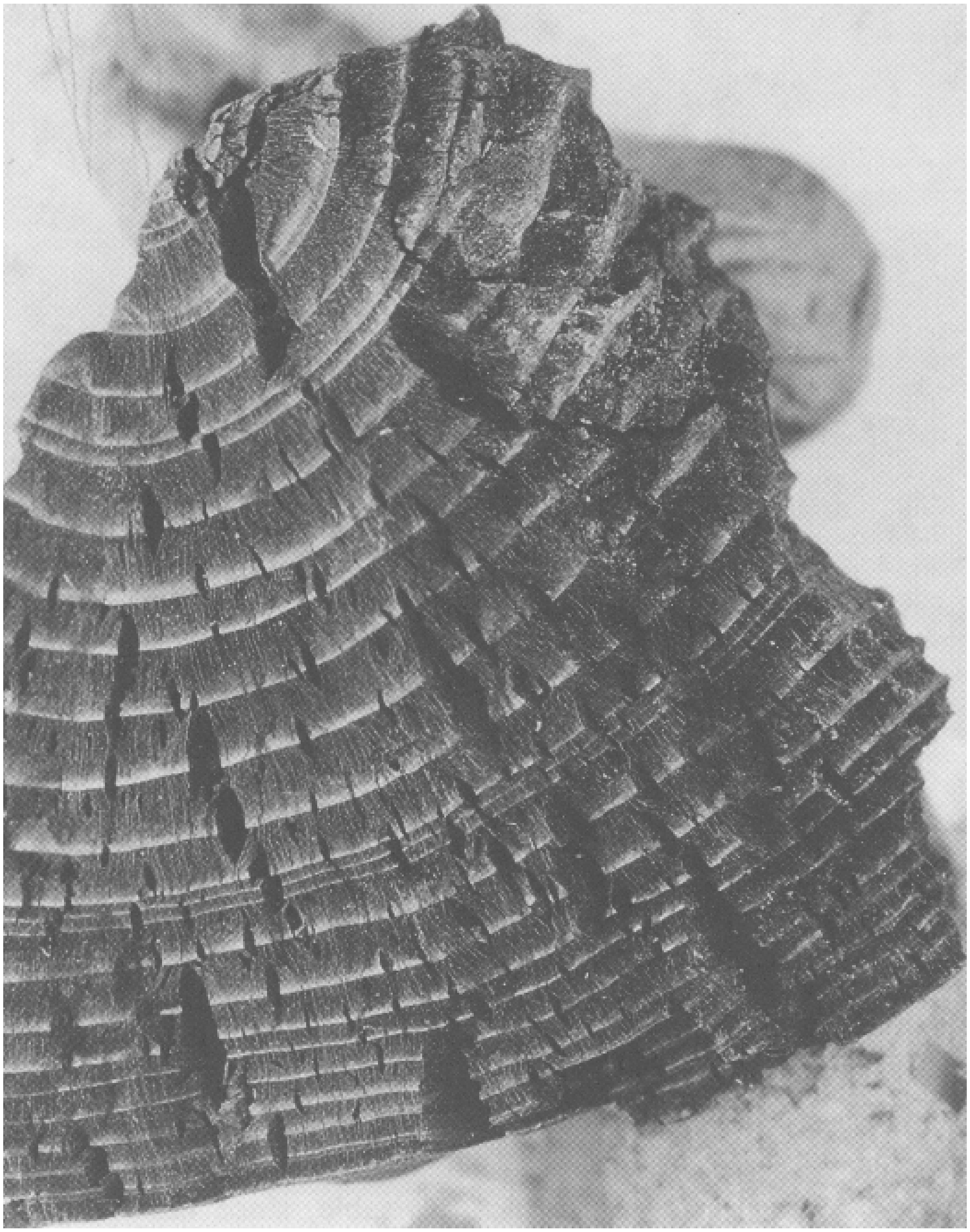


Figure 7. 12 Charcoal samples can also be used for archaeological dating. Because the charcoal is inert, it is well preserved in the soil so that the wood does not decay through time. Charcoal is very fragile and care has to be taken when collecting these samples. Unlike green wood or old beams, charcoal samples should not be sanded. These samples can be broken to expose a clean surface of the cross sectional view (from Stokes and Smiley 1968).

can be cut with a very sharp blade. A freshly broken surface is perfect for dating because all of the wood structure is visible in reflected light. Snapping carbonized wood is a finicky procedure and takes some practice. The dendrochronologist is also effectively breaking an archaeological artifact or ecofact (a natural object found at an archaeological site) in this type of sample preparation, and therefore should proceed conservatively.

Dean (1978) has developed a key to inside and outside dates that are identified in archaeological samples (Table 7.1). This key can really be used on any tree-ring sample, and helps researchers determine the quality of the dates. For identification of the inside date of the sample a "p" is used for a pith date, while "fp" is used to designate a date far from the pith, and "+/- p" is used to indicate that the pith is present, but because of poor ring condition on the inside of the sample, an exact pith date cannot be determined. Likewise for the outside of the sample, a "B" designates that bark is present, "G" means beetle galleries are present, and "L" means that the sample has a smooth surface and patina suggesting that the outside is the true cutting date of the sample. A "c" means that the outer ring is present all the way around the circumference of the sample. This usually only occurs when the outside date is the true cutting date. Erosion of the outer surface will usually cut across ring boundaries, differentially removing the outer surface of the sample. With the degradation of the outer surface of the sample, various symbols such as "r", "v", "vv", "+", and "++" indicate a lessening confidence that the outside date represents a cutting date for that sample. This nomenclature can be used for any application of dendrochronology where the inside or outside date of the sample is important.

Table 7.1 Symbols used to mark archaeological samples. Dendroarchaeologists working on wood use a series of codes to demonstrate the quality of the outside dates. The presence of beetle galleries, patina, the smoothness of the outer surface, and presence of a complete ring around the circumference of the section can all indicate whether an accurate death date can be determined for the tree (From Nash 1997 and 1999).

Table --- Symbols used to mark archaeological samples.

Symbols used with the inside date	
Year	No pith ring is present.
p	Pith ring is present.
fp	The curvature of the inside ring indicates that it is far from the pith.
± p	Pith ring is present, but because of the difficult nature of the ring series near the center of the specimen, an exact date cannot be assigned to it. The date is obtained by counting back from the earliest date ring.
Symbols used with the outside date	
B	Bark is present.
G	Beetle galleries are present on the surface of the specimen.
L	A characteristic surface patination and smoothness, which develops on beams stripped of bark, is present.
c	The outermost ring is continuous around the full circumference of the specimen.
r	Less than a full section is present, but the outermost ring is continuous around the available circumference.
v	A subjective assessment that, although there is no direct evidence of the true outside of the specimen, the date is within a very few years of being a cutting date.
vv	There is no way of estimating how far the last ring is from the true outside.
+	One or more rings may be missing from the end of the ring series, whose presence or absence cannot be determined because the specimen does not extend far enough to provide an adequate check.
++	A ring count is necessary because, beyond a certain point, the specimen could not be dated.
Note:	The symbols B, G, L, c, and r indicate cutting dates in order of decreasing confidence. The + and ++ symbols are mutually exclusive but may be used in combination with all other symbols.

Chronologies Used in Dendroarchaeology

Long-term tree-ring series have been constructed that have application for archaeological regions worldwide (Cufar 2007). Excellent preservation of wooden beams in arid environments has made dendrochronology prominent in archaeology in the American southwest. This preservation has enabled the creation of pine (*Pinus* sp.), fir (*Abies* sp.), spruce (*Picea* sp.), Douglas-fir (*Psuedotsuga menziesii*), and juniper (*Juniperus* sp.) chronologies that extend back 2,300 years (Kuniholm 2001). The bristlecone pine chronology (*Pinus longaeva*) is over 8,700 years long (Ferguson *et al.* 1985) and provides important dates for volcanic events (LaMarche and Hirschboeck 1984) and climate reconstruction (LaMarche 1974) and has been used in the calibration of the radiocarbon curve (Becker 1991, Friedrich *et al.* 2004). Long oak chronologies extending back 11,000 years have been developed in Ireland and Germany, providing the master chronologies needed for obtaining construction dates on structures throughout the region (Pilcher *et al.* 1984, Becker 1993, Baillie 1995, Jansma 1996, Cufar 2007). The eastern Mediterranean chronology has wood that goes back 9,000 years before the present, but has a number of gaps left to be filled (Kuniholm 2003). These chronologies have been developed from modern specimens, samples taken from consecutively deeper layers of oaks in bogs, and from archaeological structures themselves. Many other long-term chronologies have been developed around the world that could possibly be used as master chronologies for archaeological dating (Table 7.2).

Applications of Dendrochronology to Archaeology

Dean (1997) categorizes the use of dendrochronological evidence in archaeology under three separate applications: chronological control, behavioral information, and environmental information. Chronological control has been the standard use of dendrochronology in

Table 7. 2 Long-term chronologies from around the world. The length indicates how far back in time from the present these chronologies extend. There are gaps in some of these chronologies and some of the archaeological chronologies do not extend to the present.

Species	**Location**	**Inside Date**	**Length**	**Reference**
Combined Pinus and Quercus	Germany	10,461 BC	12,460	Friedrich *et al.* 2004
Pinus sp.	Germany	9,494 BC	11,370	Becker 1993
Quercus petraea *Quercus robur*	Germany	8,021 BC	10,076	Becker 1993
Juniperus sp.	Eastern Mediterranean	7,020 BC	9,000	Kuniholm 2003
Pinus longaeva	White Mountains, North America	6,716 BC	8,700	Ferguson *et al.* 1985
Quercus petraea *Quercus robur*	Ireland	5,218 BC	7,272	Pilcher *et al.* 1984
Various species	Swiss Chronology	4,086 BC	6,086	Egger *et al.* 1985
Quercus petraea *Quercus robur*	France	3,659 BC	5,659	Girardclos *et al.* 1996 Lambert *et al.* 1996
Quercus sp.	Netherlands – Floating Chronology	2,258 BC	1,100	Jansma 1996
Fitzroya cuppressoides	Chile	1,634 BC	3,622	Lara and Villalba 1993
Sabina przewalskii	China	1,580 BC	3,585	Shao *et al.* 2007
Sequoiadendron gigantium	California, USA	1,229 BC	3,220	Brown *et al.* 1992
Pinus aristata	Arizona, USA	662 BC	2,262	Salzer 2000
Quercus petraea *Quercus robur*	Poland	474 BC	2,474	Krapiec 1996
Pinus sp. *Pseudotsuga sp.*	Southwestern United States	322 BC	2,327	Dean 1997
Taxodium distichum	Southeastern USA	AD 372	1,600	Stahle *et al.* 1988
Pinus sylvestris	Fennoscandia	AD 443	1,555	Briffa *et al.* 1990
Lagarostrobos franklinii	Tasmania	AD 900	1,210	Cook *et al.* 1992
Larix sibirica	Polar Urals	AD 961	1,008	Graybill and Shiyatov 1992

archaeology, although in Bannister's (1963) article summarizing the state of dendroarchaeology, the useful chronologies were confined to the Southwest and Great Plains in the U.S., Western Europe, and Russia. Since that time, the application of dendrochronology has become more popular around the globe, making master chronologies available in many more regions than previously realized. Dendrochronological dates are useful in archaeology because they are accurate to the year without any error. Because of this accuracy, tree rings have been used to calibrate the radiocarbon curve and have, on occasion, upset previously determined archaeological chronologies (Baillie 1995). Dean (1997) notes that tree-ring dating of artifacts provides a suite of behavioral information "…including treatment of trees as natural resources, use of wood as raw material, seasonal timing of tree felling, sources of wood, tools and techniques of tree felling and wood modification, differential use of species, use of dead wood, reuse of timbers salvaged from older structures, stockpiling, structure remodeling and repair…". Also, the expansion of new applications of dendrochronology has been producing environmental records of climate and possible resource availability that can be used in archaeological interpretation (Speer and Hansen-Speer 2007). *Dendroecological* records are becoming more available around the world and are not dependent upon preservation conditions in archaeological sites. The prevalence of dendroecological studies can extend the benefit of dendrochronology to archaeologists that do not have preserved wood on their particular sites.

Construction dates

Construction dates are the most common application of dendrochronology to archaeology (Bannister and Robinson 1975, Billamboz 1992). This is the information that Douglass (1929) provided for the archaeological ruins throughout the southwestern U.S. Additional work has been done since that time, providing initial construction dates as well as expansion and repair dates, enabling the archaeologist to interpret human behavior and habitation periods.

Archaeological dates from the southeastern U.S. are becoming more common as cabins and other historical structures from the settlement of North America are dated (Figure 7.13 and 7.14). Stahle (1979) successfully dated 24 cabins from Arkansas that had cutting dates that ranged from 1825 to 1911. This work helped to extend the living chronologies for yellow pine (*Pinus* sp.), eastern red cedar (*Juniperus virginiana*), white oak (*Quercus* sp.), and baldcypress (*Taxodium distichum*) further back in time, providing a resource for future dating attempts. Bonzani *et al.* (1991) were able to use wooden planks from a lock system on the Main Line Canal in Pittsburg, Pennsylvania to extend a white pine (*Pinus* sp.) chronology back to A.D. 1658. Dendrochronology provides the ability to verify or reject previously held beliefs for construction dates of historical homes. Bortolot *et al.* (2001) dated a cabin that was thought to have been constructed in 1814, but was actually constructed in 1876. It has often been the case that these homes have been built later than previously thought.

The wood in historical structures throughout Europe is an important resource that has been extensively used to obtain dates of construction and to develop long chronologies (Eckstein 1972, Becker and Delmore 1978, Becker 1979, Baillie 1982, Laxton and Litton 1988, Billamboz 1992). Extensive archaeological collections now enable broad scale analysis of towns in Europe and allow researchers to compare construction dates to earliest historical documentation of the towns. Westphal (2003) used 5,002 beam samples from 87 towns that were constructed between A.D. 800 and A.D. 1300 between the Elbe and Lower Oder rivers in Germany. He founds that

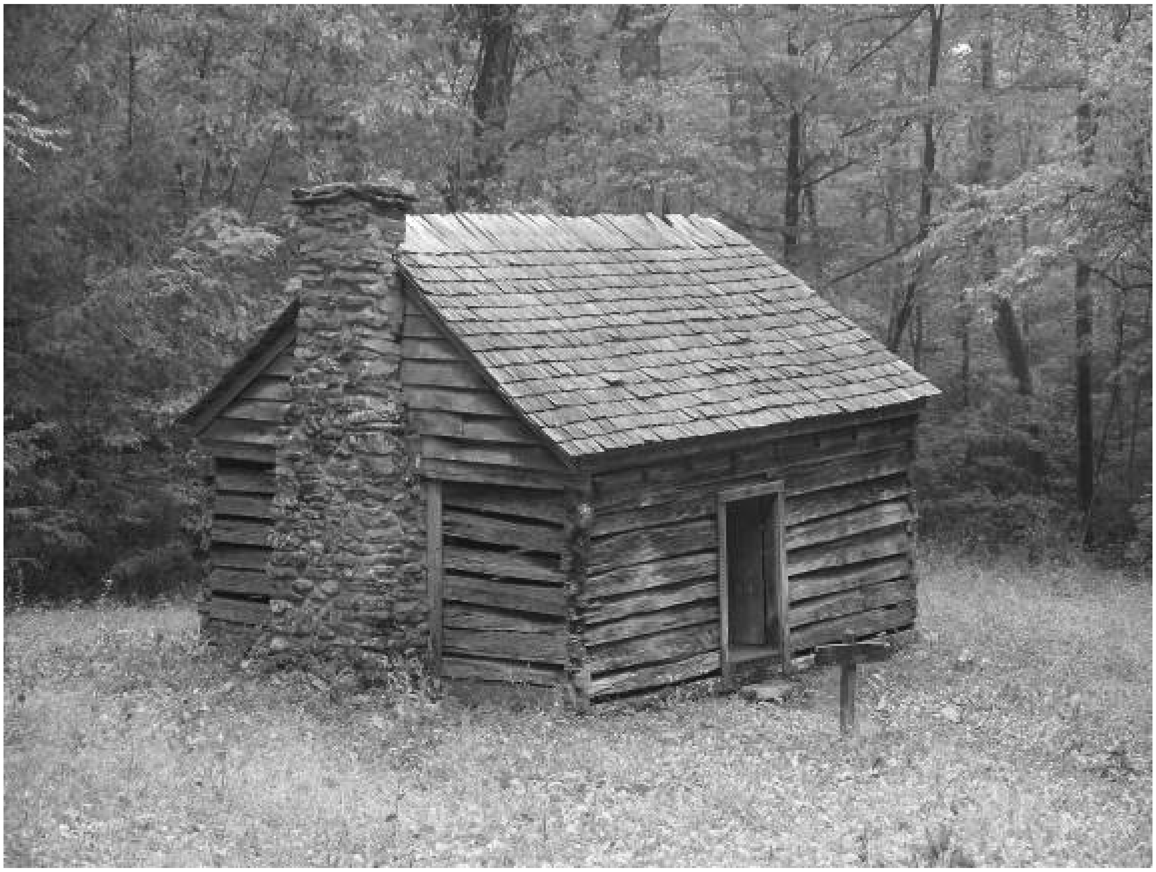


Figure 7. 13 A log cabin from the southern Appalachian Mountains. Log cabins from the eastern United States are a great resource for old chronologies and a dendroarchaeologist can provide construction dates for these dwellings (photo by Jim. Speer).

Figure 7. 14 Cross section of a beam from a log cabin. Many pioneer log cabins have very old wood incorporated in their structures. Some of these beams can prove problematic in determining accurate outside dates because the outer rings were often removed as the timbers were shaped for construction. Care must be taken to sample through an area that has complete outer rings as observed in the cross section (photo by Jim. Speer).

on average the towns were constructed 40 years prior to any written comment of it being a place and 50-60 years prior to it being called a town. In some cases, 250 years passed before there is any written mention of the town. Eckstein's (1972) summary article noted at that time dendrochronology laboratories were established in most European countries or analysis could be done in neighboring countries. He also noted that most of this work was conducted on historical structures which provided a large amount of wood and extended their chronologies back in time. Work in Finland has dated wooden causeways that both provide behavioral information on past cultures and a large quantity of wood for extending our chronologies (Zetterberg 1990).

Dating Artifacts

Lavier and Lambert (1996) report on research conducted at the Laboratoire de Chrono-Ecologie in France where they frequently date wood from paintings, furniture, sculptures, and covers of books. They take this work further and examine where the wood came from, how the artwork was made, how wood was chosen, and the time between felling trees for the artwork and when the work was completed (Lavier and Lambert 1996). All of this work demonstrates some of the unique contributions that dendrochronology and wood anatomy can make to archaeological research, specifically dealing with the behavioral information to which Dean (1997) referred.

Wooden panels were used in the Netherlands and England as the medium for paintings of the 14^{th} through 16^{th} centuries (Fletcher 1976, 1977, Eckstein *et al.* 1986). These panels can be dated to determine when the paintings were actually completed and to verify their authenticity. Also, if the date of the painting is known from historical records, dendrochronological dates can be used to determine behavioral aspects of how the wooden panels were processed. Exact dating on wooden panels is hampered by the practice of cutting away the outer surface of the wood, possibly in an attempt to remove damage by wood boring insects (Baillie 1982).

Dating musical instruments is also possible in dendrochronology if there are enough rings in the instrument and the proper master chronology can be found for comparison (Figure 7.15). It is often the case that wood from exotic locations can be used in the construction of artifacts. This foreign wood makes finding the proper master chronology a challenge in dating art and artifacts. Besides dating the Messiah violin of Stradivari (Grissino-Mayer *et al.* 2004) as related in chapter 1, Grissino-Mayer *et al.* (2005) dated the Karr-Koussevitzky double bass (Figure 7.16). With this analysis they found that the instrument had 317 rings on its face plate (the most rings ever recovered from a musical instrument) but the last rings grew in 1761 demonstrating that the instrument was not made in 1611 by the Amati Brothers as was originally thought.

Climate Reconstructions

Archaeologists have made good use of dendroclimatic reconstructions of temperature and precipitation to explain environmental resource limitations and subsequent migration patterns (Dean *et al.* 1985, Grissino-Mayer 1995, Ahlstrom *et al.* 1995, Kaye and Swetnam 1999, Van West and Dean 2000) and have used streamflow reconstructions to provide paleoenvironmental information for an area (Nials *et al.* 1989). Stahle *et al.* (1998a) reconstructed the last 800 years of climate variability from bald cypress in the southeastern U.S. This chronology provided the background information of the climate during the establishment of the Roanoke and Jamestown colonies along the east cost of the U.S. The Roanoke colony was established during the most extreme drought recorded in the 800-year chronology and the Jamestown colony was established

Figure 7. 15 Rings on the face of a cello. Tree rings are clearly evident on the face plates of musical instruments and can be crossdated against master chronologies from the region where the wood for the instrument was harvested (photo from Topham and McCormick 1997).

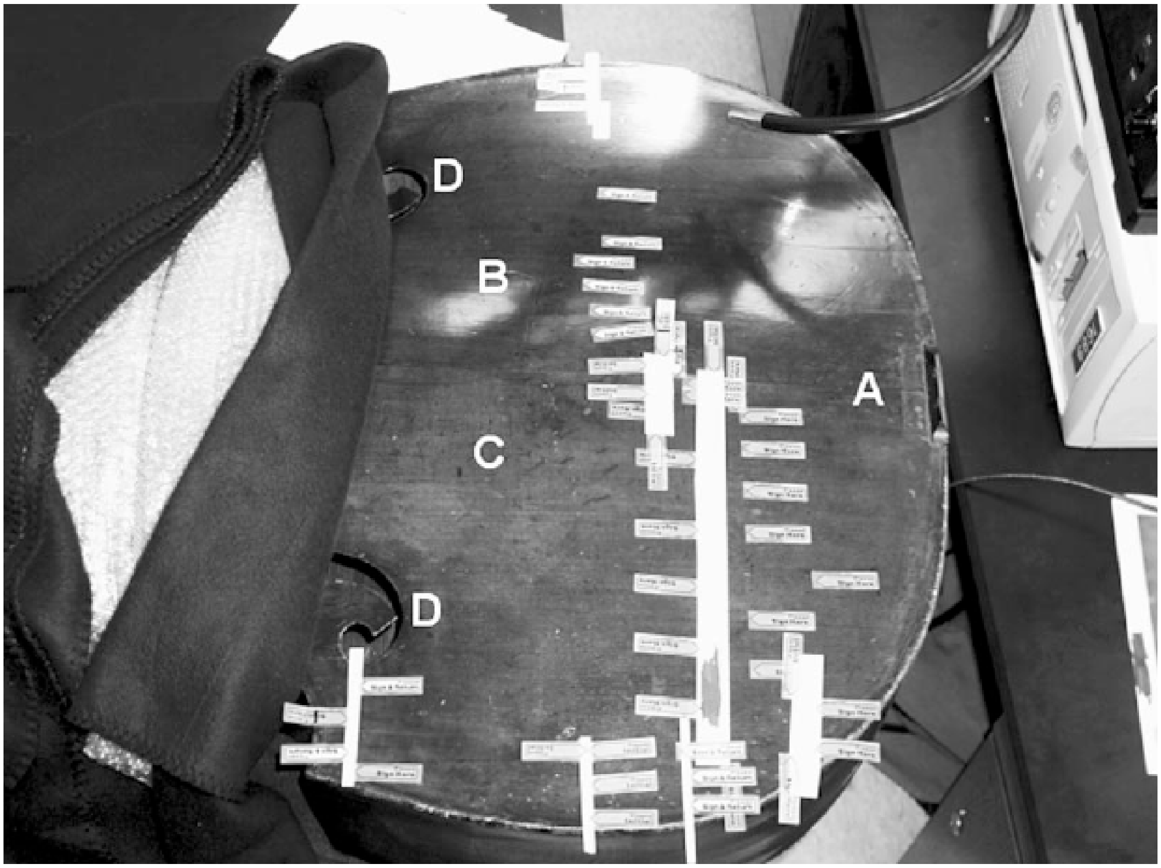


Figure 7. 16 The Karr-Koussevitzky double bass marked up for measurement (from Grissino-Mayer *et al.* 2005).

during one of the driest 7-year stretches during that same time period. Such climatic data can help archaeologists interpret the archaeological record in the context of the past climate of the area.

Ecological Reconstructions and Anthropogenic Ecology

Dendroecology is a recent branch in the field of dendrochronology (starting in the 1970s) that uses tree rings to reconstruct environmental records other than climate (Fritts 1971, Fritts and Swetnam 1989). It is a field that has not been used to its full capacity in archaeological research. Dendroecology can be used to develop records of fire history (Swetnam and Baisan 1996), insect outbreaks (Swetnam *et al.* 1985, Speer *et al.* 2001), and acorn production (Speer 2001). Researchers are developing long records of these variables that can be useful to archaeologists interested in anthropogenic ecology and resource availability (Speer and Hansen-Speer 2007). Billamboz (1992) used the cutting dates for timbers in two lake dwellings in southwest Germany and found some distinct periods of forest clearance in 1767-1730 B.C. and 1511-1480 B.C. These clearance events were associated with settlement phases and were documented by the gradual shift to smaller timbers and a change in the tree species that were used for structural timbers over time. This use of archaeological timbers to understand silvicultural practices of past cultures has been termed **dendrotypology** and demonstrates another set of information that can be obtained from archaeological wood (Billamboz 1992, Billamboz 2003).

Fire in the southwestern United States. Native American use of fire is an issue that has been debated for the last half century (Pyne 1982, Swetnam 1990, Agee 1993, Vale 2002, Wagner 2003). Native Americans may have used fire to aid in hunting, to improve grasslands, and in warfare (Stewart 1936, Shinn 1978, Pyne 1982). Lightning ignition of fires is also very common in the southwestern United States and produces a natural background of fire occurrence (Swetnam and Baisan 1996). Swetnam and Baisan (1996) argue that ignition sources are not the limiting factor, but that the appropriate fuel and climatic conditions control the occurrence of fire.

Work by Wilkinson (1997) has shown some effect from Native American burning as demonstrated by an increase in fire occurrence during times of Spanish pressure on Native American encampments. In the Sacramento Mountains of New Mexico, she found that broad scale disturbance from anthropogenic sources did not occur until the introduction of grazing in the 1880s and fire suppression in the early 1900s. This local effect on the fire regime was identified by comparing fire occurrence over a broad area and in a specific forest type to individual sites histories. Such an approach makes the broad scale pattern the norm to which irregular fire histories can be compared and described.

Fire in the eastern United States. In the southeastern United States, the fire issue is not so clear. Many people believe that fire is a natural part of the oak woodlands (Abrams 1985, 1992, 2000). Recent work, however, argues that much of past fire occurrence is from the direct effect of Native American and Euro-American burning (Jenkins *et al.* 1997, Sutherland 1997, Guyette *et al.* 2002). In the southeastern United States, few fire histories extend much before 1800. Most of fire history chronologies in the eastern U.S. are from oak trees but the full suite of hardwood trees have not been examined for fire history. More regional work, use of other hardwood tree species, and a longer time perspective may help to answer questions of Native American burning in the southeastern United States.

Culturally Modified Trees. Culturally modified trees (CMT) provide direct evidence of Native American use of trees (Figure 7.17) (Swetnam 1984, Mobley and Eldridge 1992, Wilkinson 1997, Towner *et al.* 1999, Lewis 2002). These trees provide the year and season of Native American occupation and can be related to social forcing factors of the time. CMTs are found throughout the ponderosa pine zone from Mexico into Canada. Native Americans were thought to peel the bark from these trees in the spring time and eat the inner cambium as a starvation food. Peeled trees generally occur in clusters of about 20 individuals (personal observation) and the scar left on the trees can easily be dated to the year of damage and sometimes the season. Mobley and Eldridge (1992) conducted a systematic examination of CMTs reporting on 967 peeled trees in the Pacific Northwest region with the oldest scarred tree dating back to A.D. 1467 (error approximately +/- 10 years, based on a ring count). While this work demonstrates the use of tree rings to determine the use of culturally modified trees, it would be much improved if crossdating was used so that the exact year of Native American activity could be determined. Slash pine (*Pinus elliotii*) and longleaf pine (*Pinus palustris*) have been modified in the southeastern U.S. by Euro-Americans since the mid-1700s for the production of turpentine as part of the naval stores industry (Grissino-Mayer *et al.* 2001). Workers would cut through the bark and into the wood of these pines, a process called chipping and collect the sap that came from these wounds. Grissino-Mayer *et al.* (2001) found a concentration chipping events in two southern Georgia sites in 1925, 1947-48, and 1954-56. These studies show that any preserved evidence of tree modification can be used to interpret the timing of past human behavior.

Figure 7. 17 Peel bark tree. Peel bark trees or culturally modified trees can provide a date that Native Americans were active on a site. These trees have axe marks in the wood at about knee height and again above head height. The bark was then peeled from the tree and most likely used as a starvation food source. In Canada these are considered artifacts and are protected by law whether they are living or dead trees in the forest (photo by Jim. Speer).

Culturally modified trees are now protected as archaeological artifacts in Canada and many locations in the United States are also starting to protect these trees.

Insect Outbreaks. Speer *et al.* (2001) developed a record of pandora moth outbreaks that extends back 622 years in south-central Oregon (see Figure 9.10). Pandora moth is a phytophagous insect that defoliates ponderosa pine, Jeffrey pine, and lodgepole pine in the western United States. The Klamath and Piute Indians used the pandora moth larvae and pupae as a traditional food source when it was available, indicating they had knowledge of its life cycle (Blake and Wagner 1987). This led early forest entomologists to speculate that pandora moth outbreaks had often recurred in the past (Aldrich 1912, 1921, Patterson 1929). These types of reconstructions can be used to demonstrate resource availability for native peoples.

Mast. Recent work in dendroecology has produced a new technique for developing mast (massive fruit production in trees; specifically acorns in this example) reconstructions from tree rings (Speer 2001) (Figure 7.18). Native American groups have been present in the southern Appalachians for at least the past 12,000 years (Yarnell 1998) and have been using nuts as a food source throughout much of their history in North America. One use of a mast reconstruction would be to determine the dependability of mast as a human food source in prehistoric times and as livestock feed in historic times.

Dendrogeomorphology in Archaeology. Geological applications of dendrochronology can also be used to inform archaeological interpretation. One of the better examples of this is the

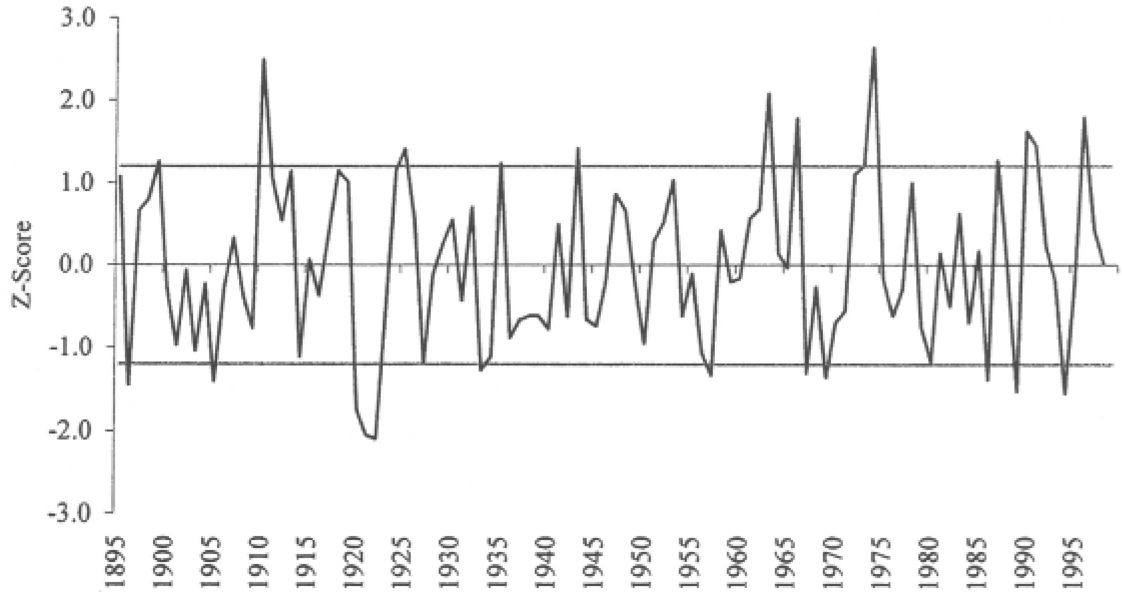


Figure 7. 18 White oak (Quercus alba) regional mast reconstruction from the southern Appalachian Region. The reconstruction is based on 165 white oak trees from Tennessee, North Carolina, and northern Georgia. Mast years are shown as z-scores with numbers larger than 1.2 and less than -1.2 considered extremely good or poor mast years respectively (from Speer 2001).

reconstruction of the eruption of Sunset Crater in A.D. 1064 in Northern Arizona by dating a growth reduction due to projectile damage from the eruption (Smiley 1958). On a broader scale, short-term global or regional temperature changes have been identified that were caused by major volcanic eruptions (LaMarche and Hirschboek 1984, Baillie 1995). Tree rings can also be used to determine bounding dates on land surfaces and some archaeological earthworks, helping to determine the chronology of archaeological sites.

Future of Dendroarchaeology

Dendroarchaeology will continue to find new applications for the chronological control that dendrochronology provides. The use of dendrochronology to determine construction dates has long been used to great benefit in archaeology. I recommend that archaeologists look more to climatic and ecological reconstructions from the various subfields of dendrochronology to develop a richer dataset for the interpretation of the archaeological record.

Chapter 8: Dendroclimatology

Introduction

One of the first and most publicly debated applications in dendrochronology has been the ability to reconstruct climate from tree rings. Because trees respond to their surroundings, they are subject to climatic stresses such as variations in temperature, rainfall, soil moisture, cloudiness days (number of days with clouds which reduces photosynthesis), and wind stress. In fact, climate seems to be one of the main controlling factors of most tree-ring growth across all spatial and temporal scales. The basic steps in a climate reconstruction are relatively simple and are often normal procedures that are done even before ecological reconstructions. But the statistical analyses of tree-ring chronologies for dendroclimatic reconstructions have become increasingly sophisticated.

Dendroclimatologists are interested in past climate so that the variation and trend of modern climate can be put into perspective. The natural range of variation of the climate system can be reconstructed from examination of the past through tree rings (Morgan *et al.* 1994). From various types of climate reconstructions (based on ice cores, marine and lake sediments, and dendrochronology) we have learned about the glacial/interglacial cycle (100,000 years), the shorter-term Holocene climate variation (past 10,000 years), and documented recent warming in the modern era (Figure 8.1). Mann *et al.* (1998) reconstructed climate variation from multiple proxies including tree rings for the past six centuries showing an abrupt increase in temperature associated with the industrial revolution (Figure 8.1). This reconstruction has been questioned from many quarters with the most constructive criticism stating that it does not take low

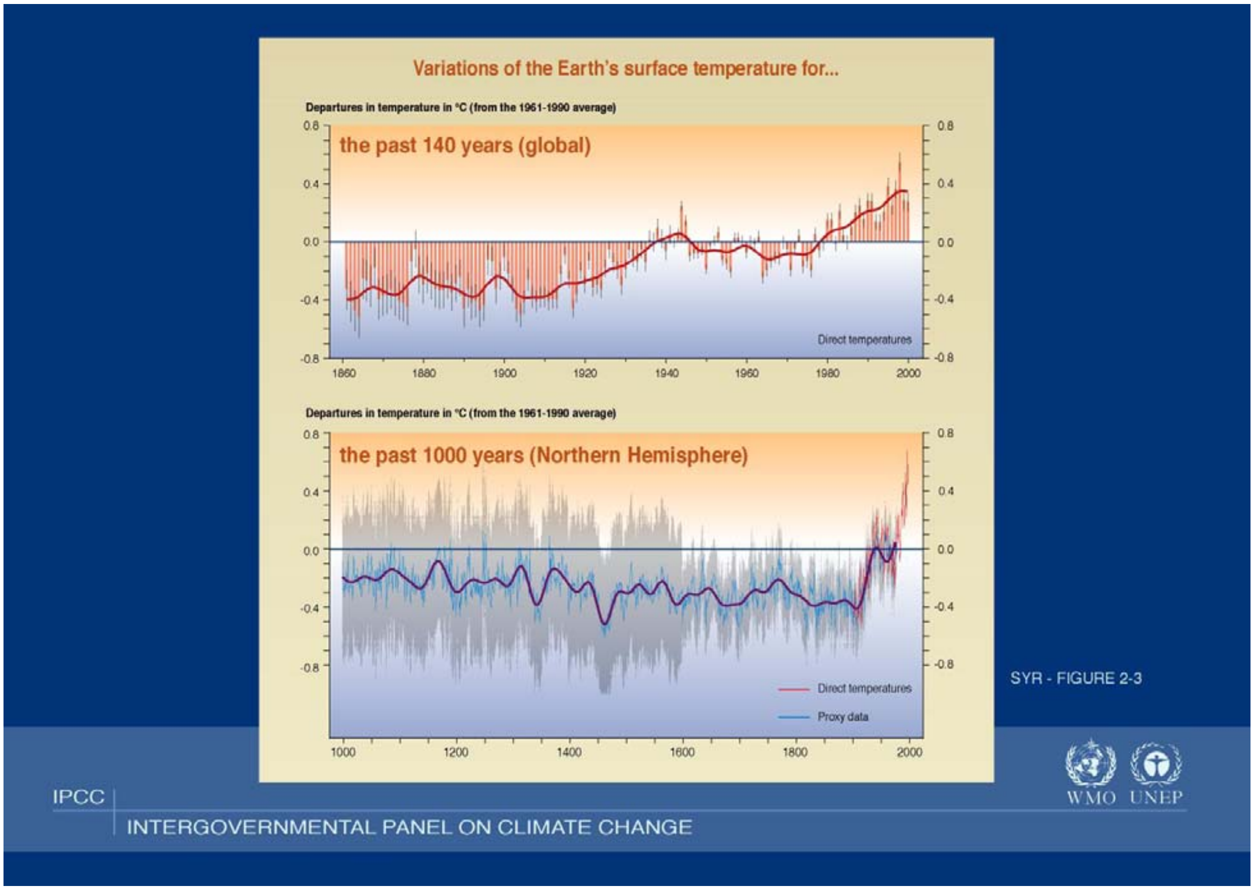


Figure 8. 1 Tree-ring climate reconstruction for the past 1,000 years. The Mann, Bradley, and Hughes (1998) "Hockey Stick" graph, which was used by the Intergovernmental Panel on Climate Change (IPCC), is built from long tree ring chronologies throughout the terrestrial land surface. The solid black line is a running average to smooth the data. There are many more recent papers that discuss improvements for this curve, because while tree rings are excellent at capturing short frequency variability, they are not very good at capturing long-term variability.

frequency climate variability into consideration as shown by lack of evidence for the Medieval Warm Period and the Little Ice Age (Moberg *et al.* 2005).

Climate phenomena, such as hurricanes, can be reconstructed from tree rings because of the specific signal recorded in ring width and in the isotopic chemistry of the rings. Climatic reconstruction, therefore, can be used to examine the proximal cause of ring width, such as changes in temperature or rainfall, or it can be used to examine broader scale patterns and phenomena that are recorded along with changes in temperature and rainfall. In the case of hurricanes, an isotopic signature can be identified in the fluctuations of wood chemistry through time (Mora *et al.* 2006). Another powerful tool is use of tree-ring networks to examine climate variability on a broad spatial scale such that inferences can be drawn about long-term changes in synoptic climatology (the flow in the climate system including pressure differences) (Hirschboeck *et al.* 1996).

Tree growth is one example of a proxy, or a natural phenomenon that indirectly records an event of interest, such as a hurricane or flood. Other examples of proxy records that record climate are coral growth, ice deposition, sediment deposition, or cave dripstone. By studying the dynamics of a region or watershed with multiple proxies, we can better understand the vegetation response to changes in climate. For example, tree-ring reconstructions of climate can be examined alongside pollen reconstructions of vegetation change to see how ecological systems respond and interact with climate change (Friedrich *et al.* 2001). Given fine enough resolution in the proxy records, a long-term record of climate and vegetation change can inform us about the mechanisms involved in vegetation change and show us possible feedback loops through microclimatic effects.

Methods for Dendroclimatology

Climate reconstruction starts with a site-level analysis of a tree species' climate response. Standard dendrochronological methods are used such as site selection, coring at breast height, crossdating, and measuring the samples (see chapters 2 and 5 for a full description). Trees are chosen from climate sensitive sites (*e.g.*, Figure 8.2), such as steep rocky slopes or northern treeline. A variety of tree ages can be used in climate reconstructions because trees may change in their climatic response with age. The oldest trees are chosen to obtain the longest chronologies, but older trees may have a weakened climate signal due to senescence. Trees with obvious injuries or sub-dominant canopy position are avoided because of possible complication of the climate signal with other micro-environmental factors. The climate signal in growth of very young trees may similarly be distorted by such factors.

Sample depth is always an important issue in dendrochronology, but of paramount importance in climate reconstruction. Sample depth is simply the number of samples that represent a phenomenon back through time. The ring-width measurements are corrected for an age-related growth trend (see standardization in chapter 2) and the resultant index values are averaged together to create a chronology with a stand-level signal that is analyzed for its climate response. The goal is to create a robust climate reconstruction that maintains a consistent climate signal whether sample depth is increased or the ring width series are standardized in a different fashion. Because we often use living trees for our climate reconstructions, we can sample at least 30

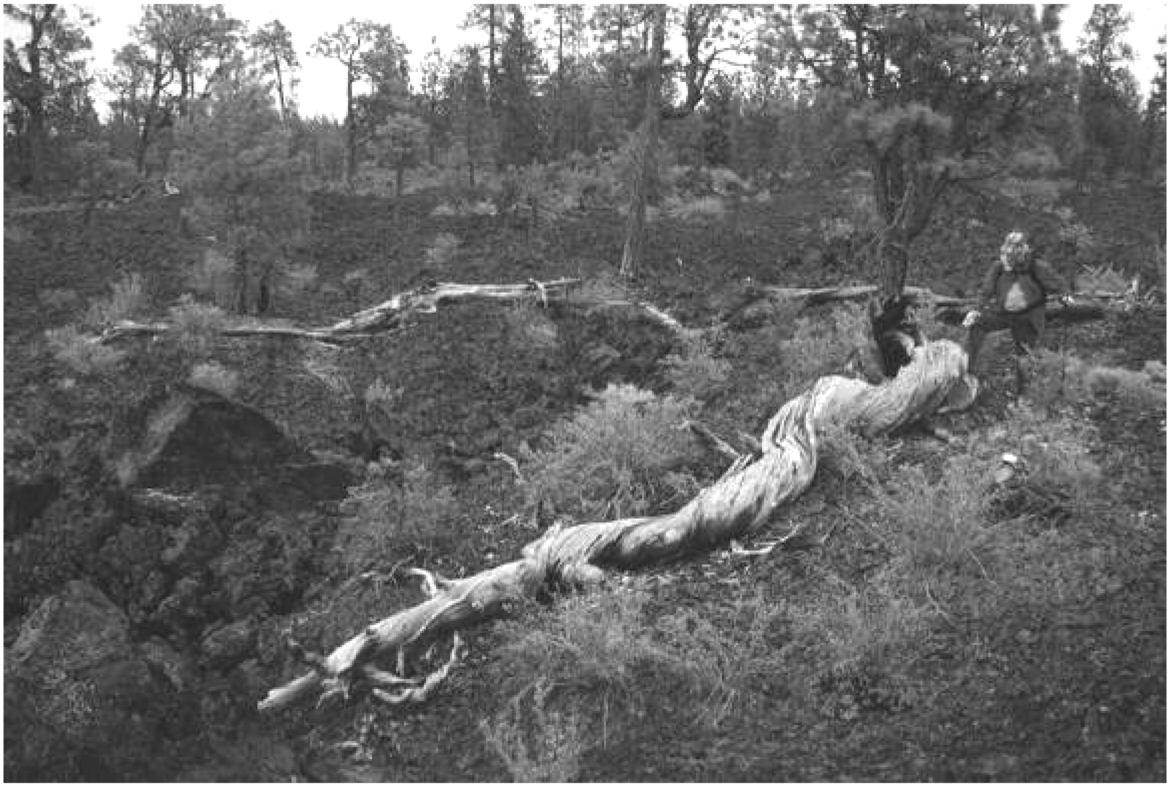


Figure 8. 2 Old preserved wood on a lava flow in Oregon. Trees struggling to grow in harsh conditions, such as this lava flow in Oregon, tend to be the oldest individuals in the species and also can be good recorders of past climate (especially precipitation records). Preservation on these sites is also very good because of the lack of soil microbes, leading to the potential for very long chronologies (photo by Tom Swetnam).

living trees (two cores per tree) for a robust sample depth in the modern era. Not all of those trees, however, established at the same time, so they fall out of the record at different times as it goes back into the past. When the chronology falls below 10 or 20 trees, growth variations of individual trees may overwhelm the common growth signal that conceptually represents the response to climate; a statistical side effect can be the increase in variance at the beginning of the chronology.

An important part of the **standardization** procedure in the processing of tree-ring measurements for dendroclimatology is the removal of non-climatic trends from the ring widths. A sensible strategy in standardization is to retain as much variance as possible at the long wavelengths or low frequencies. Such variance represents the gradual fluctuations in growth over periods of decades and longer. A negative exponential or linear trend line can be used to remove the age-related growth trend from the time series. These line fits should be examined on an individual core basis to make sure that the curve accurately represents the ring-width series. Chronologies can also be truncated after the irregular juvenile growth and the steep curve from an age-related growth trend have leveled out. Such truncation will result in removing many years from the beginning of each tree, but can sometimes simplify the standardization curve that is required to process a site. **Cubic smoothing splines** are often used in many dendrochronological applications because they produce a flexible curve that fit the data fairly closely. Splines, however, should be used with caution and with full knowledge about the variance that is being removed. LaMarche (1974) argued that the use of raw ring widths can sometimes provide a more accurate climate reconstruction because real climatic trends in the data may be removed during the standardization process. He was working in a unique circumstance with bristlecone pine (*Pinus longaeva* and *Pinus aristata*) trees from above treeline. His chronologies were longer than 1,000 years in length so that he could omit the juvenile growth from the trees and still examine long-term climate changes.

The first step in a climate reconstruction (and most dendrochronological studies) is to examine the **climate response** of the chronology which can be accomplished with a simple correlation matrix or a **response function analysis**. Climate variables such as monthly temperature, precipitation, and Palmer Drought Severity Index (PDSI) should be gathered for each research area and entered into a spreadsheet. Individual climate station data can be obtained from the Historical Climate Network (HCN) and climate division data can be obtained from the National Climate Data Center (NCDC) for the entire United States back to 1895. Another recently developed data set is the PRISM data set (see Appendix E for web address) which was developed at Oregon State University and takes individual climate station data and models the signal over the landscape based on a physiological model. This data set provides accurate climatological information for locations that have not been previously monitored. Other historical data can also be used to calibrate dendroclimatic reconstructions such as grape harvest data in France (Guiot *et al.* 2005).

Climate division data is often preferred to individual site data for many reasons. First, it is often hard to find an individual climate station that is near to your sampling site and similar in microenvironmental condition. Second, most individual stations have some data gaps in their records, while the climate division data draws on many climate stations and has been corrected for changes in the location of individual stations and for these data gaps. A correlation matrix can be created in almost any statistical package including Excel, to compare the master chronologies to every month of climate data. This analysis will reveal which months of climate data are correlated with ring width. The significant months can then be aggregated into seasons that are appropriate for each tree species being examined. Such *a posteriori* determination of the effective climate window for a particular site and species enables researchers to document the climate response of the chronology rather than forcing a hypothetical climate window onto a species for a given location (Fritts 1976: 34)

Simple linear regression can be used to develop a model for the reconstruction of one climate variable (Duvick and Blasing 1981). With the 100 years or more of climate data from the local climate division, a model can be built from half of the data (the calibration set) and tested against the other half of the data (the verification procedure) (Fritts 1976). If the calibration and verification procedures meet the statistical requirements of the study, then a significant climate reconstruction can be completed for the length of the chronology by repeating the calibration on the full length of overlap of climate and tree-ring data and substituting the long-term tree-ring data into the regression equation. Sometimes the model is extended to multiple linear regression by including more than one tree-ring series as predictor variables, or by including tree-ring series that are lagged relative to the climate series (Meko *et al.* 1980). More sophisticated models can also be used to examine the response of trees to climate. Graumlich (1993) used response surfaces, Woodhouse (1999) used neural networks, and Meko and Baisan (2001) used binary classification trees to find the most accurate way to identify the climate signal in tree-ring chronologies.

Some research in climate reconstruction has used **Principal Component Analysis** (PCA) to reduce the number of climate variables, produce orthogonal factors (completely independent variables), and to create variables that represent similar climate measures (LaMarche and Fritts 1971, Mann *et al.* 1998). PCA plots a cloud of climate variables in as many dimensions as there are variables, and then creates a best fit line through the data that represents most of the variance of all of the climate factors. This first line is called the first eigenvector. Then a second eigenvector is fit to the data so that it is orthogonal (or completely perpendicular and independent) to the first eigenvector. This process continues until all of the variance in the original data set is captured. PCA generally produces two to five eigenvectors which represent a large part of the variance in the original data set (often some 70 variables). In climatic reconstruction, PCA can be used to reduce the climate variables, the tree-ring variables, or both. Regression analysis can then be used to model the relationship between the eigenvectors of transformed climate data and transformed tree-ring variables. The process of combining PCA and regression analysis usually explains more variance in the tree-ring chronology than simple linear regression could with untransformed climate variables.

Spatial regression methods using PCA in dendroclimatology were reviewed by Cook *et al.* (1994). A novel approach using PCA on the tree-ring chronologies in a moving spatial window was developed by Cook *et al.* (1999) to combine a dense network of tree-ring sites and create a regular grid of PDSI reconstructions throughout the United States. This use of PCA, which will be discussed more in the next section, reduces chronologies to modes of tree-ring variation for geographic regions centered on gridpoints. PCA is a powerful tool for reducing a complex set of variables to the common signal and is likely to have more application in dendroclimatology in the future.

Applications of Dendroclimatology

Tree response to climate from many sites in a region or across a continent can be used to map the climate variables that affect tree growth in different regions (Fritts 1976: 35). With a **network of chronologies**, spatial patterns of effective climate can be determined. Furthermore, with the time depth provided by dendrochronology, the spatial patterns can be studied to determine the size and distribution of climate events such as droughts through time. Brubaker (1980) conducted one of the earlier dendrochronological network analyses to examine climate response across the Pacific Northwest using PCA. She found that the first eigenvector responded to Spring-Summer rainfall and the second eigenvector responded to summer temperature and winter rainfall. This signal remained constant over the 400-year chronology that she developed. LaMarche and Fritts (1971) started collecting a climate network of tree-ring chronologies to reconstruct broad scale drought throughout the U.S. and Canada. A reconstruction of PDSI from the network established a long-term context for the dust bowl drought of the 1930s in western North America (Stockton and Meko 1975) and revealed a bi-decadal drought rhythm with a weak statistical link to the Hale Sunspot Cycle (Mitchell *et al.* 1979). Expansion of the geographical coverage of tree-ring collections, especially in the eastern USA, resulted in a climatically screened network of chronologies whose statistical properties and drought signal were analyzed by Meko *et al.* (1993), This initial network was further developed by Cook *et al.* (1999), who examined tree response to PDSI in order to map drought reconstructions for the continental U.S. on a 2° latitude by 3° longitude grid for 1700 to 1978. Their landmark paper provided long-term drought reconstructions for the entire U.S. that were then used to examine the intensity of the Dust Bowl drought and other climatic phenomena in comparison to this long climate window. Stahle *et al.* (2000) used a similar network with a broader spatial coverage and expanded temporal depth to examine drought across western North America, including Mexico, and found a mega-drought in the 1600s that was a much more extreme event than the 1930s Dust Bowl.

Broad-scale tree-ring networks, such as those used in the PDSI reconstructions, can be more generally applied in **synoptic climatology**, the study of climate from the perspective of atmospheric circulation. Circulation patterns can be inferred from reconstructed patterns of precipitation, temperature and pressure (e.g., Fritts *et al.* 1971, Blasing and Fritts 1976, Fritts 1976, Fritts and Shao 1992, Hirschboeck *et al.* 1996, Barber *et al.* 2004, Girardin *et al.* 2006).

The compiling of **Hemispheric climate reconstructions**, begun in the 1970s, brought to light standardization issues that arise when different species and age chronologies are compared across different regions. Researchers from around the globe standardize their tree-ring chronologies differently depending upon the expected signal in the chronology and the goal of the research. When many chronologies are combined for broad-scale analysis, the raw ring-width measurements have to be standardized with one technique across all sites, even though the sites are likely to be affected by different climatic forces. Briffa *et al.* (2001) reconstructed mean summer temperature from wood density of tree rings from 387 sites in the Northern Hemisphere for the past 600 years. They used a new technique called **Age Band Decomposition** (ABD) in which the tree-ring series are decomposed into predetermined age bands, averaged together, scaled for equal mean and variance, then recombined into a master series of relative growth changes. This technique may better preserve the low-frequency (multi-decade to century) signal in long chronologies.

Dendrochronological records of global climate variability must contain a widely distributed network of climate reconstructions from around the world. Outside of the North America and Europe, much explorative dendrochronological research was conducted by LaMarche *et al.* (1979a, 1979b, 1979c, 1979d, 1979e) in the Southern Hemisphere in Australia, New Zealand, South Africa, Argentina, and Chile. Much more work was accomplished in South America as a dendrochronology laboratory was established in Argentina and local researchers took on tree-ring investigations (Villalba *et al.* 1985, Roig *et al.* 1988, Villalba and Boninsegna 1989, Lara and Villalba 1993).   Natural climate variability in northern Africa and the eastern Mediterranean region is becoming of great interest as General Circulation Models are projecting severe drying here associated with increased greenhouse gases (Seager *et al.* 2007). Several recent tree-ring studies have been advancing dendroclimatology in the region and have developed a broad network of tree-ring chronologies (e.g., Touchan *et al.* 2003, 2007). Recent work in India has reconstructed the Indian Monsoon back to A.D. 1835 using teak (*Tectona grandis*) (Shah *et al.* 2007). Work in China is examining the climate response on natural forests that are stressed by the proximity of the Loess Plateau (Du *et al.* 2007) and a 680 year reconstruction has examined the strength of the Asian Monsoon and the effect of the Little Ice Age on the Qinghai-Tibetan Plateau (Huang and Zhang 2007). Work in Siberia has continued to develop long chronologies from high latitudes that are useful in examining modern climate changes (Vaganov *et al.* 1996, Hantemirov *et al.* 2004). Cook *et al.* (1992, 2000) reconstructed warm season temperature for Tasmania from Huon pine (*Lagarostrobos franklinii*) back to 1600 B.C. This reconstruction showed a weak signal representing the Medieval Warm Period in the 1100s and the Little Ice Age in the 1600s, suggesting that these events were stronger in the Northern Hemisphere than in the Southern. Their record also showed higher temperatures over the last 25-year period than any other time during their 1090 year reconstruction (Cook *et al.* 1992). Although this finding is not conclusive proof of global warming, it does support the theory. Climate reconstructions from New Zealand also show that tree growth since 1950 is significantly higher than any prior period since A.D. 1500 when the oldest chronologies start (D'Arrigo *et al.* 1998).

Beyond simple reconstructions of temperature and precipitation, researchers are exploring correlations with other natural variables and strengthening our understanding of the connectivity of the global circulation system. The location of the Cook *et al.* (2000) reconstruction on the relatively small landmass of Tasmania enabled a **sea-surface temperature** reconstruction for the southern Indian Ocean between 30° and 40° S. This teleconnection between marine and terrestrial systems can help us understand the climate system with its fully complex interactions. Work in West Africa in a variety of tree species has also been able to show a relationship between tree growth and sea surface temperature (Schoengart *et al.* 2006). Villalba *et al.* (1998b) examined the connection between tree growth in South America and **sea-level pressure** over the Pacific to explain long-term precipitation changes. These connections with the climate system are leading a better grasp of the complexity of broad scale atmospheric circulation patterns and interconnectedness of the global system.

Climate Indices

The **El Niño Southern Oscillation** (ENSO) is a prominent example of teleconnections in our climate system that has raised popular as well as scientific awareness of broad scale climatic processes. El Niño was a phenomenon noted in the Peruvian fisheries where the waters became warm around Christmas time and the fisheries failed. Later investigation discovered that this change, called El Niño, was the same change as the **Southern Oscillation Index (SOI)** which is quantified as the variability in the pressure difference between the town of Darwin on the northern tip of Australia and the island of Tahiti. The scientific community first took note of ENSO as a global phenomenon during the 1972-1973 El Niño event. The 1982-1983 El Niño drove greater scientific interest in this phenomenon. Finally, the 1997-1998 El Niño was strong enough and public media was active enough that El Niño became a household word. The escalating interest in teleconnections (the interconnection of physical parameters over long distances such as sea level pressure in the Pacific Ocean affecting weather around the world) has lead scientists to look for other long-term oscillations in the climate system that may lead to climate prediction and a deeper understanding of the linked marine-terrestrial system. Stahle and Cleaveland (1993) used networks of chronologies from Mexico, Texas, and Oklahoma to reconstruct the SOI for the period from 1699 to 1971. Forty one percent of winter SOI was explained by tree-ring predictors and the reconstruction correlated significantly with an independent winter SOI measure. Stahle *et al.* (1998b) continued to examine winter SOI effect on terrestrial chronologies from North America. They were able to explain 53% of the variance in the tree-ring chronologies for the period from A.D. 1706 to 1977. D'Arrigo and Jacoby (1991) examined millennial length chronologies developed from archaeological wood samples from the northwest corner of New Mexico. The desert southwest is a region that is strongly affected by El Niño, receiving drier conditions on either side of an El Niño. Principal components from five of their six chronologies explained 30% of the variance of the SOI data for the period A.D. 1865-1970 (D'Arrigo and Jacoby 1991).

The **Pacific Decadal Oscillation** (PDO) (Mantua *et al.* 1997, MacDonald and Case 2005), **North Atlantic Oscillation** (NAO) (Barnston and Livezey 1987), and the **Atlantic Multidecadal Oscillation** (AMO) (Gray *et al.* 2004) are three of the more important marine phenomena that affect climate in the Northern Hemisphere besides ENSO. Warm phases of PDO occur when the eastern North Pacific is warm and the central North Pacific is cool; this temperature gradient switches during cool phases of PDO. Biondi *et al.* (2001) reconstructed PDO back to A.D. 1661 based on a network of chronologies of Jeffrey pine (*Pinus jeffreyi*) and big-cone Douglas-fir (*Pseudotsuga macrocarpa*) in a transect from northern Baja California to southern California. MacDonald and Case (2005) were able to develop a millennial length record of PDO from limber pine in California that demonstrated that PDO had a strong 50 to 70 year period, but that it was not consistent through time. Over the past 1,000 years, this signal was only evident for about half of the time. On the eastern coast of North America, NAO is measured by the height of the 500mb isobar with a positive phase representing below-normal heights in the high latitudes of the North Atlantic and above-normal heights over the central North Atlantic. The phase of the NAO affects both the North Atlantic jet stream and the meridionality of the Rossby Waves (meanders in high-altitude winds associated with the polar-front jet stream) (Hurrell 1995). The NAO has a 1.7-7.5 year periodicity that creates alternately cold or warm conditions in Europe associated with this pressure variation. D'Arrigo *et al.* (1993) demonstrated a tree-ring response to NAO from Scots pine (*Pinus sylvestris*) chronologies located in Scandinavia and successfully reconstructed sea-surface temperature for the North Atlantic back to A.D. 1713. Gray *et al.* (2004) found that the AMO, which is a 60-100 year variation in Atlantic sea-surface temperature, was a consistent pattern throughout their record extending back to A.D. 1567.

Climatic Gradient Studies

Dendrochronological studies along gradients can be useful to examine climatic and environmental changes. Because ecotones are by definition transition zones, they are particularly sensitive to climate change and will rapidly bear evidence of shifting vegetation responses. High latitude studies are likely to show the first evidence of global warming because these locations are likely to warm more than the middle latitudes. Elevational gradients show the same vegetation changes as latitude gradients, but over a much shorter spatial scale. Both ecotones and high latitudes are being studied to see if predicted changes to temperature are occurring and to determine the vegetational response to these changes.

Latitudinal Gradient

Jacoby *et al.* (1996) examined climate response of trees for a North-South transect through Alaska covering from 62°N to 72°N latitude. In the 300-year record of their northern chronologies, they found recent decades exhibited a warming trend. Their southern chronologies and those located along the coast with a strong maritime influence did not show this warming trend. This evidence fits with the predictions of general circulation models and our understanding of the importance of gradient studies. Jacoby and D'Arrigo (1999) reviewed four climate reconstructions from northern latitudes and high elevation (in Mongolia, Siberia, Alaska, and a general Northern Hemisphere reconstruction) and found that all of these reconstructions showed unusual and persistent warming since the 1800s. They also noted other evidence such as glacial retreat and that trees once limited by low temperatures were becoming limited by moisture stress instead. D'Arrigo and Jacoby (1993) found that trees growing at their northern limit showed an increase in growth since the mid-1800s which is consistent with expectations of global warming. The authors successfully modeled the observed increase in tree growth with projected changes in climatic parameters such as temperature and precipitation with little residual signal. Because other climatic parameters explained these changes, it was concluded that there was no direct affect from CO_2 fertilization.

Treeline Studies

Trees growing at treeline are often limited by cold temperature and can be useful for long term temperature reconstructions (e.g. Esper *et al.* 2003). Treeline studies are an alternate use of dendrochronology to reconstruct climate through its effect on establishment of trees at the cold-limited high elevation extent of the species (Nicolussi *et al.* 2005) and can be an indication of broad scale climate changes. Esper and Schweingruber (2004) report on a recent broad-scale treeline advance throughout the northern Arctic region, suggesting that this present trend is associated with the reported Northern Hemisphere warming. LaMarche and Mooney (1967) and LaMarche (1973) examined remnant bristlecone pine (*Pinus longaeva;* Figure 8.3) wood from above treeline and found that warmer conditions lasted from the beginning of their record at 5,300 B.C. to 2,200 B.C. extending treeline. Cooler and wetter conditions lasted from 1500 B.C.

Figure 8. 3 Bristlecone pine trees in Methuselah Grove. For climate reconstructions, we go to high latitude or high elevation (as in this picture) to get tree ring chronologies that are sensitive to temperature. This is the Methuselah Grove of the White Mountain Bristlecone Pine Trees in California. Most of the trees in this picture are between 3,000 and 4,000 years old. The old age of these trees, combined with crossdated samples of the sub-fossil wood on the ground, allow the reconstruction of long chronologies of temperature fluctuations extending back approximately 8,000 years before present (photo by Jim Speer).

to 500 B.C., and then a cool dry period dominated from A.D. 1100 to A.D. 1500 resulting in the lowering of treeline.

Treeline sites can also exhibit stressful conditions in which trees in tropical environments produce annual rings, even though excess moisture prevents annual ring formation at lower elevations (Speer *et al.* 2004). In the Dominican Republic at 19.5°N Latitude, heavy rain in the lowlands makes West Indian pine (*Pinus occidentalis*) trees produce 3-4 rings per year (FAO 1973, van der Burgt 1997). At the highest elevation on the island, and along the margin of an area of loose rocks without much soil development, the trees are stressed enough by the lack of moisture that the January to March dry season forces them to systematically shut down, producing reliable annual rings (Figure 8.4).

Dendrohydrology: Water Table Height and Flood Events

Water table changes, land subsidence, flood height and energy, and streamflow can all be reconstructed using tree-ring data. **Dendrohydrology** is the subfield of dendrochronology that uses tree rings to reconstruct these phenomena (Schweingruber 1996). Dendrohydrological records can be reconstructed through suppression or release events in trees associated with water table changes and land subsidence, scars and growth changes associated with flood events, establishment of trees on newly deposited surfaces (Figure 8.5), and changes in growth as a response to climatic phenomena that drive river discharge.

Stream behavior can be documented by a variety of effects on tree growth that include flood scarring, tree leaning from undercutting, and establishment of trees on new sediment surfaces

Figure 8. 4 Old *Pinus occidentalis* growing on a high elevation site in the Dominican Republic. Annual dating of tree rings in the tropics is possible on unique sites where the tree growth shuts down for some part of the year. This site is called Conuco del Diablo (Cornfield of the Devil) and is located on the flank of one of the highest peaks in the Dominican Republic. Trees stop growing in the dry season from January to March in part because the rocky earth prevents much soil development or water retention. These trees have been used to build a chronology for the region (see Speer *et al.* 2004).

Figure 8. 5 The age of a delta or any sedimentary deposit can be determined from trees growing on that sediment. In this photo, four different age surfaces are discernable based on the structure of the vegetation, with the youngest being the bare sediment in the delta, the second oldest is the low vegetation in the left of the image, the third oldest is just above that and inland from the road, the oldest vegetation is on the hill slope at the top of the image (photo by Jim Speer).

(Gottesfeld and Gottesfeld 1990) (Figure 8.6). For example, a flood history of the Potomac River in Washington D.C. was determined using tree rings to date flood scars (Sigafoos 1964). The height of the scars can also be used to document the height of flood waters in the past. Begin (2000) recorded ice scarring on the trees surrounding lakes in Quebec, Canada to record lake flood events. Yanosky and Jarrett (2001) found distinct variations in the wood anatomy of oak trees; they identified white rings that were formed from open fibers when a tree's root were submerged in water and earlywood vessels when a tree was submerged and stripped of leaves at the end of the growing season. These distinct anatomical changes are an excellent indicator of past flood damage.

Information about long-term patterns of streamflow, flooding, and water level in reservoirs is relevant to anyone who makes decisions about water allocation (Meko and Woodhouse in press). Streamflow reconstructions, for example, can help municipal water managers plan for the natural variability in water resources (Woodhouse 2001). Correlations of ring width to streamflow data from the Colorado Front Range was used to reconstruct streamflow along the South Platte River and Middle Boulder Creek back to A.D. 1703 (Woodhouse 2001). Stockton and Jacoby (1976) reconstructed stream flow for 12 stream gauge stations in the Upper Colorado River Basin and found that flow was at record high levels in the early 1900s based on their 450-year reconstruction. This meant that the water allocation for the Colorado River based on the early 1900s levels could not be met during a normal year of stream flow. This was actually known at the time of the allocation decision based on research done by Douglass and Schulman. The commission reduced the amounts that were allocated because of this higher growth shown in the tree-ring chronologies, but they did not adjust it enough (see Schulman 1938 for published

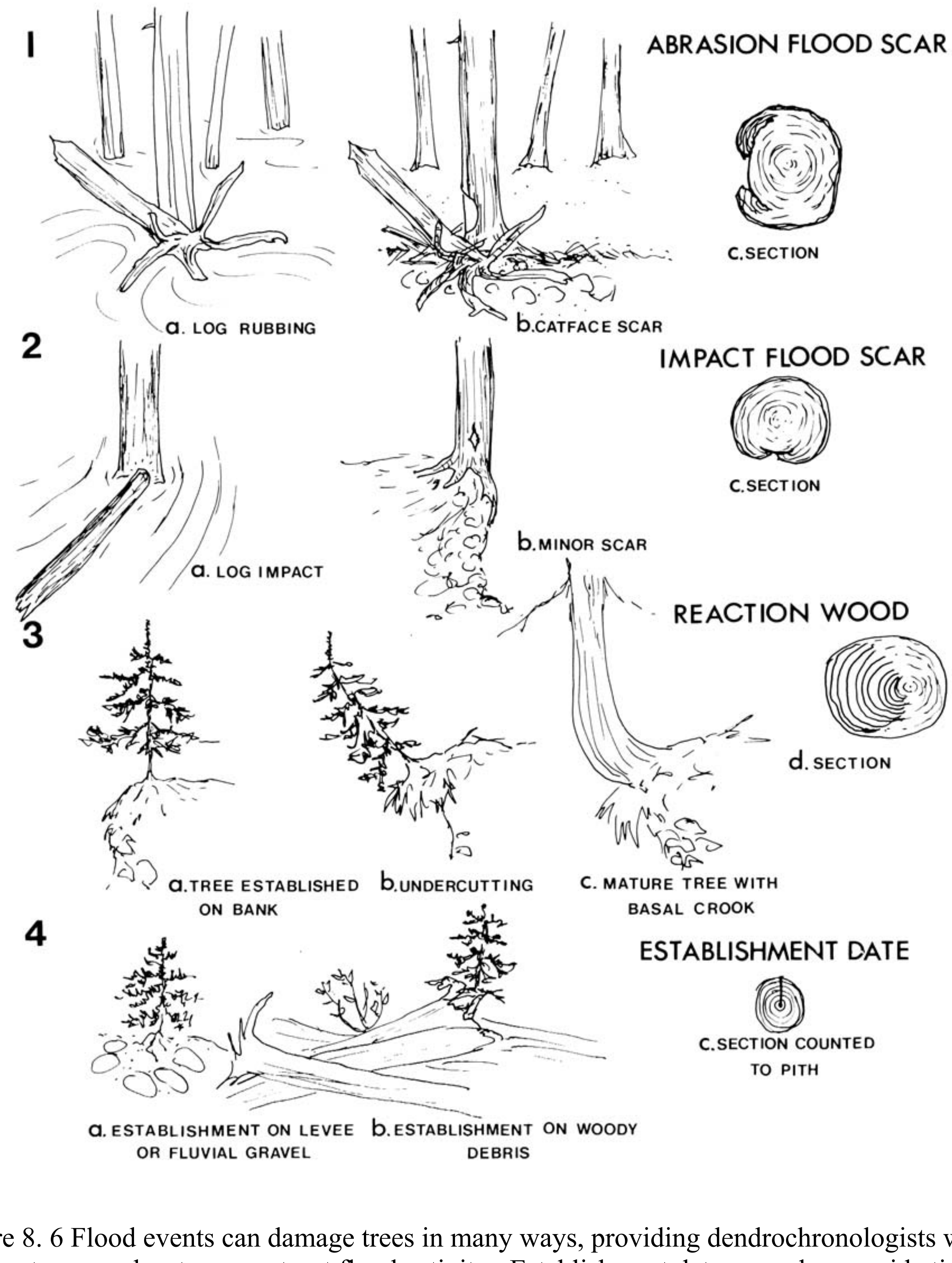


Figure 8. 6 Flood events can damage trees in many ways, providing dendrochronologists with different approaches to reconstruct flood activity. Establishment dates can also provide timing for these events (from Gottesfeld and Gottesfeld 1990).

reconstructions). Cook and Jacoby (1977) used standard climate reconstruction techniques to document drought frequency in the past as it relates to water supplies in the Hudson River Valley of New York. Other work has demonstrated the direct connection between frequency of drought events and the reliability of water reserves in various reservoirs (Stockton and Jacoby 1976, Jain *et al.* 2002, Woodhouse *et al.* 2006).

Another application of dendrohydrology is to provide information about the timing and extent of ecological changes as water levels rise or lower. Phipps *et al.* (1979) used the growth of loblolly pine near the margin of the Great Dismal Swamp to document anthropogenic ditching and subsequent drainage of the swamp. Schweingruber (1996) observed a similar phenomenon with spruce trees growing along the margin of a bog in the Swiss Jura Mountains. The marked release in growth made dating the drainage events readily observable. Changes in hydrology can also be related to landslide events, broadly called mass movement events.

Segment-Length Curse

The ability to obtain a low-frequency climate signal from a chronology is dependent in part upon the length of the individual ring-width series that contribute to the chronology. The limitation is imposed by the detrending of individual ring-width series in tree-ring standardization, and becomes a problem when trying to reconstruct climate over a long period of time from a chronology that has been formed by splicing together relatively short tree-ring segments.. This phenomenon, called the **segment length curse**, was originally proposed by Cook *et al.* (1995), who demonstrated the issue with modeled chronologies composed of sine waves with 1000, 500, and 250 year wavelengths, and supplied illustrations with real chronologies from the bristlecone pines in the White Mountains of California.

The segment-length curse must be considered when examining long chronologies that have been constructed from shorter series. Cook *et al.* (1995) used a very conservative spline of a horizontal line fit through the mean of the series and, with the bristlecone pine, a negative exponential curve fit through the series. They suggested that the **Regional Curve Standardization** (RCS; Briffa *et al.* 1992) technique may better preserve the low-frequency information of long chronologies composed of many short series such as the European oak (Quercus sp.; Pilcher *et al.* 1984) chronology or Scots pine (*Pinus sylvestris)* chronology from Fennoscandia (Briffa *et al.* 1990). St. George and Nielson (2002) applied this technique to oak trees in southern Manitoba to reconstruct hydroclimatic events while maintaining the long-term variability in their chronology.

Archaeological Uses of Climate Reconstructions

Climate reconstructions have long been used to provide an environmental backdrop to the settlement patterns of native populations (Dean *et al.* 1985, Dean 1997). Grissino-Mayer (1996) developed a climate reconstruction for El Malpais, New Mexico, that extends back to 100 B.C. This 2000-year long precipitation record delineates drought and moisture episodes for much of the southwestern U.S. He compared this climate reconstruction to major changes in Native American settlement patterns and found that settlement patterns change during periods of high variability in climate. Stahle *et al*. (1998a) examined bald cypress (*Taxodium distichum*) growth in southern Virginia and found that the Roanoke and Jamestown colonies were established during two of the most severe droughts recorded in their 800-year record. Both of these colonies struggled and Roanoke failed soon after they were established which demonstrated the communities' reliance upon the resources provided by a temperate climate. (See Chapter 7 for additional discussion.)

Use of Climate Reconstructions for Future Prediction

Policymakers and laypeople are interested in discerning the future climate of the Earth. Studies of past climate can give us an idea about climatic variability and the causal mechanisms that should hold true in the future (Vaganov *et al.* 1999, Briffa 2000). For example, Cook *et al.* (2004) examined climate variability for the past 1200 years in the western U.S. and found that instances of higher temperature (such as the Medieval Warm Period, here reconstructed as A.D. 900 – A.D. 1300) corresponded to drought, suggesting that future climatic warming may result in an increase in aridity in this area. Other tree-studies have examined the effects on past stream flow and water supplies, changes in tree response to climate, and changes in related climate parameters (see Chapter 10). Studying the past provides researchers with an understanding of the natural range of variability so that we can prepare to adapt to climatic changes in the future.

Chapter 9: Dendroecology

Introduction

Dendroecology uses dated tree rings to study ecological events such as fire and insect outbreaks. Dendroecology was developed as a field of study by Theodor Hartig and Robert Hartig in the late 1800s in Germany, with Bruno Huber continuing the tradition from 1940-1960 (Schweingruber 1996). In the United States, dendroecology did not develop until the 1970s with early work proposed by Hal Fritts (Fritts 1971). Since the 1970s, dendroecology has greatly expanded (see Fritts and Swetnam 1989) to include the study of fire history (Dieterich and Swetnam 1984), insect outbreaks (Swetnam *et al.* 1985), masting (synchronous fruiting in trees; Speer 2001), stand-age structure (Lorimer and Frelich 1989), pathogen outbreaks (Welsh 2007), and endogenous disturbance history (Abrams and Nowacki 1992). I exclude from dendroecology the subfields of dendroclimatology and geological applications of dendrochronology which are included in the definition given for dendroecology in the Multilingual Glossary of Dendrochronology (Kaennel and Schweingruber 1995). All three of these subfields of dendrochronology have a sufficient amount of research, refined methods, and techniques to be addressed independently. For this work, I define dendroecology as analysis of ecological issues such as fire, insect outbreaks, and stand-age structure with tree rings. Therefore, dendrohydrology, dendroclimatology, and dendrogeomorpology are described in Chapters 8 and 10. Furthermore, some research tools used in dendroecology such as stable isotopes, dendrochemistry, and x-ray densitometry are treated in greater depth in Chapter 11.

Methods for Dendroecology

General methods of dendroecology usually involve the standard field and laboratory analyses described in Chapter 5, with particular emphasis on establishment dates for succession studies, scarring from fires, or suppression and release events to document insect outbreaks or episodes of logging. Some methods are specific to dendroecology; for example, in order to determine exact establishment dates, cores are often taken at ground level and special care is directed towards obtaining pith.

Stand-Age Structure

A stand-age structure analysis is a useful technique for many of the studies that follow. Stand-age structures require that all living and dead trees be sampled in a plot to quantify the current forest composition and past conditions (Lorimer and Frelich 1989, Abrams *et al*. 1995, Bergeron 2000, Daniels 2003). Exact age dating is important to provide a complete picture of the establishment and mortality of all tree species on the plot (Gutsell and Johnson 2002). This method can be used as the basis for a study on succession dynamics (Abrams *et al*. 1995, Bergeron 2000), endogenous disturbances such as gap dynamics (Kneeshaw and Bergeron 1998), or for fire history in a stand replacing fire regime (Bergeron 2000).

A stand-age structure analysis can be conducted in a circular plot, square plot, or along a transect. One preferred technique is to use a band transect. In this method, a tape measure is laid out for the length of the transect (50 m for example) and all living and dead trees within a designated distance (e.g. 1 meter) of either side of the tape are sampled. Although sampling along the transect is very intensive, the larger size classes are often not well represented because larger trees tend to grow at lower densities than smaller trees. Subsequent bands can be added to the outside of the base transect, therefore, in which trees of large diameter at breast height (DBH) are sampled. For example, in addition to the complete sample within one meter of either side of the tape, all trees greater than 20 cm DBH within two meters of either side of the band can be sampled, and all trees greater than 40 cm DBH within three meters of either side of the tape can be sampled. This sampling technique results in a 100 percent sample of all age trees in a 2 X 50 meter transect and all larger trees within a four meter or six meter swath, increasing the sample depth of the larger trees. Only the data from the inner transect is used when estimating the number of trees in each age class or when quantifying the percentage of each species recorded. Careful field notes should be kept during sampling that record the location of each tree that is cored, the species, DBH, and sample ID of each tree. With this data, one can examine the interaction among trees and plot out the distribution of different tree species along the transect. Transects are particularly useful for crossing boundaries or ecotones, such as examining vegetation patterns on either side of a stream channel or across an edge from woodland to forest interior. Transects can also be run along contours to maintain a similar sampling pool of trees that are growing at the same elevation and aspect.

Selective and opportunistic sampling can be used to achieve a stand-age structure study that would otherwise be too difficult to sample or be untenable due to a lack of permission to sample extensively. Samples were taken from stumps in a clear-cut forest in coastal British Columbia in order to analyze the regeneration and growth characteristics of western red cedar (*Thuja plicata*) (Daniels 2003). Western red cedar develops heartwood decay and can grow to diameters of 160 cm, making accurate sampling of pith dates difficult with an increment borer. Daniels (2003) was able to determine that tree size was a poor indicator of tree age, recruitment was continuous and most likely affected by light gaps more than broad-scale disturbance, and mortality events were gradual and continuous through time. She concluded that current regeneration rates were sufficient to maintain the species on these sites (Daniels 2003). Daniels' research demonstrates the usefulness of opportunistic sampling when cross sections or intensive sampling are required.

Ring Width Analysis

Analysis of ring widths can be used to deduce disturbance events such as suppression from insect outbreaks, decline in growth associated with atmospheric pollution, trade-off between incremental growth and reproductive effort (masting), and release events associated with growth into canopy gaps. These applications use the same basic techniques as a dendroclimatic study, except that climate is often noise in these chronologies and should be controlled or removed so that the effect of the disturbance agent can be isolated. If a disturbance is expected to be recorded throughout the entire stand, such as with an insect outbreak study, older trees will often be targeted for sampling because they provide a greater temporal depth. Sometimes, complete stand inventories are conducted and ring widths are examined on trees throughout the stand such as with a stand age structure (Filion *et al.* 1998). Individual disturbances can also be targeted, for example trees growing in or around a light gap, in order to document the timing and response to such a disturbance (Thompson *et al.* 2007).

Tree Scars

Various types of ecological phenomena may leave scars on trees that provide a record of events for the dendrochronologist. A commonly studied disturbance is fire which causes scars in the trunk when part of the cambium is killed by excessive heat during a surface fire (see Swetnam and Baisan 1996). Animal herbivory and damage to roots by mifrating caribou on trees also leaves behind a record of their effect and can even be used to estimate population levels (Spencer 1964, McLaren and Peterson 1994, Payette *et al.* 2004).

Basal Area Increment

Basal Area Increment (BAI) can be used as a type of standardization (see Chapter 2 for more on standardization) in which annual growth increments are calculated by subtracting the area of a cross section in year t-1 from year t. The result is an estimation of the two dimentional growth increment added to the cross sectional area of the tree. This calculation is useful because it removes any age-related growth trend resulting from adding the same volume of wood on an ever increasing cylinder, while maintaining suppression and release events that may be due to forest disturbances (LeBlanc 1990a, Phipps 2005).

Applications of Dendroecology

Gap Phase Dynamics

Intensive sampling coupled with a detailed analysis of tree growth histories and stand-age structure can result in a chronology of gap-phase dynamics in which trees respond to openings in the canopy due to dominant tree mortality. Tree-level ring-width series record suppression and release events, enabling dendrochronologists to document major disturbances that affect the growth of mature and understory trees (Lorimer and Frelich 1989). Gap-phase dynamics are the most common disturbances in many closed-canopy forest sites including the tropics and temperate forests such as the eastern deciduous forest in the United States (Picket and White

1985) and old-growth forests of the Pacific Northwest (Lertzman *et al.* 1996). Gaps provide limited resources, sunlight and growing space, to the lower levels in a dense forest, and may provide the chance for suppressed understory trees to recruit into the canopy. Kneeshaw and Bergeron (1998) examined gap dynamics in the southern Boreal forest near Quebec. They found that aspen (*Populus tremuloides*) established soon after fire and as the forest aged it became dominated by individual tree gap dynamics. Over time, balsam fir (*Abies balsamea*) replaced aspen and larger gaps occured as a result of spruce budworm defoliation. As gap size increased, shade intolerant species were preferred and eastern white cedar (*Thuja occidentalis*) dominated. Daniels (2003) found a similarly complex establishment pattern in coastal British Columbia where western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and Pacific silver fir (*Abies amabilis*) competed for dominance. Western hemlock and Pacific silver fir depended on gaps to recruit into the canopy while western redcedar did not require gaps and could regenerate under the closed canopy.

Forest Productivity and Succession

Ring-width analysis can be used to examine forest health and productivity over time (Kienast 1982, Eckstein *et al.* 1984, Greve *et al*. 1986, Graumlich *et al.* 1989, Biondi 1999). For example, Biondi (1999) examined the growth of ponderosa pine (*Pinus ponderosa*) in a forest stand near Flagstaff, Arizona. The stand did not experience wild fires during the 20th century and Biondi (1999) documented a decline in growth since 1920 associated with increased forest density. These changes were compared to the past 400 years of tree growth to determine if this was a unique pattern in the history of the stand. In another project, Graumlich *et al.* (1989) examined changes in net primary productivity (NPP) of forests by measuring ring widths, demonstrating that forests in the Cascade Mountain Range in western Washington State were increasing in growth. They attributed this recent increase to warming summer temperatures and increased absorbed solar radiation rather than any CO_2 fertilization effect. Cook *et al.* (1987) took a different approach to examine forest decline in red spruce in the Southern Appalachians. They examined the relationship between climate and tree growth and found that the trees stopped responding to climate after 1967 and started to decline. They suggested that this response, not related to climatic forcing, could be due to anthropogenic pollution. **Fir waves** are another phenomenon in the eastern United States in which large swaths of fir trees die synchronously, but the agent for this mortality was unknown until the 1980s. Marchand (1984) examined tree growth and age structure in these fir stands and found that wind abrasion on the windward side of the stand caused these trees to die back while other fir trees established on the leeward side of the stand. The fir wave phenomena did not kill the stand but created a banded pattern of different stand ages. All of these specific studies are examples of how dendrochronologists can reconstruct the past to determine if modern growth of trees is similar to growth in the past, providing temporal perspective to current forest health issues.

Recent work in dendroecology has produced a new technique (**dendromastecology**) for developing mast (massive fruit production in trees; specifically acorns in this case) reconstructions from tree rings (Speer 2001). Mast reconstructions require the researcher to consider multiple variables in a tree's signal, peeling apart one layer of signal after the other, until a large percentage of the overall pattern can be explained by climate and biological factors that control tree growth. The aggregate tree growth model discussed in Chapter 2 is a conceptual model of this approach, where the age-related growth trend can be standardized out of the series, and then climate can be removed through regression analysis with significant correlates in the climate variables. Finally, the signal that is left may be a biological signal such as masting in the tree (Speer 2001). Mast reconstruction is a new technique that still has to be tested in multiple species and locations around the world. Speer (2001) demonstrated that mast reconstructions were achievable on oak species in the eastern United States; good climate data and a long calibration data set of masting in the tree species of interest, however, are necessary for this type of work. Speer (2001) also found that there was not a strict trade-off between incremental growth and reproductive effort as was suggested by ecological theory. Instead, the oaks in his study had the ability to store carbon as carbohydrate and starches (most likely in their roots) so that the carbon drain for acorns in one year was actually carried by energy production over multiple years. This suggests that mast reconstructions will not be evident on all sites, because Speer (2001) found only 25% success in mast reconstructions in his site/species chronologies. Mast fruiting may be a strong control of seed predator populations and also affect the ability of masting species to compete in a diverse forest.

Forest succession, the development of the forest community through time on a site following a stand-repalcing disturbance such as glacial retreat, volcanic eruptions, or farming can be assessed by examination of establishment dates of different tree species on one or multiple sites (Abrams and Nowacki 1992, Fastie 1995). Fastie (1995) explored primary succession dynamics in Glacier Bay Alaska after the glaciers had retreated. He used historical records of glacier retreat for the past 250 years to document the age of his plots located at increasing distances from the present foot of the glacier. Fastie (1995) found that in this area, primary forest succession was accelerated because of proximity to seed sources along the trimline of the glacier, which is the highest elevation that the glacier ice reaches. Mature trees left above the trimline produced seed that repopulated the newly exposed ground. Abrams and Nowacki (1992) demonstrated variable mechanisms of succession by documenting a case of accelerated succession in the deciduous forests of Pennsylvania that was due to an exclusion of fire followed by thinning of the overstory trees in multiple logging operations. This management practice removed fire tolerant oak and pine trees from the site and encouraged late-sucessional red maple (*Acer rubra*), sugar maple (*Acer saccharum*), and black cherry (*Prunus serotina*) to gain dominance in a forest that used to be maintained by frequent fire. Dendrochronologists can add information to larger ecological theories through exact dating of establishment and growth of trees in complex forested ecosystems.

Old Forests

Dendrochronologists tend to find old trees in surprising locations. The concept of "longevity under adversity," first published by Schulman (1954), has lead dendrochronologists to find extremely old trees on lava flows, cliff faces, and high mountain peaks. Since then, many dendrochronologists have continued to find old trees in unexpected places. Stahle (1996) documents old trees throughout the eastern United States in locations that were previously assumed to have been completely logged around the 1900s. Most eastern states still have living trees that established prior to the founding of the United States (Stahle 1996). Orwig *et al.* (2001) document four sites within 80 km (50 miles) of Boston that have trees in excess of 250 years old. Kelly *et al.* (1992) record eastern white cedars growing on the Niagara Escarpment in southern Ontario that are over 1,000 years old. In the western U.S., Grissino-Mayer *et al.* (1997) developed a 2,000 year climate reconstruction from trees growing on the El Malpais lava flow in northwestern New Mexico and from dead trees that were well preserved on the rocks of the lava flow. They found some of the oldest documented Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine trees growing in this extremely harsh environment with roots delving into the volcanic rock under a thin film of soil. Bristlecone pine trees (*Pinus longaeva*), the oldest living non-clonal organisms (Currey 1965, Ferguson 1968), epitomize the principle of "longevity under adversity." Found in the White Mountains of eastern California in cold, arid conditions at elevations of more than 10,000 feet, these trees grow so slowly that more than 100 rings may be contained in less than an inch of wood. As in many areas where long-lived trees are found, bristlecone pine forests have very little understory, usually only a few tundra herbs. The oldest trees studied by dendrochonologists are often not found in classic old-growth forests with complex understory vegetation, but are instead discovered in sites with sparse tree density on harsh sites (Orwig *et al.* 2001).

Dendrochronologists have been documenting the age of the oldest trees in each species that produces tree rings, providing an understanding of the maximum age attainable by each species (Brown 1996). By recognizing the maximum age attainable by each species, managers can formulate strategies that take into account the temporal scale of the trees they manage. Documentation of the maximum age of trees and the sites on which they grow enable researchers to better understand the concept of old-growth forests and even provide insight into how organisms age and survive to extreme old age (Appendix B; see the World Wide Web for an updated OLDLIST and Eastern OLDLIST).

Dendropyrochronology

Reconstruction of fire histories is one of the major applications of dendrochronology for use in management of forests and the reestablishment of fire as a disturbance agent. Any prescribed fire policy in the United States must be supported with scientific evidence for that tract of land. These federal and state laws have motivated fire reconstructions on many parcels of land which, in turn have generated a comprehensive view of the role that fire plays in these fire-prone landscapes. The goal of the dendrochronologist is to determine the natural range of variability for fire on a particular site (Landres *et al.* 1999). The natural range of variability describes the past occurrence of fire, how frequently it affects a site, and the area that it has covered in the past. From this information, forest managers can determine how fire has behaved on their land in the past and how fire regimes have changed in the 20th century (Heyerdahl and Card 2000).

Three main fire types occur around the world. **A surface fire** is one that burns over the ground surface, consuming duff and fine fuels. These fires usually move through an area fairly quickly and burn at a low to moderate severity. Many forest types, such as ponderosa pine (Figure 9.1), red pine, and giant sequoia (Figure 9.2) depend on these frequent low-severity surface fires to remove competition and to burn off the duff layer, allowing seedlings access to mineral soil. Oak woodlands also seem to be dependent upon frequent fire to maintain this forest type. **Stand-replacing fires** occur less frequently when fuels have built up to a critical level and often cause high tree mortality. These fires will often burn through the canopy of the trees and, therefore, are also called **crown fires** (Figure 9.3). Some pine forests, such as lodgepole pine, are adapted to this type of fire. Stand-replacing fires burn through a forest and kill the mature trees. Many of the trees that are adapted to a stand-replacing fire regime have **serotinous cones**

Figure 9. 1 A ponderosa pine stand in Oregon that has received multiple thinning and prescribed fire treatments. Note the triangular catface (fire scar wound) at the base of the closest tree on the left. The trees record multiple fires that burn through the site at low intensity (photo by Jim Speer).

Figure 9. 2 A catface can be a huge scar when it occurs in giant sequoia. Giant sequoia is a fire adapted tree species that needs fire to regenerate (photo by Jim Speer).

Figure 9. 3 Stand replacing fire in *Pinus sylvestris*. This is a crown fire that will burn through most of the stand, killing the mature trees. These trees have serotinous cones that open and disburse seeds when the cones are heated, leaving behind a seed bank on a rich mineral soil which starts the regeneration process after the fire (photo by Tom Swetnam).

which only open to spread their seed when they are heated, as a coating of resin or woody layer is burned off. Stand-replacing fires occur frequently in the boreal forest where dry summers in a continental climate combined with little topographic relief, warm winds, and convective storms result in fire that can burn a large area of the landscape. The third type of fire is a **ground fire** that actually burns under ground in the organic-rich soils of histosols. These fires are common in Alaska where they can burn for more than 30 years as they smolder through the thick organic layers of plant material on the ground.

Surface Fire. Each type of fire requires a different sampling method to accurately record the occurrence of fire in the past. Surface fire regimes will burn frequently on a site but leave mature trees alive that record the fire. Pine ecosystems seem to be the most adapted to surface fires and are most frequently sampled for long-term fire history. Fire histories in this type of forest are most productively accomplished by cutting fire scarred samples from stumps, down logs, and living trees from these sites. Surface fires are often pushed by the wind and move uphill as they consume fuels. Fire can burn more intensively on the uphill sides of the trees because the fire can eddy there in a vortex from the rising air currents. Also, pine needles and cones collect on the uphill side of the tree and provide more fuels for the fire to burn hotter at this location. The first time a tree is scarred, the fire does not usually damage the xylem of the tree. The cambium is killed because the fire heats it through the bark, later causing the bark to slough off. The scarred part of the tree will have an area of thinner bark and, if a pine tree, pitch will collect in it. Once the tree is initially scarred, it is more likely to along the exposed portion of the cambium when subsequent fires burn. Repeated fires create a triangular scar, called a **catface**, at the base of the tree (Figure 9.4).

Figure 9. 4 A catface scar on a living ponderosa pine tree with a partial section removed from the left base of the tree. Subsequent fires kill off the living cambium and leave behind a scar which the tree tries to heal over. By tracing the vertical fissures in the wood that follow the ring boundaries, one can count the number of these scars on the face of the wound to get an estimate of the number of fire scars preserved on the sample. Then a decision is made about which trees to sample based on the number of scars recorded and on the preservation of the sample (whether there is much rot) (photo by Jim Speer).

Repeated fire scars in a catface can be sampled by taking a partial section from living or dead standing (snags) trees (Figure 9.5; Arno and Sneck 1973, Cochrane and Daniels 2008). This sampling technique involves two cuts with a chainsaw along the cross sectional surface through a cat face followed by two plunge cuts along the edges of the sample to break it loose. The resultant sections have all of the fire history information from bark to pith (Figure 9.6) while leaving most of the base of the tree for stability and transport of substances through the xylem. Heyerdahl and McKay (2001) reexamined 138 trees six years after sampling partial sections for a fire history reconstruction in order to investigate the impact of fire scar sampling on the health of the trees. They estimated that only 8% of the cross sectional area was removed in sampling and that these trees did not have greater mortality than a control group of 386 similar sized trees that were not sampled for fire history. They conclude that partial sampling from the catface of pine trees is a non-lethal sampling technique that provides needed information for land management (Heyerdahl and McKay 2001).

Hardwood trees can also scar from surface fires. This has most frequently been recorded in oak trees growing in open woodland settings (Abrams 1985, Smith and Sutherland 1999, 2001). In this case, the trees tend to grow on flat ground and fire scars are not recorded in a catface, but are recorded on multiple sides of the stem wherever a fissure in the bark allows the cambium to heat up to a temperature which can kill the cambium. Therefore, old oak trees can record multiple fire scars, but a full cross section is needed to document past fires. Some hardwood trees develop catfaces due to successive fires, but these are not common as most hardwood trees develop rotten wood near the wounds, which can obscure the tree rings and the scar (Speer unpublished data).

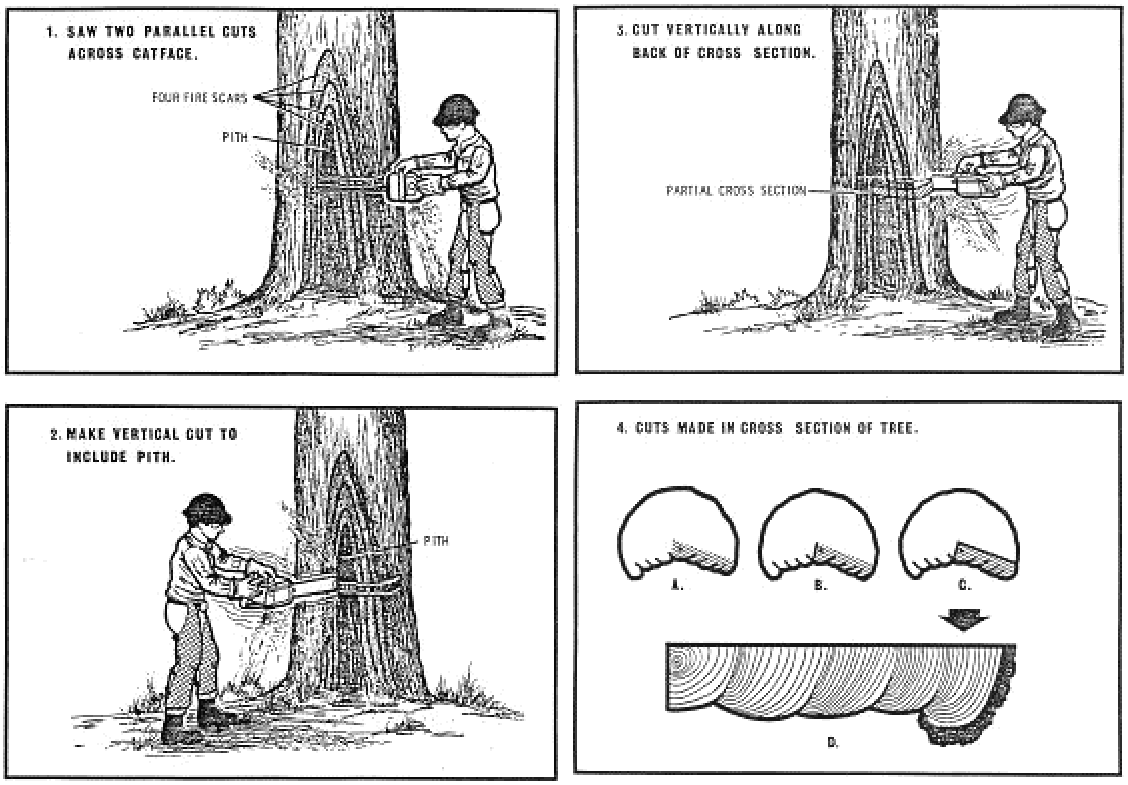


Figure 9. 5 We take partial sections from living trees to get a complete history of fire through the modern era, but leave the tree standing and healthy. In this process, the fieldworker uses a chainsaw to take two horizontal cuts and two plunge cuts to remove the fire scarred section while leaving most of the tree behind for support and conduction of fluids (from Arno and Sneck 1973).

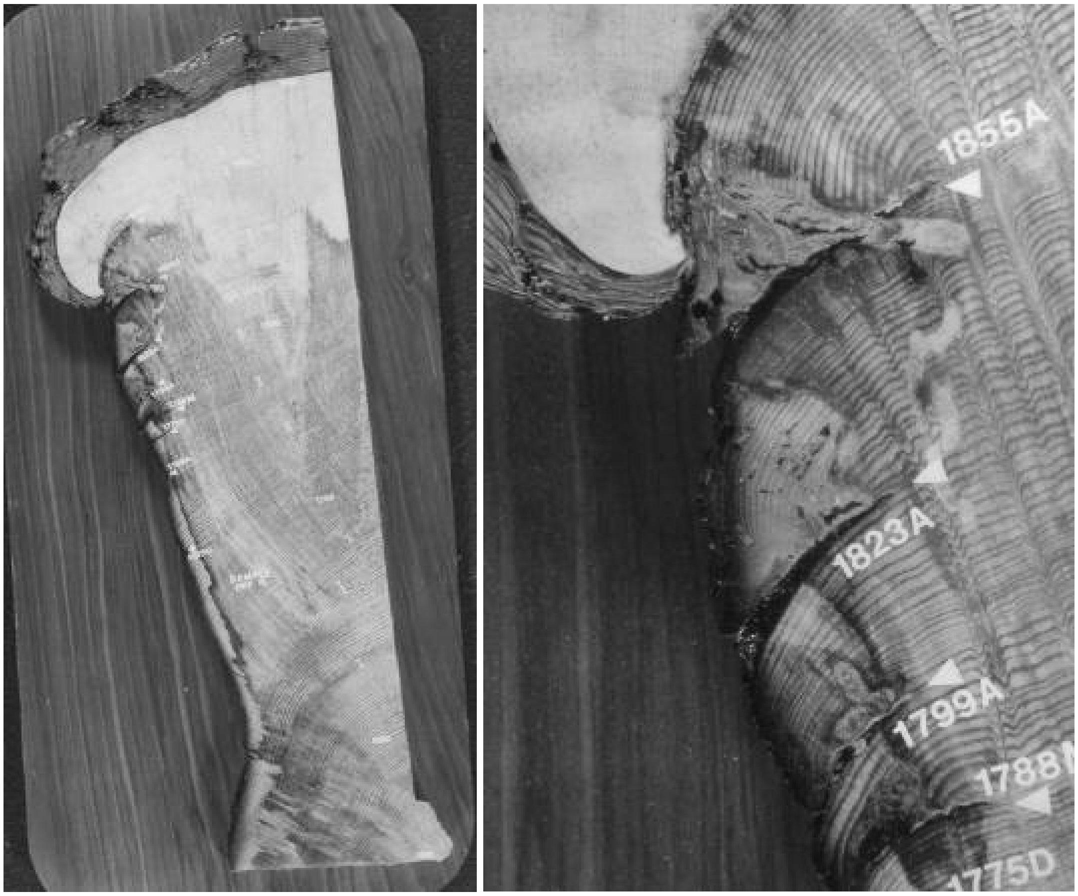


Figure 9. 6 A partial section from ponderosa pine with a close up showing the fire scar dates. This partial section only removes a small portion of the living cambium and the rest of the tree is left for support and growth. The individual scars are obvious from the bark to the inside of the tree where it started to record fires. By looking closely at the fire scarred samples, the season of the fire can be determined based on the position of the scar on the earlywood or latewood within the ring (photo by Jim Speer).

Stand-replacing fire regime. Past fire occurrence of a **stand-replacing fire** type can be documented by stand-age structure recording the time since last fire (Heinselman 1973). This technique uses a stand-age structure in areas that have been identified as different fire events based on areal photos or a stratified random sampling protocol across the landscape to determine where the age-breaks occur (Johnson and Gutsell 1994). Within the bounds of each area, a plot can be established and a stand-age structure analysis conducted. This stand-age structure is likely to demonstrate that all of the trees in each patch are a single cohort with similar establishment dates controlled by the time since the last fire. This type of study requires the researcher to take a core near the ground surface and hit pith to get the most exact age estimate for each tree (see stand-age structure methodology above). Extensive landscape studies that examine fires scars along with establishment dates and survivorship curves can be used to interpret the entire fire history of a landscape that can include surface and stand-replacing fires in lodgepole pine and sub-alpine fire forests (Sibold *et al.* 2006, 2007).

Ground fires. **Ground fires** can possibly be documented from root damage or scarring to living trees, although I am unaware of any dendrochronological studies that have examined these types of fire regimes. Most ground fires burn in regions with a rich organic peat layer that formed from an old bog. These areas do not always support many trees and any trees that were able to grow there may be killed by the passing of the fire. As long as the mortality of the tree can be attributed to the fire, the death dates of those trees can be used to determine the time of the event.

Seasonal Resolution of Fire Scars. Just as the year in which a fire occurred can be ascertained through crossdating, the season of burn can be determined from the position of fire scars in the earlywood or latewood of some trees (Swetnam and Baisan 1996, Figure 9.7). For example, if a few cells of earlywood were formed before the cambium was killed and seasonal growth was stopped in that part of the tree, researchers can infer that the fire occurred early in the tree's growing season, often in the spring. A latewood scar indicates a fire burned the tree late in its growing season, and a scar between two fully formed rings signifies a dormant season fire. Knowledge of the season of past fires enables land managers to reintroduce fire to the landscape in a natural way. If fires are forced on the landscape in a different season than occurred naturally, different plant species will be favored by affecting sprouting, fruiting, and flowering. Native American use of fire can also potentially be determined by looking for a change in the fire season from the natural fire regime.

Fire in the southwestern United States. Studies of fire effects on trees have been conducted since the early 1900s (Clements 1910, Anonymous 1923, Show and Kotok 1924, Presnall 1933). In the 1980s, crossdated fire histories became much more common in the southwestern U.S., leading to a better understanding of the spatial and temporal patterns of fire in many pine ecosystems (Madany *et al*. 1982, Dieterich and Swetnam 1984, Swetnam *et al*. 1999). Forest managers can use prescribed burning to return the forests to a more natural condition and improve forest health (Swanson *et al.* 1994, Morgan *et al*. 1994, Fule *et al*. 1997, Landres *et al*. 1999, Swetnam *et al*. 1999). Fire history records easily extend before the late 1800s, which was a time of heavy grazing by sheep and cattle and was followed by fire suppression by the U.S. Forest Service (Savage and Swetnam 1990). Swetnam and Baisan (1996) demonstrated how

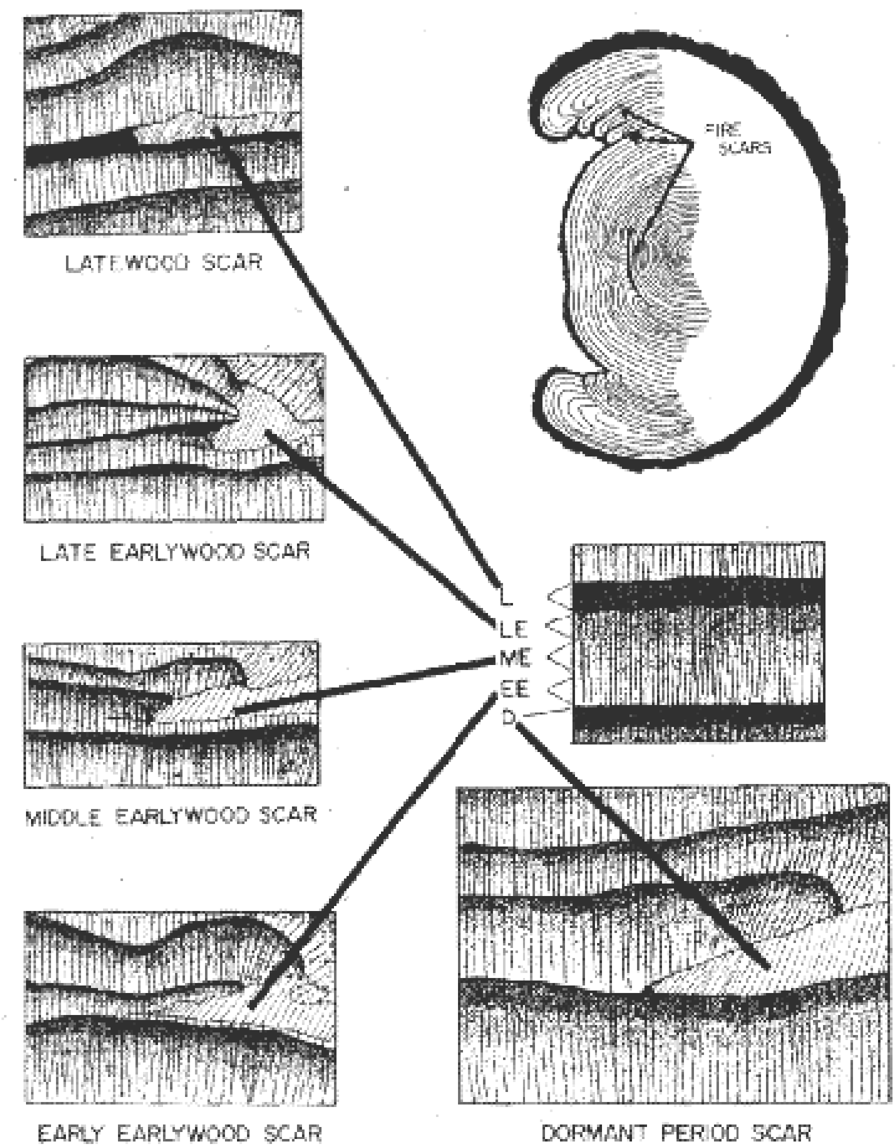


Figure 9. 7 A fire scar is a three dimensional wound where the living cambium meets the dead cambium. Right at that point we can determine the year and the season in which the fire occurred based on the position of the scar in the ring. If a few early wood cells formed before the cambium was killed, then it is termed an early-earlywood scar. If the scar appears in the middle of the earlywood, then it is named a middle-earlywood scar. The same is true for the late-earlywood fire scar. When the scar appears only in the latewood, it is called a latewood scar. If the scar appears right on the ring boundary with neither early wood formed before it or latewood formed around it, it is called a dormant season fire. The season of the dormant fire scars can generally be assigned to spring or fall by the dominance of other scars in the earlywood or latewood from that site (from Swetnam and Baisan 1996).

dendrochronological records can be used to examine fire across multiple spatial scales (Figure 9.8). Fires history data is collected on the individual tree basis. Researchers can also examine whether fires are recorded on multiple trees, and thus reconstruct a fire's spread through a site. Then multiple sites can be examined in a watershed to see how the fire has spread across the watershed. Finally sites throughout a region can be examined to identify common fire years that occur in many separate watersheds because of the appropriate climatic forcing. The result is a reconstruction of fire on multiple spatial scales and different driving factors can influence fire events at each scale. For example, Swetnam and Betancourt (1990) have shown that fire occurrence in the Southwest can often be explained by climate patterns, especially at the broad scale. Swetnam *et al*. (1999) examined fire histories from 55 sites throughout the southwestern U.S. that extended back to the 1600s (Figure 9.9) and found that regional fire occurrence was driven by long-term climate fluctuations such as El Niño.

Fire in Scandinavia. New innovations in the methodology to examine the spatial dimension of fire are being conducted in Sweden (Niklasson and Granström 2000). Dendropyrochronology has had great success in documenting the temporal component of past fires, but has lacked a rigorous systematic sampling across space that could enable the reconstruction of the spatial aspect of surface fires. Niklasson and Granström (2000) collected 1133 samples from 203 points that were approximately spaced two kilometers apart across an area covering 19 X 32 km. This network of sampling points enabled researchers to examine the area burned by past fires in a *Pinus sylvestris* chronology extending into the 1100s, which successfully documented the spread of fires across the landscape so that spatial and temporal patterns could be compared. Researchers also found an impact from human-caused ignitions in Scandinavia by early settlers

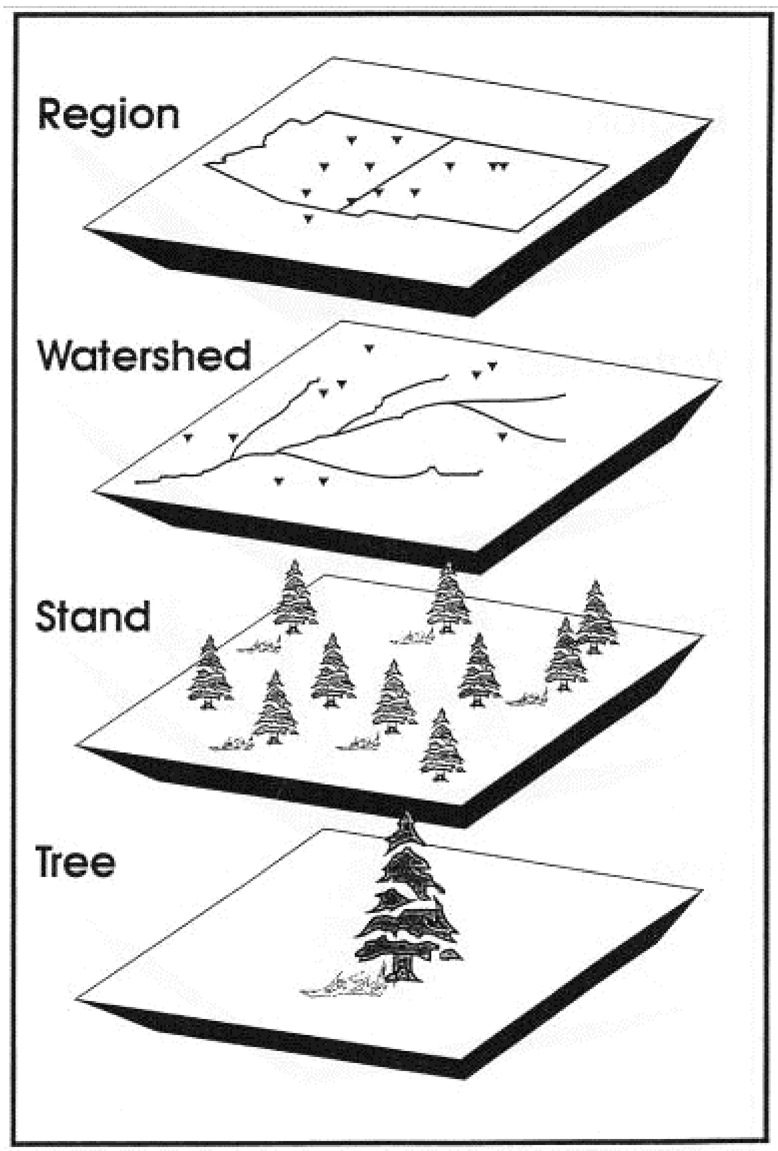


Figure 9. 8 Fire history data can be collected on multiple spatial scales to understand the driving factors of this natural disturbance. Fire scars are collected from an individual tree, but are usually analyzed at the stand level to examine spreading fires. Multiple stands can be sampled in a watershed to look at fire spread across the landscape. Many such watersheds can be sampled on a regional basis to understand how climate can drive fire occurrence at this broadest scale (from Swetnam and Baisan 1996).

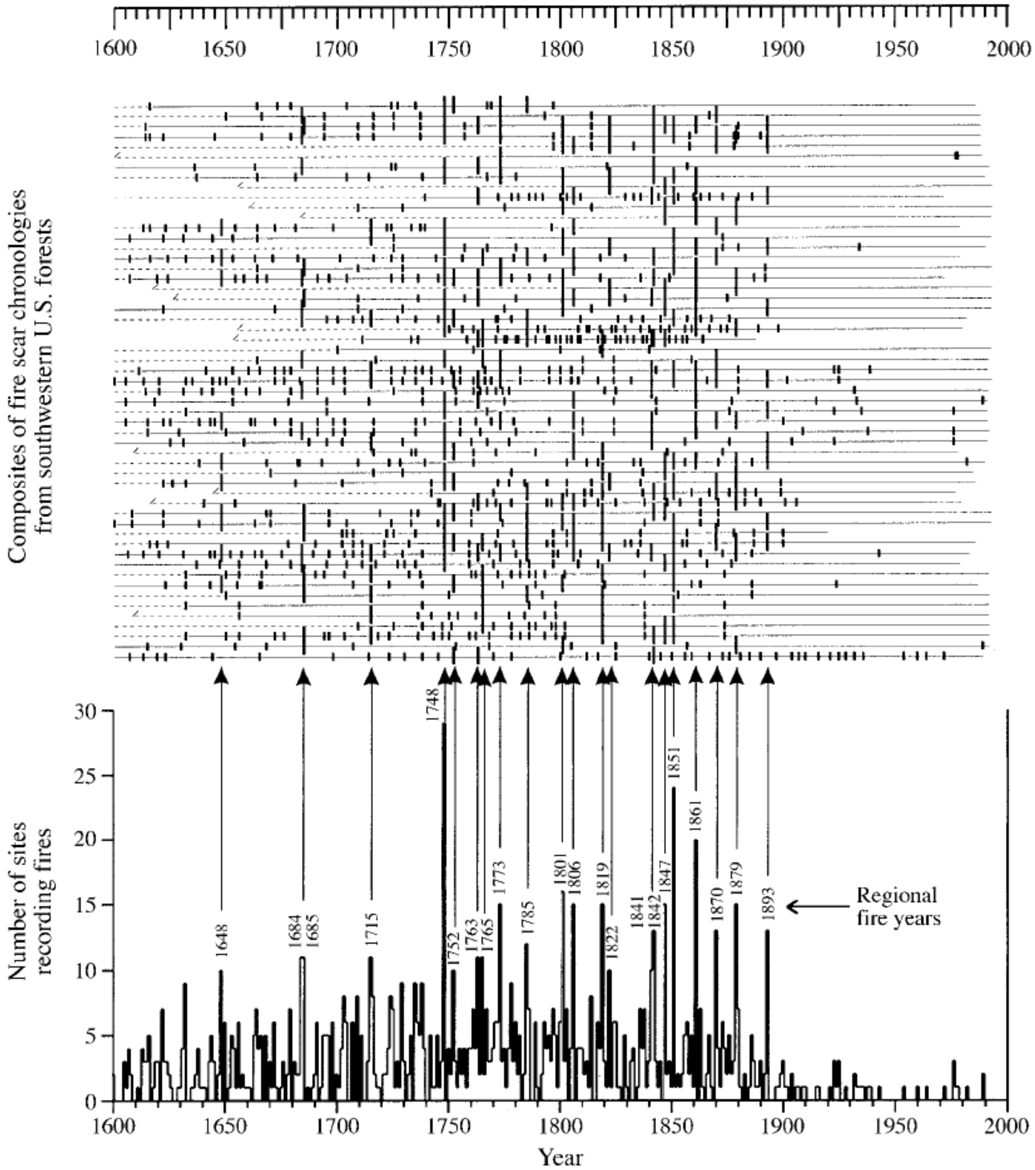


Figure 9. 9 A fire history chart for a network of 55 site-level chronologies extending back to A.D. 1600 throughout the southwestern United States (Swetnam *et al.* 1999). Each horizontal line in the top part of the graphic represents an individual site while each tic mark on that line represents a separate fire event that affected many trees on the site. The bottom part of the graph is a composite of fire charts throughout the western United States and Northern Mexico.

around the 1600s, probably for the purpose of improving cattle grazing conditions and for slash-and-burn agriculture (Lehtonen and Huttunen 1997, Groven and Niklasson 2005). Fires tend to cease around the late 1700s because of increased value of timber and a likely resultant attention to conservation of this resource (Groven and Niklasson 2005).

Fire in Canada. Considerable fire history research has been done in Canada from the mixed hardwood forests of south-central Ontario (Dey and Guyette 2000), to the boreal forest (Bergeron 1991) and even at the latitudinal treeline at 58° North latitude (Payette *et al.* 1989). Bergeron (1991) examined fire occurrence on mainland sites versus island sites to determine the driving factors that control fire frequency. He documented more frequent/less intense fires on the red pine (*Pinus resinosa*) and common juniper (*Juniperus communis*) dominated rocky islands because of fuel limitation, in contrast to less frequent/stand replacing fires on the mainland that was dominated by balsam fir (*Abies balsamea*), black spruce (*Picea mariana*), and paper birch (*Betula papyrifera*) on a site that was more moist and had greater fuel accumulation. A decrease in fire frequency over the past 120 years was found in this study and attributed to a decrease in long-term droughts associated with warming since the Little Ice Age (Bergeron 1991, Bergeron and Archambault 1993). Studies from 55° to 59° North latitude have examined the variability of fire rotation periods across biomes from boreal forest through the forest tundra and into the shrub tundra (Payette *et al.* 1989). It was estimated that the northern boreal forest fire rotation period was 100 years while shrub tundra fire rotation period was greater than 7,800 years.

Conclusions from Dendropyrochronology. Fire history has been one of the main tools of dendroecologists, supplying much information about disturbance ecology over the past 30 years. While working with this application, researchers have perfected techniques for seasonal resolution of dating scars preserved in the trees and have made advances in spatial as well as temporal analysis. In the next section, the study of insect outbreaks adds to our knowledge of disturbance ecology.

Dendroentomology

The study of insect outbreaks has become a major subfield of study in dendrochronology because forest managers are interested in the historical effects of insects on their managed lands. Dendroentomology documents past occurrence of insect outbreaks and gives an understanding of insect population dynamics including duration of outbreaks, interval between outbreaks, and the spread of insect outbreaks (Swetnam *et al.* 1985). As with all dendrochronological applications, dendroentomology provides a long-term perspective for ecological dynamics in a forest system.

The earliest study of insect outbreaks using tree rings was conducted by a German botanist, Ratzeburg (1866), who dated outbreaks of a defoliating caterpillar with annual resolution (Ratzeburger 1866, as cited in Wimmer 2001 and Studhalter 1955). In an introductory textbook on forestry, Hough (1882) shows a graphic of the reduced growth of tree rings related to the defoliation of insects in the eastern U.S. The presence of this graphic and statement in a forestry textbook in the late 1800s demonstrates the general knowledge of tree growth, the ability to date ecological phenomena with tree rings, and the effect of insects on trees and their growth. The field of insect outbreak reconstructions started in earnest in the 1950s and 1960s when a series of publications made this discipline more accessible to researchers (Blais 1954, 1957, 1958a, 1958b, 1961, 1962, 1965, Hildahl and Reeks 1960). Blais (1958a) documented a decrease in ring width of balsam fir and white spruce due to the effects of eastern spruce budworm (*Choristoneura fumiferana*). In 1960, Hildahl and Reeks published a study on the effect of forest tent caterpillar (*Malacosoma disstria*) on trembling aspen in Manitoba and Saskatchewan. Blais (1962) did much to establish the techniques for studying insect outbreak dynamics in his study of eastern spruce budworm in Canada. Long-term reconstructions covering the past 200-300 years have demonstrated that spruce budworm has increased in frequency, extent, and severity caused by human changes in the forest ecosystems (Blais 1983). Swetnam *et al.* (1985) published a manual on how to approach insect outbreak studies that became a standard in the field. This publication helped to codify an approach to insect outbreak reconstruction that was quickly followed from the 1990s to the present with a flurry of dendrochronological insect outbreak publications. Canada is one of the more active areas in insect outbreak reconstruction with work by Krause and Morin (1999), Zhang and Alfaro (2002), and Campbell *et al.* (2007).

Insect outbreak studies come in many different forms depending upon how the insects affect the trees; insects may be defoliators, cambium feeders, or root parasites. The defoliators focus on a type of tree and consume leaves or needles from those tree species. Examples of these types of insects include western spruce budworm (*Choristoneura occidentalis*) (Swetnam and Lynch 1993), Douglas-fir tussock moth (*Orgyia pseudotsugata*) (Swetnam *et al.* 1995, Mason *et al.* 1997), and pandora moth (*Coloradia pandora*) (Speer *et al.* 2001) (see Table 9.1 for a more comprehensive list). Insects that feed on the cambium, usually killing the tree, include bark beetle larvae (*Dendroctonous* and *Ips* species) (Eisenhart and Veblen 2000). Finally, an example

Table 9. 1 Insects that have been studied using dendrochronology.

Common Name	**Scientific Name**	**Type**	**Publication**
Spruce Beetle	*Dendroctonos rufipennis*	Cambium feeder	Eisenhart and Veblen 2000
Mountain pine beetle	*Dendroctonos ponderosae*	Cambium feeder	Shore *et al.* 2006, Campbell *et al.* 2007
Forest tent caterpillar	*Malacosoma disstria*	Defoliator	Hildahl and Reeks 1960
Gypsy Moth	*Lymantria dispar*	Defoliator	Asshof *et al.* 1999
Larch Sawfly	*Pristiphora erichsonii*	Defoliator	Case and MacDonald 2003
Pandora Moth	*Coloradia pandora*	Defoliator	Speer *et al.* 2001
Western Spruce Budworm	*Choristoneura occidentalis*	Defoliator	Blais 1962 Swetnam and Lynch 1993
Tussock Moth	*Orgyia sp.*	Defoliator	Mason *et al.* 1997
Two-Year Spruce Budworm	Choristoneura biennis	Defoliator	Zhang and Alfaro 2002
Periodical cicadas	Magicicada sp.	Root parasite	Speer unpublished data

of a root parasite is the periodical cicada (*Magicicada* sp.), a group of insects that are restricted to the eastern United States and spend 99 percent of their life cycle feeding on the xylem fluid in the roots of trees. Recent research has demonstrated that they do not greatly affect the trees but may cause a reduction in growth when they oviposit in the branches of the trees. They may also increase the growth of the trees by providing a nutrient pulse when their carcasses decompose after a massive emergence in the eastern United States (Speer unpublished data). Researchers can also document the spread of invasive species such as the hemlock wooly adelgid (*Adelges tsugae*), gypsy moth (*Lymantria dispar*), and the emerald ash borer (*Agrilus planipennis)* and use the techniques of dendroentomology to reconstruct the effects of fungus on tree populations such as the chestnut blight (*Cryphonectria parasitica*) and the Dothistroma needle blight (*Dothistroma septosporum)* (Welsh 2007). Insects that cause mortality of the host trees, such as wooly adelgid, emerald ash borer, and many bark beetles, are more difficult to reconstruct because a mortality event could be caused by many different factors and that ends the record for those particular trees. Repeated outbreaks of these insects may be recorded by the response of other trees in the stand that are released by the mortality of the host species.

From the different groups, dendroentochronologists reconstruct a greater variety of defoliating insects than any other type. Calibration of the tree-ring record with historical documentation of past insect outbreaks has been very helpful in determining the insect's effects on the trees (Brubaker and Greene 1979, Swetnam *et al*. 1985, Wickman *et al*. 1994). Comparisons of ring patterns during periods of known outbreaks in a study area can identify a tree-ring signature specific to that insect species. By examining the defoliation effects of tussock moth and spruce budworm in the same tree, researchers have, in some cases, been able to differentiate between the signature of the two species and subsequently document past outbreaks of each species (Brubaker and Greene 1979, Wickman *et al*. 1994, Mason and Torgerson 1987). Douglas-fir tussock moth produced a four to five-year signature of sharply reduced growth, while the western spruce budworm entailed more gradual but longer outbreak periods (often 10 years), leaving a signature of less abrupt but more persistent growth reduction (Wickman 1963, Brubaker and Greene 1979). The differentiation of outbreak patterns aptly demonstrated the effectiveness of dendrochronology in identifying specific **ring signatures** for phytophagous (leaf-eating) insects throughout the length of the tree-ring chronologies. However, when western spruce budworm and Douglas-fir tussock moth outbreaks occur simultaneously or closely spaced in time, they cannot always be differentiated in trees or stands that were defoliated in the past by both species (Swetnam *et al*. 1995).

Reduction in tree growth reflects the period when defoliation significantly impacts tree health and does not usually begin precisely with the onset of the insect population's increased growth (Swetnam and Lynch 1993). Stored food reserves can delay defoliation-induced growth loss by one or more growing seasons (O'Niell 1963, Kulman 1971, Brubaker and Greene 1979). Since a tree requires time to replace lost foliage following severe defoliation, its growth may be inhibited for several years after the insect populations have crashed (Duff and Nolan 1953, Mott *et al*. 1957, Wickman 1963, Brubaker and Greene 1979, Alfaro *et al*. 1985, Lynch and Swetnam 1992).

Researchers have developed techniques for differentiating climate-related ring-width suppressions in the host trees from those produced by insect outbreaks (Wickman 1963, Koerber and Wickman 1970, Brubaker and Greene 1979, Swetnam *et al*. 1985). Climate subtraction techniques have been developed and widely-tested in studies of the western spruce budworm (Brubaker and Greene 1979, Swetnam *et al*. 1985, Swetnam and Lynch 1993, Wickman *et al*. 1994, Swetnam *et al*. 1995, Weber and Schweingruber 1995). In the Swetnam *et al*. (1985) approach, a non-host "control" tree species is collected from an adjacent site as the host species and its tree-ring chronology compared to the host series. The common climate signal can be then subtracted from the host chronology, thereby isolating the species-specific factors for further study. However, some error or noise may be introduced into the analysis due to differing responses to climate between the host and non-host tree species (Swetnam *et al*. 1985).

Speer *et al.* (2001) developed a record of pandora moth outbreaks that extends back 622 years in south-central Oregon (Figure 9.10). Pandora moth is a phytophagous insect that defoliates ponderosa pine, Jeffrey pine, and lodgepole pine in the western United States (Figure 9.11). The Klamath and Piute Indians used the pandora moth larvae and pupae as a traditional food source when it was available, indicating they had knowledge of its life cycle (Blake and Wagner 1987). This led early forest entomologists to speculate that pandora moth outbreaks had often occurred in the past (Aldrich 1912, 1921, Patterson 1929). Pandora moth and ponderosa pine trees are well adapted to each other so that only two percent tree mortality occurs with the outbreaks (Patterson 1929, Massey 1940, Bennett *et al*. 1987). Speer *et al.* (2001) were able to identify a distinct ring width pattern or signature that is associated with an outbreak of this insect in ponderosa pine forests (Figure 9.12). This signature was calibrated from sites with historically documented outbreaks and was applied to reconstructing outbreaks in the past. Further analysis

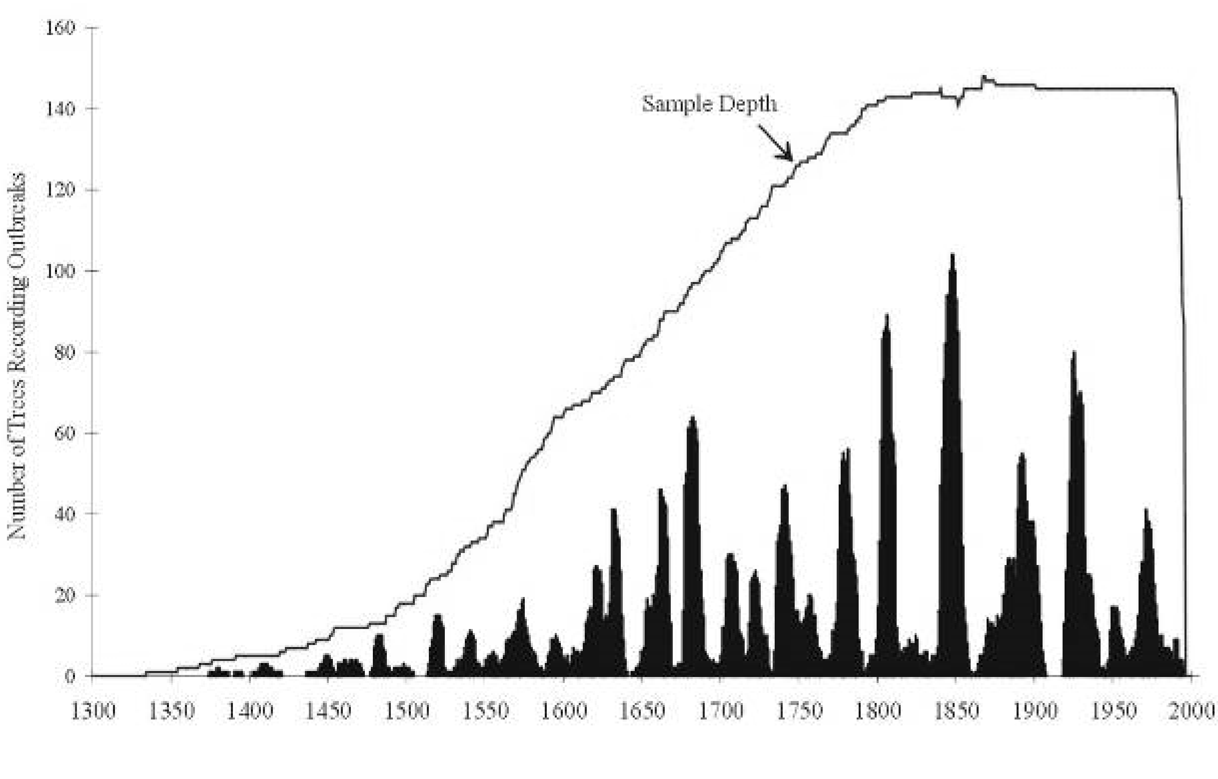


Figure 9. 10 A 622-year pandora moth reconstruction from south-central Oregon. The top line represents the number of trees recording outbreaks through time. The sample depth decreases further back in time with 20 trees still recording outbreaks at A.D. 1500. The dark area shows the number of trees recording outbreaks through time throughout the entire south-central region of Oregon (from Speer *et al.* 2001).

Figure 9. 11 A ponderosa pine forest denuded of needles by pandora moth (from Speer *et al.* 2001).

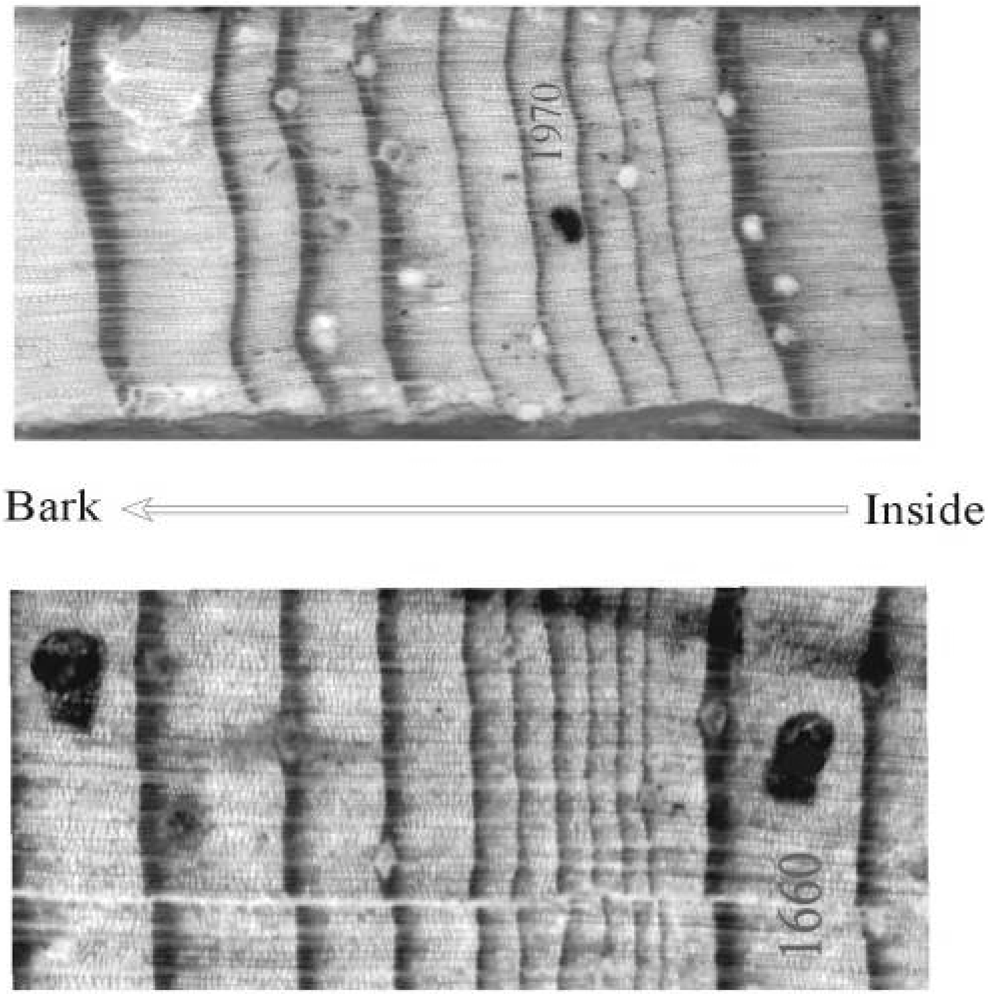


Figure 9. 12 A tree ring signature has been identified for pandora moth in which the first year is half the size of normal, the next two years are the smallest in the series, and subsequent years gradually return to normal growth. Thin latewood throughout the outbreak is another characteristic of the signal. Here, the upper photo shows a tree affected by a documented pandora moth outbreak in the 1960s which was used as a calibration for inferred pandora moth outbreaks with the signature starting in A.D. 1661, as seen in the bottom photo (from Speer 1997).

demonstrated that pandora moth was recorded on multiple trees within a site and between sites (Figure 9.13).

Mountain pine beetle (*Dendroctonus ponderosae*) has become a major influence in the western United States and Canada, with an outbreak from 1999 to the present affecting more than seven million hectares in Canada alone (Taylor *et al.* 2006). Bark beetle outbreaks can be reconstructed by documenting the mortality of host trees and occasionally from scars that are preserved on trees that live through the outbreak. Tree death is recorded indirectly as release in trees that survive the outbreak (Taylor *et al.* 2006). These types of reconstructions are more difficult because a distinct signature for cambium feeding insects does not exist like it does for most defoliating insects. The economic impact of the recent mountain pine beetle in Colorado and neighboring states and the large outbreak in British Columbia has brought more attention on this insect to try to understand if these events are natural or triggered by other factors such as forest management practices and/or climate change.

Stem Analysis. Potential wood volume increases of a forest stand can be reduced during insect outbreaks either through mortality of the host trees or suppression of radial growth and this reduction has implications for forest management policies. For example, while pandora moth outbreaks typically cause almost no loss due to mortality, the amount of volume reduction due to the effects of defoliation can be quite substantial (Massey 1940, Wickman 1963, Koerber and Wickman 1970, Speer and Holmes 2004). Growth loss during outbreaks may be offset by a growth increase after the insect population has crashed, a phenomenon observed with spruce budworm and Douglas-fir tussock moth outbreaks (Wickman 1980, Alfaro *et al*. 1985, Swetnam

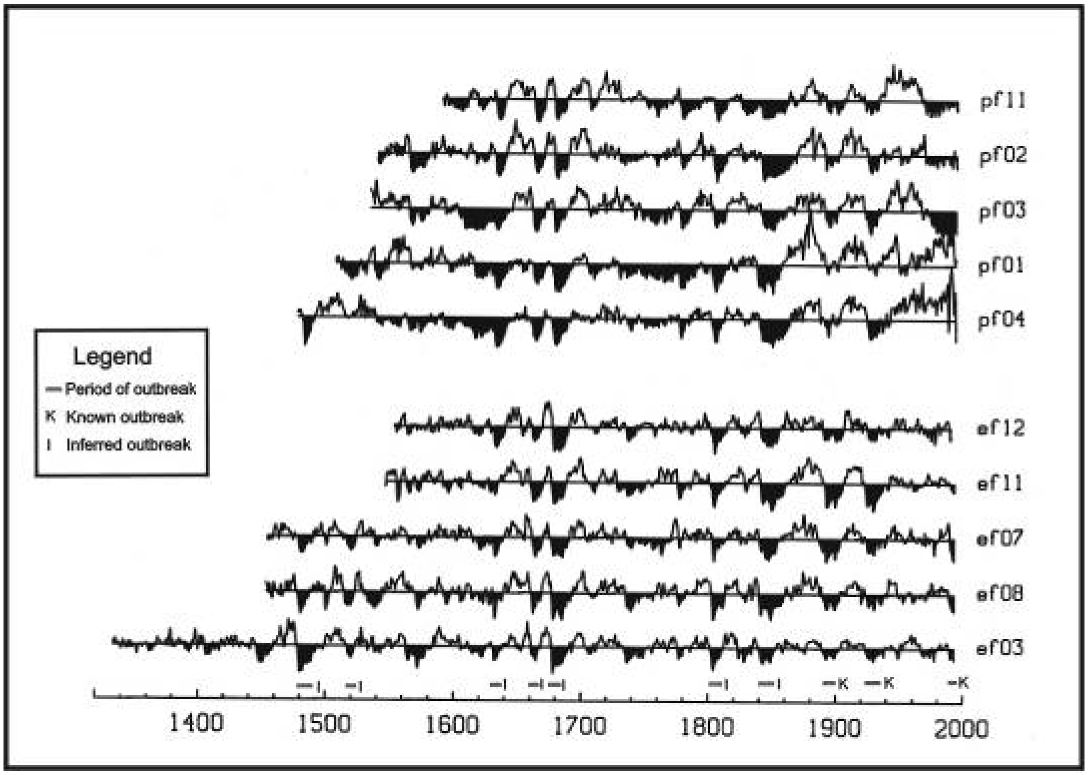


Figure 9. 13 Insect outbreaks often affect many trees both on an individual site and on multiple sites. In this graphic, each horizontal line is an individual tree with its ring width index plotted through time, and two sites (pf and ef) are represented. Dashes at the bottom of the graphic indicate known (K) outbreaks and inferred (I) outbreaks. Each outbreak event is recorded not only by all trees from the same site, but by trees on different sites, demonstrating that pandora moth outbreaks occurred on a broad scale and affected multiple sites (from Speer 1997).

and Lynch 1993). This effect may be attributable to factors such as reduced competition among trees for resources and nutrient cycling associated with frass (excrement) accumulation.

Stem analysis has been used extensively to investigate the effects of insect defoliation on growth allocation (Figure 9.14). The standard technique, with refinements by Duff and Nolan (1953 and 1957), involves taking multiple cross sections along the stem of the tree. The ring widths are then measured from each cross section and used to estimate three dimensional growth throughout the entire tree (Figure 9.15). Duff and Nolan (1957) and LeBlanc (1990a) suggested sampling a section midway between each internode to allow for quantification of height and radial growth in every year. Yet for trees a few centuries in age, it is very difficult or impossible to identify internodes on the external surfaces of the main stem. Thus, with increasing age it becomes impractical to determine all of the annual height increments; however cross sections can be taken at regular intervals along the trunk instead (Figure 9.15). LeBlanc *et al*. (1987) note that stem analysis affords increased accuracy in determining the overall tree response to disturbance, but mentioned the added effort might preclude its widespread application. They also mentioned the additional difficulty when studying older/larger trees because of the obscurity of the internodes as trees age. The effort of conducting a stem analysis is worthwhile, however, if the researcher wants to visualize the changes in wood volume due to defoliation and loss of photosynthetic potential (Figure 9.16).

Conclusion of Dendroentomology. The tools developed from dendroentomology are now being used for other forest health agents such as fungal pathogens (Welsh 2007) and to address complex disturbance systems involving multiple agents (e.g. Thompson 2005). These concepts

Figure 9. 14 Here, the author is taking samples from a 600 year old ponderosa pine tree for a stem analysis to examine the wood volume lost due to pandora moth defoliation. This is also an example of opportunistic sampling, because this tree was killed by a winter storm in 1993, enabling easy sampling in 1996 without having to cut down a living tree (photo taken by Tom Swetnam).

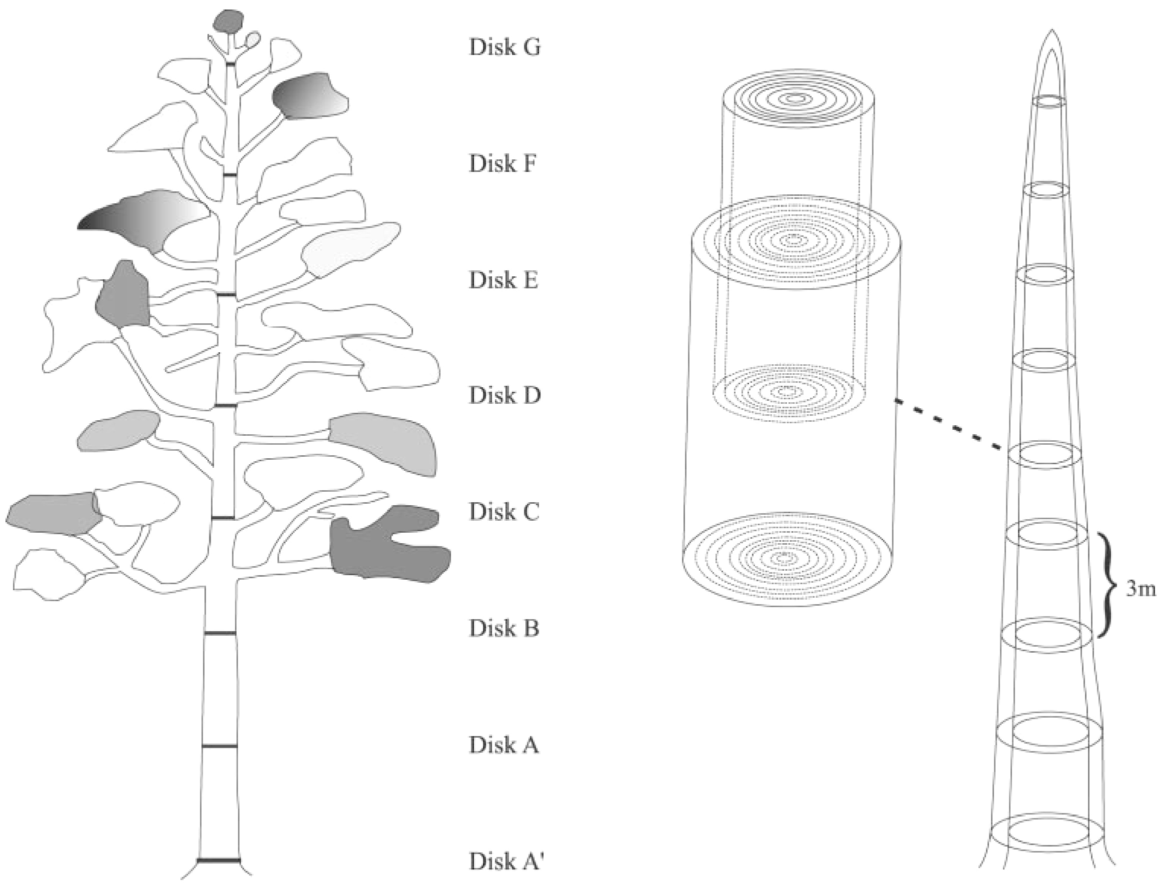


Figure 9. 15 Diagram showing how samples taken every 3 meters up a tree can be used to calculate wood volume for the whole tree (from Speer and Holmes 2004).

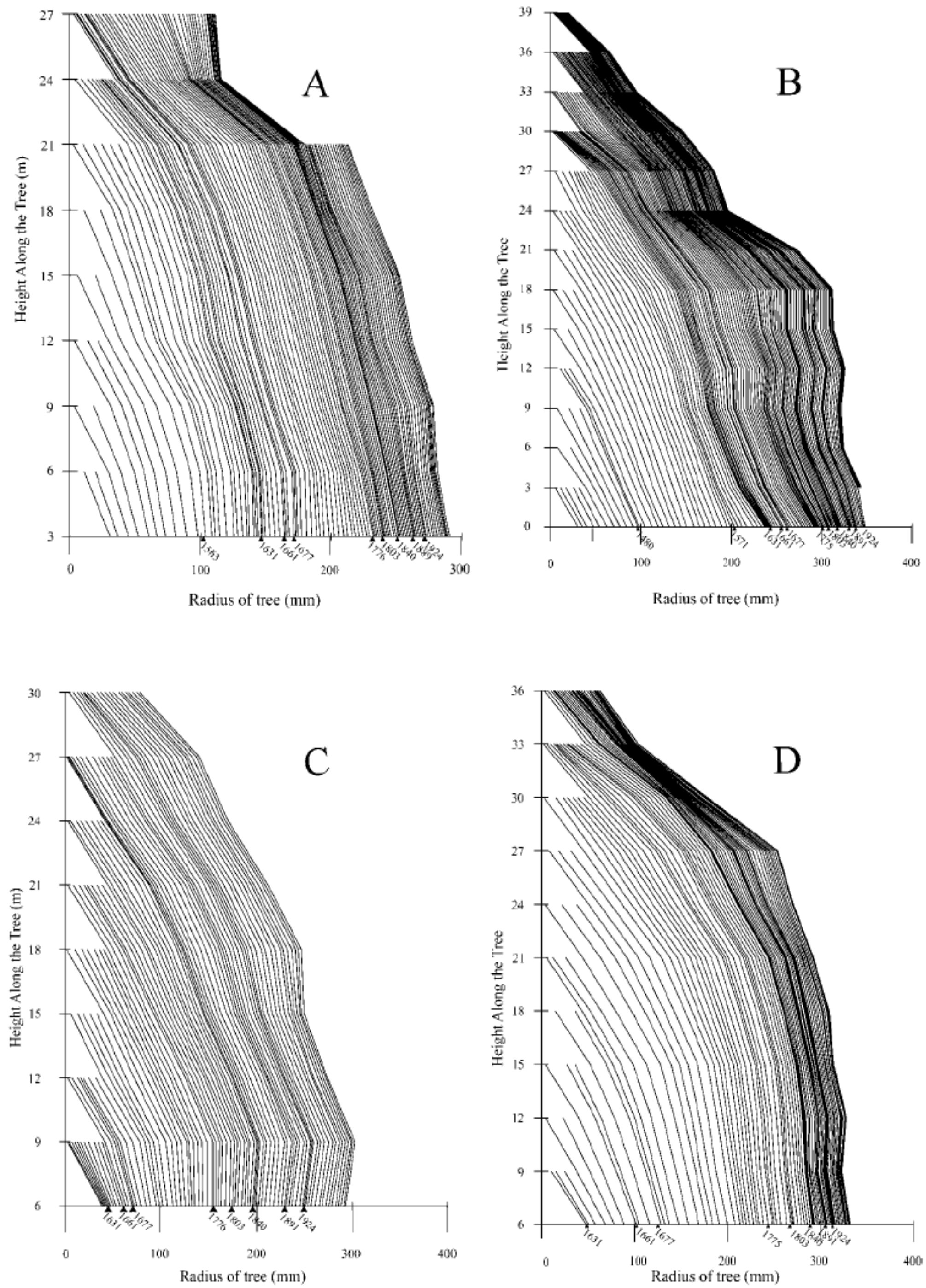


Figure 9. 16 Examples of four trees showing changes in wood volume with height of the tree. The dates and arrows along the x-axis show where pandora moth outbreaks resulted in a decrease in wood volume (from Speer and Holmes 2004).

take advantage of the aggregate tree growth model, limiting factors, site selection, and replication, just to name a few of the main principles of dendrochronology that are applied and honed through insect outbreak studies. These techniques continue to grow as researchers expand to new insect systems such as periodical cicadas and mountain pine beetle. The management concerns of foresters force the research agendas of many scientists as we react to public concern and governmental interest.

Wildlife Populations and Herbivory

Dendrochronology can be used to determine the dates of herbivory on trees, to estimate wildlife populations through resource availability linkages, and even to study fishery populations based on covariance with sea surface temperature measures (Spencer 1964, Schweingruber 1996, Speer 2001, Drake *et al.* 2002). Past fluctuations in animal populations can be documented through scars left on trees such as those from porcupine (*Erethizon epixanthum*) feeding on small branches of pinyon pine in Mesa Verde, Colorado (Spencer 1964) or expanding into northern treeline in Quebec (Payette 1987). A study on Isle Royale National Park in Michigan demonstrated how the removal of wolves (*Canis lupus*) resulted in an increase in moose (*Alces alces*) populations which then overgrazed balsam fir trees (McLaren and Peterson 1994). Hessl and Graumlich (2002) examined the effects of an elk herd on aspen regeneration in Wyoming, finding high elk populations reduce the recruitment of aspen trees. Speer (2001) was able to reconstruct masting and found a significant correlation between the regional white oak mast reconstruction in the southern Appalachians and black bear population estimates. Wildlife population reconstructions and examination of ecological interactions help zoologists study wildlife population fluctuations and increase understanding of complex food web interactions.

The long-term perspective of dendrochronology provides the time depth needed to examine the behavior of animals over multiple generations.

Dendrochronology can also provide valuable information for the management of fisheries. Drake *et al.* (2002) documented a significant correlation ($r^2 = 0.23$, $p < 0.05$) between Sitka spruce tree growth and Northeast Pacific salmon stocks, suggesting that both tree and fish responded to, or were tracking, the same environmental variable such as sea-surface temperature. They were able to take this relationship further by reconstructing salmon populations which were verified against other known salmon stock data. Clark *et al.* (1975) documented fluctuations in albacore tuna (*Thunnus alalunga*) populations by examining tree growth response to broad-scale atmospheric flow patterns that affected sea surface temperature in the north Pacific, influencing both tree growth and tuna populations. This technique of examining synoptic climate linkages between terrestrial records from trees and sea surface temperature or circulation patterns has enabled dendrochronologists to shed light on broad scale circulation and temperature phenomena that also affect fish populations. This type of analysis effectively extends the usable range of dendrochronological reconstructions and, in these examples, aids fishery managers.

Distributional Limits of Species

Biogeographers have long been interested in the factors that control the range limits of different tree species. Range limits may also mark the ecotone boundaries between different biomes. An **ecotone** is a zone of change from one vegetation type to another that often results in high plant and animal diversity. Ecotones are interesting to study because they are the first place that will demonstrate a response to climate change and because of their inherently high level of biodiversity. Some of the main variables controlling tree species distribution seem to be temperature, precipitation, and disturbance. In a study at the northern range limit of red pine, Bergeron and Brisson (1990) found that the species is restricted to island sites that have more frequent fire (a disturbance process), which may limit the competitive ability of boreal forest species, enabling red pine to maintain itself at 48° North latitude. Conkey *et al.* (1995) documented growth of jack pine in a marginal location at the eastern edge of its range limit in Acadia National Park, Maine. Jack pine is an early successional species that is fire adapted, but was able to survive in a marginal habitat because of the thin soil that prevented later successional species from out-competing it (Conkey *et al.* 1995). Copenheaver *et al.* (2004) studied a prominent ecotone at Buffalo Mountain, Virginia between dense forest and mountain top balds (grassy openings on a mountain top that are not above tree line). They used transects and stand age structure analyses, founding that some of these balds are stable while others are being invaded by the surrounding forests. In a study across an elevational gradient in northern Arizona, Fritts *et al.* (1965) documented that trees growing on the semiarid lower forest border were more sensitive to climatic variability. This lower treeline is controlled by a lack of soil moisture and produces sensitive tree-ring chronologies. Fine-scale analyses of the factors that control a species' range help biogeographers better understand the distribution of species. This understanding of the controlling mechanisms also helps scientists predict future range limits under a changing environment.

Treeline and Subarctic Studies

High elevation treeline (the elevational limit to which trees can grow because of temperature or moisture limitations) is another interesting ecotone where mountain-grown trees may take on a shrub-like form, called krumholz. Krumholz growth can occur in response to harsh winter weather where conditions under the snow pack are more conducive to survival over the winter. Historically, treeline has been studied as a proxy for temperature fluctuations, with the understanding that elevational treeline is limited by cold temperatures (LaMarche and Mooney 1967, LaMarche 1973, LaMarche and Stockton 1974). Daniels and Veblen (2003) found that precipitation controlled the local elevation of treeline in northern Patagonia and that disturbance locally lowered treeline. They also documented that treeline in Chile and Argentina was limited by lower precipitation as well as low temperatures and predicted that treeline advance may be restricted in a warming climate because of a lack of precipitation (Daniels and Veblen 2003, Daniels and Veblen 2004). Lloyd and Graumlich (1997) also found that treeline is dependent upon moisture as well as temperature, suggesting that treeline response to future warming may depend heavily on water supply. Similar studies have been conducted in high latitudes at the transition to artic tundra. Au and Tardif (2007) examined tree rings in the shrub dryas (Dryas *integrifolia*) in subarctic Manitoba, Canada. They found that these shrubs produced datable annual rings and could demonstrate that the shrubs were sensitive to previous October precipitiation and current year's May temperature. As dendrochronological methods advance, we can now begin to see the complex interactions of the effect of climate as well as disturbances in controlling factors of altitudinal and latitudinal treeline.

Interactions of Multiple Disturbances

Dendrochronologists have separately studied disturbances such as fire, insect outbreaks, blown down trees, avalanches, and herbivory. In the last fifteen years, researchers have started to examine the interaction of multiple disturbances on the same site, giving managers a more complete idea of the how processes affect one another on a given landscape (Hadley 1994, Veblen *et al.* 1994, Kulakowski and Veblen 2002, Kulakowski *et al.* 2003, Thompson 2005). Veblen *et al.* (1994) found that snow avalanches create fire breaks resulting in smaller fires, while fires and avalanches kill mature trees which delays the onset of bark beetle outbreaks because the remaining trees were not large enough for selection by bark beetles. Kulakowski *et al.* (2003) found that spruce beetle outbreaks in Colorado also affected the fire regime resulting in fewer occurrences of surface fires. They suggested a mechanism of the bark beetle outbreaks resulting in higher moisture on the forest floor because Reid (1989) observed a proliferation of mesic understory herbs. Similar observations have been made after mountain pine beetle outbreaks in Bristish Columbia where an increase in soil moisture was documented due to a decrease in transpiration (Kathy Lewis personal communication). Kulakowski *et al.*'s (2003) finding of fewer surface fires following bark beetle infestation was contrary to previous research that suggested bark beetle outbreaks resulted in an increase in forest fires due to an increase in available fuels (Stuart *et al.* 1989, McCullough *et al.* 1998). Build up of fuels usually occurs after stand-replacing fires, so a difference in the scale of the effect might result in these opposite conclusions. Kulakowski *et al.* (2003) state, however, that their observation also holds for stand-replacing fires. The time since defoliation can also be an issue in fire occurance, where extensive needle fall occurs a few years after defoliation which could increase the spread of fire. Those fine fuels decompose quickly and the stand is left with much standing fuel, but may not have the fine fuel necessary to carry a fire, resulting in a decrease in fire occurance. Controversial issues such as these remain to be examined with further dendroecological research.

Researchers have found that natural disturbances regenerate forests and make them less susceptible to subsequent disturbances until the forest matures (Kulakowski and Veblen 2002).

After the 1997 blowdown event in the Routt National Forest, Colorado, which took down over 10,000 hectares of subalpine forest, Kulakowski and Veblen (2002) found that forests which had experienced stand-replacing fire within the last 120 years were less susceptible to wind damage because of their vigor. Anderson *et al.* (1987) found that fire suppression in a ponderosa pine forest in western Montana enabled Douglas-fir to proliferate over the last 100 years providing more host trees which resulted in an increase in duration and intensity of western spruce budworm outbreaks. As a way to control the outbreaks, they suggest that fire be reintroduced to maintain the ponderosa pine forest and reduce Douglas-fir density, bringing this forest back into its historical condition. Only after managers understand the complex interactions among natural disturbances, will they be able to manage their forests tracts in an ecologically sustainable fashion.

Other Applications in Dendroecology

Schweingruber (1996) has developed a program of ecological examination in Switzerland that focuses on the growth and adaptation of plants to environmental stressors. He is also expanding his work to tropical environments and tundra environments by studying wood anatomy and rings in perennial herbs and shrubs. Tree rings have been used to determine the factors that drive wet heartwood occurrence in forest trees, which is heartwood that has unusually high water content. Krause and Gagnon (2006) found trees growing in an area of a high water table were more likely to have wet heartwood as well as suppressed growth due to the stress of growing in a frequently saturated soil. Root age can be determined from tree-ring analysis, which provides an understanding of how roots develop in different tree species (Krause and Morin 2005). Studies of black spruce and balsam fir in Quebec demonstrated that adventitious roots grew more than

60% of their length in the first year of development while lateral roots produced 93% of their elongation in their first 10 years (Krause and Morin 2005). This work is useful for our understanding of how roots grow and suggests that the major structure of a root develops fairly quickly. Other research in root wood anatomy will be presented in the chapter on dendrogeomorphology (Chapter 10) because this can be a useful tool in examining soil erosion. Maximum latewood density of annual rings has been found to correlate with Normalized-Difference Vegetation Indices (NDVI) which are an estimate of vegetation productivity or net primary productivity (NPP) from satellite imagery (Malmstrom *et al.* 1997, D'Arrigo *et al.* 2000). This correlation is useful for broad scale estimates of forest productivity and change associated with global climate change, which is an area likely to take on greater importance in the presence of global warming. This work demonstrates that interesting frontiers still exist to be studied with dendrochronology. More of these new directions of research will be discussed in Chapter 12.

Conclusion

Dendroecology has been and is becoming more useful for exploring a wide range of research topics that can provide important information to wildlife, fisheries, and forest resource managers. Combining the study of tree rings and ecology can help us understand the dynamics of natural processes such as disturbance and the interactions between multiple natural phenomena. Trees can provide long-term records on many different phenomena at different spatial scales, enabling dendroecologists to contribute to important discussions on scaling laws that could aid management in a changing environment.

Chapter 10: Dendrogeomorphology

Introduction

Geomorphology is the study of landforms and the earth surface processes that form and modify them (Gärtner 2007a). **Dendrogeomorphology** uses tree rings to date geological processes that affect tree growth such as landslides, river deposits, or glacial activity.. I consider dendrogeomorphology to include the subfields of of **dendroglaciology** (the study of the movement or mass balance of glaciers), **dendrovolcanology** (the study of past volcanic eruptions), **dendrohydrology** (the study of stream dynamics), and **dendrosiesmology** (the study of past earthquake events and fault movements through the use of tree rings) (Table 10.1).

The use of dendrochronology to reconstruct geological phenomena was pioneered in North America over 100 years ago. Sherzer (1905) used the growth of spruce trees to estimate the ages of glacial moraines in the Canadian Rockies and Selkirk Mountains in Canada as one of the first dendrogeomorphological applications. In another early application, dendrochronology helped resolve a boundary line dispute between Texas and Oklahoma (Sellards *et al.* 1923). The Red River marked the boundary between the two states, but because its stream channel meandered over time, the relative location of the state line changed. By examining the age of trees on different land surfaces, the researchers were able to determine the location of the historical boundary. Dendrogeomorphology really became established as a subfield in the United States in the 1970s and its applications have expanded since this time (Alestalo 1971, Shroder 1978, 1980, Shroder and Butler 1987, Butler 1987, Schweingruber 1996, Wiles *et al.* 1996).

Table 10. 1 Geomorphic events and how they can be reconstructed using tree rings. Table modified from Shroder 1978, Sheppard and Jacoby 1989, and Wiles *et al.* 1996.

Process	Event	Possible responses	Citation
Volcanic	loss of photosynthesis	suppression	Smiley 1958, Yamaguchi 1983
	lava flow and temperature stress	suppression	
	atmospheric cooling	suppression	LaMarche and Hirschboeck 1984
	crown defoliation from tephra fallout	suppression	Smiley 1958, Yamaguchi 1983
	eluviation of leachates harmful/favorable to growth	suppression/release	
	reduced aeration of soils due to burial	suppression	
	direct encounter with flow	scarring	
	denudation of surface	tree establishment	Yamaguchi and Hoblitt 1995
	gas release	suppression	
Flodplain dynamics	debris impact during floods	scarring	Gottsfeld and Gottsfeld 1990, McCord 1996
	accretion of point bars	tree establishment	Gottsfeld and Gottsfeld 1990
	erosion of banks	tilting/mortality	Gottsfeld and Gottsfeld 1990
	inundation by sediment	mortality and burial	Sigafoos 1964
	flow dynamics	ring width variability	Woodhouse 2001
Lake ice dynamics	direct ice push	scarring	Begin 2000
Glacial	physical impact from glacial ice	scarring	Lawrence 1950, Luckman 1988
	inundation by glacial sediment	suppression/sprouting	Wiles *et al.* 1999
	temperature stress from proximity of ice	suppression	Lawrence 1950, Wiles *et al.* 1996

	advance/retreat	missing rings/mortality/ establishment	Smith and Laroque 1996, Wiles *et al.* 1999
	denudation of surface	tree establishment	Sigafoos and Hendricks 1961, 1972, Wiles et al. 1999
	mass balance change	suppression/release	Laroque and Smith 2005
	isostatic adjustment	tree encroachment	Begin *et al.* 1993
Mass movement	inclination	reaction wood	Corominas and Moya 1999 Fantucci and Sorriso-Valvo 1999
	shear	suppression	Shroder 1978
	corrasion	scarring	Corominas and Moya 1999, Shroder 1978
	exposure of roots	suppression/root mortality, change in cell thickness of roots	Danzer 1996, Gärtner *et al.* 2001
	inundation	suppression/sprouting/ mortality	Hupp 1984, Begin and Filion 1988, Corominas and Moya 1999
	denudation of surface	tree establishment	Hupp 1984, Hupp *et al.* 1987
	change in hydrology	release/suppression	Fantucci and Sorriso-Valvo 1999
Earthquake	shear	suppression/missing rings	Jacoby *et al.* 1988
	inclination	reaction wood	Sheppard and Jacoby 1989
	change in water table	suppression/release	Atwater and Yamaguchi 1991, Sheppard and Jacoby 1989
	extreme ground shaking	suppression/missing rings	Sheppard and Jacoby 1989
	broken tree tops	suppression/mortality	Jacoby 1997
	root system or major limb damage	suppression	Jacoby 1997, Bekker 2004

Shroder (1980:165) outlined a process-event-response system for the analysis of dendrogemorphological phenomena. He identified seven basic events:

1) inclination,

2) shear of rootwood or stemwood,

3) corrasion (which is abrasion or some removal of wood through contact),

4) burial of stemwood,

5) exposure of rootwood,

6) inundation, and

7) denudation (or the removal of vegetation).

In response to these events he categorized seven responses (Shroder 1980: 165):

1) reaction wood growth,

2) growth suppression,

3) growth release,

4) ring termination and new callous growth,

5) sprouting,

6) succession, or

7) miscellaneous structural or morphological changes in external or internal wood character

This systemic approach is still useful today for dating possible events and responses of trees to geomorphic phenomena.

Most tree-ring sampling for geomorphological research needs to involve targeted sampling in which the direct effects of landslides, earthquakes, glaciers, or soil creep can be identified. Because of the variety of phenomena that can cause reaction wood or scarring in a tree, samples must be selected from areas that have been affected by the process of interest (Shroder 1980, Butler 1987). Targeted or directed sampling uses the basic dendrochronological principle of site selection discussed in Chapter 2. Random sampling on the landscape is likely to miss these geomorphological events or require a huge amount of sampling to detect such localized events.

Sources of Information

Reaction wood

Trees will react structurally to being tilted by producing reaction wood. Gymnosperms (conifers) will thicken cell walls and produce more cells on the downhill side of the tree while angiosperms (flowering trees such as the hardwoods) will thicken the tracheids on the uphill side of the tree (called tension wood), both in an attempt to straighten the tree (Figure 4.18). This reaction wood can be used to determine the timing of events that tilted the tree trunk, such as landslides or earthquakes (Gärtner 2007a). Changes in the circularity of stem growth can record geomorphic changes through time. To sample for these events, a full cross section of the stem of the tree is preferred, although one can core on the downhill and uphill side of the tree through the reaction wood in an attempt to date such a tilting event. Note that this coring location is contrary to previous sampling protocols discussed in Chapter 5 as it is targeting reaction wood, whereas such studies as climate reconstruction try to avoid this irregular growth. By examining the reaction wood of trees in an area of the Eastern Pyrenees in Spain that experienced frequent landslides, researchers were able to reconstruct landslide activity there (Corominas and Moya

1999). The reaction wood documented slope instability over the past 70 years, revealing that landslide activity had increased in modern times compared to the early portion of the chronology from 1926-1959.

Death dates

Death dates can be obtained by crossdating dead wood samples against a living tree-ring chronology to determine the advance of a glacier, when landslides occurred, or any other natural event that results in the death of a tree. Preservation of the sample and its outermost rings then determines how far back in time one can crossdate the event that caused tree mortality. Factors that contribute to the quality of wood preservation include climatic conditions (hot and humid or dry and cold for example), where the tree is located (whether the tree is a standing snag, sitting on soil, suspended in the air, buried in sediment, or buried in a lake in anoxic conditions), and innate resistance of the wood itself to weathering and decay (sequoia and cedar wood for example).

Death dates can also be used to determine the sedimentation rates on a slope (Figure 10.1). When a tree dies and falls across a slope, it will remain there for some period of time catching sediment that comes down slope in overland flow of water. The sedimentation rate can be determined from the amount of sediment present and the time since death of the log (Hart 2002). Various factors complicate this process. If the tree died and stayed standing for 10 years, and then fell to become a sediment trap, the accumulation rate would be underestimated because of the 10 years that the tree remained standing.

Figure 10. 1 Coarse woody debris is composed of logs that fall in the forest. They may fall across a slope and act to catch sediment during overland flow of water. These trees are very important for sediment retention. If death dates can be established in the trees and the amount of sediment can be measured that accumulates behind the log, then sedimentation rates can be determined (photo from LaMarche 1968).

Establishment dates

Ecesis is the process of vegetation becoming established on previously bare ground that was denuded by flooding or glacial activity (McCarthy and Luckman 1993). Establishment dates of trees can be used to provide a bounding date on when that material was deposited or wiped clean, but there is often a lag (from ecesis) between the time when the event occurred and when trees first establish on the site. This lag can depend upon seed source, suitability of the substrate, or climate. Estimates for this time period can be made on local sites of known disturbance to calibrate a local record. When determining the bounding date for a surface and estimating time of ecesis, one assumes that the oldest tree on that surface has been sampled (Wiles *et al.* 1996). The techniques used for this process are the same as those for a stand-age structure employed by dendroecologists (see Chapter 9). The goal is to document a cohort of tree establishment on a surface that was cleared or deposited by some geomorphic agent such as a volcanic eruption, landslide, or debris flow. One of the main problems with determining the age of a land surface with tree rings is the lag time between when the surface formed and how long it took trees to establish on the site (successional dynamics). This lag time can be driven by climate, the biology of the trees, distance to a seed source, and presence of seed dispersers (Fastie 1995). All of these factors combine, leaving some doubt as to the exact age of the surface, but establishment dates do provide a bounding date of the earliest possible time that the surface could have been formed.

Wound Events

Trees can be damaged during geomorphic events and these wounds can be dated to reconstruct rock falls or other damaging occurrences. For example, debris flow events were reconstructed near Valais region of the Swiss Alps using tree scars and eccentric growth from trees being dislodged in past debris flows (Stoffel *et al.* 2005). They were able to extend the debris flow records from 80 years of historical data to 397 years from tree-ring records and found that the peak of debris flow occurrence was in the 1800s. Scars can be caused by many sources, so location of the scar and clustering of scar events is important for documenting past geomorphic phenomena. Other possible geomorphic causes of tree scars include landslides, avalanches, flood waters, and ice flows.

Coarse Woody Debris (CWD)

Course woody debris (CWD) is an important component of the dead wood in any forest because it acts as a sediment trap, nutrient source, and increases habitat (Figure 10.1, Daniels *et al.* 1997, Hart 2003, Campbell and Laroque 2005, Campbell and Laroque 2007). Foresters and geomorphologists have defined stages of wood decay from recent (decay class I) to old (decay class VI). In a dendrochronological study on the southwestern coast of British Columbia, researchers successfully calibrated the decay classes of cedar by determining the time since death of the tree (Daniels *et al.* 1997) enabling foresters to more accurately assess how long logs had remained on the ground as a sediment trap. It was also noted that no classification system was appropriate for snags because of their slower decay rate while they are standing above the ground surface. Gore *et al.* (1985) developed a model to estimate the maximum likelihood estimate of the average number of years that a bole would stand before it fell based on empirical evidence; however their model does not take tree species or site conditions into consideration. An understanding of CWD and its dynamics through time help in stream restoration and provides information on habitat changes in riparian areas.

Roots

Root analysis can be used as part of a whole-tree analysis as demonstrated in the study conducted by Krause and Eckstein (1993) who found that root increment was significantly correlated with temperature. Gärtner (2007b) discusses the usefulness and difficulties of using roots to determine rate of soil erosion, deposition, and other damages to trees through geomorphic agents. He notes that little work to date has been successful in the use of roots, but current work with anatomical features of roots have promise in providing information in the future. Gärtner *et al.* (2001) and Gärtner (2007b) have demonstrated different anatomical characteristics for roots at different depths in the soil (Figure 10.2) and have shown that this change in root wood anatomy can be used to determine the year and even the season of subaerial exposure of roots through erosion.

Subfields of Dendrogeomorphology

Dendrovolcanology

Volcanic eruptions can be documented with tree rings through 1) the direct effect on tree stems from the shock wave, ash fall, or debris from the eruption, 2) mortality of trees on a site, or 3) a global cooling event from the injection of gases and aerosols into the atmosphere. A number of fascinating studies have linked trees to notable volcanic eruptions (Smiley 1958, LaMarche and Hirschboeck 1984, Yamaguchi and Hoblitt 1995, Briffa *et al.* 1998, Jacoby *et al.* 1999). Yamaguchi (1983) was able to use suppression events in Douglas-fir to document major eruptions from Mount St. Helens. In a subsequent collaborative effort, Yamaguchi and Hoblitt (1995) used establishment of trees to determine bounding dates on a series of lava flows since A.D. 870 and determined that Mount St. Helens has had dormant periods that have lasted from

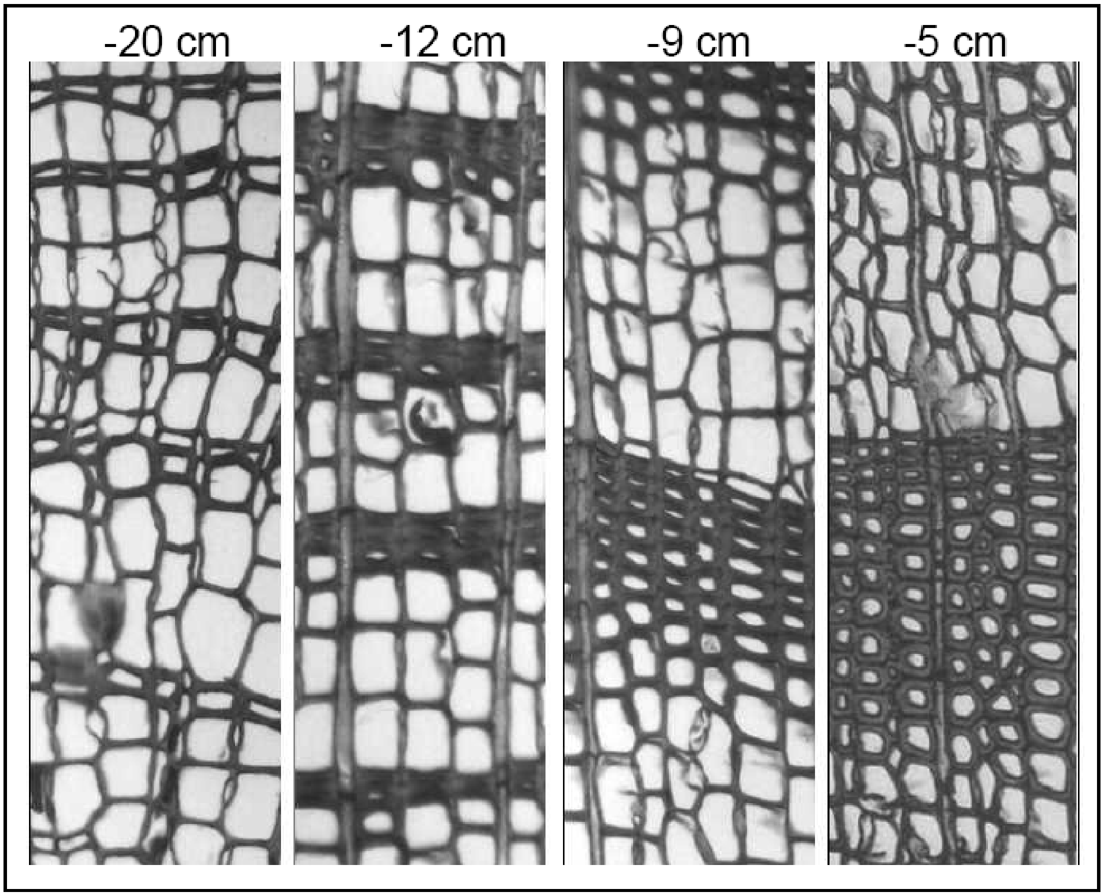


Figure 10. 2 Wood structure for roots of *Larix decidua* at four different depths in the soil (5, 9, 12, and 20 cm; from Gärtner 2003). Note the lack of latewood thickening for roots from deeper locations in the soil.

123 to 600 years during their record. In Arizona, an eruption date of A.D. 1064 was determined for Sunset Crater (Smiley 1958) by the presence of narrow rings in archaeological wood collected from nearby Wupatki ruin, an Ancestral Pueblo site occupied from approximately A.D. 900-1275. Large eruptions near the equator can put enough sulfur dioxide and aerosols into the stratosphere to reduce global temperatures for 1-3 years. If temperatures get cool enough during the growing season of the trees, then a frost ring can be produced. LaMarche and Hirschboeck (1984) identified frost rings in the bristlecone pine chronology at 3,000 m elevation in the White Mountains of California that were related to major volcanic eruptions such as Krakatau in A.D. 1680, Vesuvius in A.D. 1785, and Tambora in A.D. 1815 among others. Jacoby *et al.* (1999) documented an extremely low density ring in 1783 in Alaska and northern Canada. They were able to compare this date to historical accounts of Inuit populations in the area that document a decrease in population. They also found that the Inuit oral traditions speak of a great disaster around that time period. This extremely cold summer apparently caused a major die-off in the Inuit in 1783. Further discussion of volcanic effects on trees and how they can be used to date events can be found in Schweingruber (1996).

Volcanic events may affect a broader spatial scale than normal climatic fluctuations, as suggested by the work of LaMarche and Hirschboeck (1984). For example, in a study of ring-width density chronologies from both North America and Europe, Jones *et al.* (1995) documented consistent years of low density in 1601, 1641, 1669, 1699 and 1912. Four of these years coincide with known volcanic eruptions. Decreased density of tree rings means that individual cell walls are less lignified, which in the case of volcanic eruptions, could be due to an increase in aerosols in the atmosphere resulting in cooler temperatures reduces lignification in late summer. Jones *et al.*'s (1995) study is also a good example of the use of spatial scale to tease apart different signals in tree-ring chronologies. They only wanted to record extreme broad-scale events so examined years with low tree-ring density on both the European and North American continents.

Dendroglaciology

Early work in dendroglaciology set the precedent for the variety of information that can be obtained from tree-ring studies as they apply to glacial research (Tarr and Martin 1914, Lawrence 1950, Sigafoos and Hendricks 1961, Sigafoos and Hendricks 1972). Glacial advance can be documented by dating mortality events of sheared trees that are deposited in outwash till and glacial retreat can be documented by the establishment of trees on newly exposed glacial till (Wiles *et al.* 1999). Between these two techniques, mortality events from glacial advance is more precise because the death of the trees can happen in a year or less, while it may take decades for trees to establish on newly exposed rock and till after glacial retreat (McCarthy and Luckman 1993). Through connections with climatic forcing factors, **glacial mass balance** (periods of growth and ablation) can also be reconstructed from tree rings (Mathews 1977, Laroque and Smith 2005). Trees that grow at the trimline (Figure 10.3) where the ice is directly next to the trees, can record fine scale glacial fluctuation in time (Lawrence 1950, Wiles *et al.* 1996). Hard work over the past few decades has produced evidence for many alpine and continental glacial changes over the past 2,000 years that have been combined into broad scale interpretation of glacial dynamics (Wiles *et al.* 2008). Such dendroglacial reconstructions as these extend many centuries into the past and clarify the mechanisms that drive glacial activity. For further reading, Smith and Lewis (2007) document the history of the field of

Figure 10. 3 A glacier may kill trees as it advances and incorporate those trees in the till. Massive glacial advances can then be dated from the mortality events of the trees. The glacier leaves the trees alive above the trimline (the highest position of the glacier up slope on the canyon walls). Trees at the trimline may survive, but their growth is stunted by the proximity of the glacier. Their suppressed growth can then be used to determine the ice accumulation of the glacier while fine scale fluctuations of the glacier can be tracked through time (photo by Jim Speer).

dendroglaciology and outline the various techniques that can be used to glean information on glacial activity.

Isostatic adjustment (the rise of land) after the retreat of glaciers has been documented using the downslope establishment of trees towards present day sea level to document the rate of this uplift (Begin *et al.* 1993). During the last glacial maximum at 21,000 calendar years ago there were approximately six kilometers of ice above the Canadian Shield. Once the weight of ice from a major glacier is removed from the terrain, the land begins to adjust to that lack of weight and to rise, sitting higher on the mantle. New land surfaces are exposed upon which trees can establish. In a research project located on the margins of Hudson Bay in Québec, Begin *et al.* (1993) dated tree establishment along transects to current sea level parallel to the slope, documenting the progressive advancement of this lower treeline. A similary pattern was identified from land adjustment after Little Ice Age glacial retreat in Glacier Bay Alaska where Motyka (2003) documented 3.2 m of uplift since the late 18th century.

Mass Movement

Tree rings can also be used to examine any mass movement such as rockslides (Figure 10.4), landslides (Corominas and Moya 1999), rock glaciers (Giardino *et al.* 1984), debris flow (Hupp 1984, Hupp *et al.* 1987), or volcanic mudflow (also known as a lahar; Yamaguchi and Hoblitt 1995). Just as with flooding, trees can be scarred by mass movements of earth, they can be killed, or fresh earth surfaces can be deposited or exposed on which trees can establish (Hupp 1984, Hupp *et al.* 1987, Corominas and Moya 1999, Fantucci and Sorriso-Valvo 1999). Soil

Figure 10. 4 Frequent rockfall down a landslide shoot may accumulate a large amount of sediment. As the trees growing on the slope are killed and fall down slope to be incorporated in the sediment pile (and in this case the lake) at the base of the slope, the wood is well preserved and can be sampled to determine the landslide frequency for the area. Landslide debris piles are also a great source of old deadwood that may have been accumulating for some time and could result in a very long chronology (photo by Jim Speer).

creep can cause curvature of stems, although it can be hard to differentiate from curvature due to wintertime snow pressure (Shroder 1980). Soil erosion can expose roots causing root mortality (LaMarche 1968, Danzer 1996) or producing cells with different cell wall thicknesses depending upon their depth in the soil (Figure 10.2 and 10.5; Gärtner and Schweingruber 2001, Gärtner 2007b).

Dendroseismology: Plate Boundaries, Faults, and Earthquakes

Any earthquake could cause damage to a tree by breaking fine and even large roots for the locally affected trees. Jacoby (1997) provides a complete review of paleoseismology from tree-ring analysis, noting that trees can be damaged directly from shaking, elevation changes, and liquefaction, or indirectly through earthquakes that induce landslides and tsunamis. A massive earthquake that triggered a tsunami and landslide killed thousands of trees sometime between A.D. 894 and A.D. 897, and was documented by studying submerged logs from Lake Washington near Seattle, Washington (Jacoby *et al.* 1992). This work combined dendrochronology with ^{14}C dating to determine a window of dates for a floating chronology (a chronology not anchored in time) composed of trees that had been killed in the same season of the same year by a tsunami triggered by this earthquake. Atwater and Yamaguchi (1991) also found evidence for a major coastal event that submerged trees in the Seattle area in A.D. 1700. Suppression of ring width over several years may be another indicator of seismological events in addition to tree mortality and damage. For example, an 1887 earthquake in Kazakhstan resulted in ring-width reduction for four to 15 years in most sampled trees (Yadov and Kulieshius 1992).

Figure 10. 5 These trees around Yellowstone Lake have been subject to gradual soil erosion; adventitious roots grew as the soil was slowly removed from the site, enabling many of the trees to survive. The flare of the roots demonstrates at what level the soil used to be (this lines up with the modern soil level in the background). The soil is being washed away and the beach cut is moving inland (photo by Jim Speer).

Considerable research has been conducted to study specific types of plate movement associated with plate tectonics and fault types such as transform plate boundaries (Page 1970, LaMarche and Wallace 1972, Wallace and LaMarche 1979, Meisling and Sieh 1980, Jacoby *et al.* 1988, Sheppard and Jacoby 1989, Lin and Lin 1998, Vittoz *et al.* 2001, Wells *et al.* 1998), convergent plate boundaries (Jacoby and Ulan 1983, Sheppard and Jacoby 1989, Atwater and Yamaguchi 1991, Veblen *et al.* 1992, Yadav and Kulieshius 1992, Kitzberger *et al.* 1995, Jacoby *et al.* 1997), strike-slip faults (Stahle *et al.* 1992, Van Arsdale *et al.* 1998), reverse faults (Ruzhich *et al.* 1982, Stahle *et al.* 1992, Van Arsdale *et al.* 1998), and normal faults (Sheppard and White 1995, Bekker 2004). Because earthquakes are the results of plate tectonics, the study of geological faults with dendrochronology uses the same techniques as earthquake reconstructions. It is important that the researcher take into account damage to trees and the spatial distribution of sampling when determining whether or not suppression of tree rings is directly related to the seismic events under study (Jacoby 1997, Bekker 2004).

Limitations in Dendrogeomorphology

As with all tree-ring work, accurate crossdating of samples is paramount for producing a solid dendrogeomorphological study. Reduced tree growth due to proximity of ice or damage from an earthquake can cause trees to have micro or missing rings for a number of years. Only crossdating can detect these locally absent rings and provide accurate dates for geomorphic events. Other restrictions apply to the application of dendrogeomorphology which are harder to correct (McCarthy *et al.* 1991, McCarthy and Luckman 1993). A lag can occur between the deposition of a surface and the establishment of trees on that surface. This lag can be affected by the climate, proximity to a seed source, and the substrate itself making it difficult to accurately determine the timing of some event. Other potential sources of error include sampling above the root collar which can underestimate the age of a surface and missing the pith of the tree (McCarthy e*t al.* 1991). Also when dealing with suppression events, it is hard to definitely assign the cause of such an event, so climate and other confounding factors must be thoroughly examined. Being aware of these possible sources of error and working to minimize them can result in accurate dating of geomorphic events in the past.

Conclusions

Dendrogeomorphology has greatly expanded in the last 20 years with a wealth of applications and studies documenting past geologic events. The researcher has to think creatively about how a past event may have been recorded by the trees in the area. The variety of sampling techniques and sources of data used in this subfield of dendrochronology are probably more diverse than in any of the other applications. As with all of dendrochronology, these studies rely on the accuracy provided by crossdating. Without it, researchers would not be able to definitely determine the timing of events or to assign a specific event to a growth response. In the next chapter, I will describe the use of chemical and isotopic analysis of tree rings which is one of the newest forms of data being drawn from tree rings.

Chapter 11: Dendrochemistry

Introduction

In this chapter, I will detail the applications of dendrochemistry which is the measurement of element concentrations within tree rings to make spatial and historical estimates of element availabilities and to understand the physiological processes that control the uptake, transport, and sequestration of elements in secondary xylem. This field also broadly includes stable isotope dendrochronology (the measurement of stable isotopes such as ^{12}C, ^{13}C, ^{16}O, and ^{18}O for climate and ecological applications) and calibration of the radiocarbon dating curve. All of these applications involve the chemical analysis of tree rings and share some similar issues in sampling and analysis.

Dendrochemistry is the use of tree rings as indicators of past chemical fluctuations in the environment (Cutter and Guyette 1993). Trees take up nutrients and elements through their roots along with absorbed soil moisture, directly from the atmosphere through their leaves, and through the bark of the tree (Donnelly *et al.* 1990, Leavitt 1992). Most chemical analysis deals with the examination of the uptake of heavy metals because they are one of the main contaminants of soil and water. Trees will take up heavy metals that often travel as part of soluble organic compounds (**ligands**) and usually become fixed as part of cell walls. Wood rays can transport the ligands from the outer rings to the inside of the sapwood. Essential elements (most commonly phosphorous) can also be transported from interior to outer rings to meet the metabolic needs of the cambium. This process is called **radial translocation** and is one of the major complicating factors of dendrochemistry which will be discussed in greater detail below.

Methods of Elemental Analysis

When sampling in the field for a dendrochemistry project, the researcher must take precautions to avoid contaminating the sample with materials like WD-40 and metals from jewelry. Cross-contamination between trees, cores, and even individual tree rings should also be prevented. New borers (before the Teflon coating is worn off) can be used to reduce contamination from the metal of the borer and the borer should be cleaned with acetone to make sure that no industrial lubricant (such as WD-40) is contaminating the samples. In the field, I wear latex gloves to avoid contaminating the core and rinse the increment borer with isopropyl alcohol or acetone between each core. Two cores can be taken from the same side of the tree separated by a vertical inch so that one core can be sanded for dating and the other can be sectioned for dendrochemical analysis based on the dating on the first core. The cores are packed in normal paper straws in the field for drying in an oven (at about 70°C) for 24 hours in the laboratory. If one wants to study volatile elements, such as mercury, air drying the samples for a longer period of time rather than oven drying is preferable because these elements may be lost through vaporization.

Normal dendrochronological preparation in which cores are glued to a core mount and their surfaces are sanded with a belt sander cannot be used in dendrochemical research for a number of reasons, which is why the two core technique described above or the vice clamp mounting technique described below are good approaches. First, while the core samples need to be surfaced and dated, they also need to be removed from the core mount for the subsequent chemical analysis. Not only does gluing make removal difficult, but glue may carry contaminants. Second, sanding with a belt sander creates a lot of dust from the often metallic components of the sandpaper that fills the surface of the cells. A good technique is to use a temporary vise clamp made of wood (Figure 11.1) to hold the core and surface the core with a stainless steel scalpel so that the ring structure can be observed for dating of the sample. Normal razor blades should be avoided because they are likely to leave metal flakes which can contaminate the wood. In some cases where the composition steel itself may provide contaminants, alternate cutting methods may be required such as the use of a laser (Sheppard and Witten 2005). Then the sample can be removed from the clamp and cut into individual samples for chemical analysis. The core samples are often cut into annual segments or blocks of rings (3-20 years) for analysis using wet chemistry, depending upon the minimum amount of wood needed for accurate analysis of the element(s) of interest. The precision of new chemical analysis techniques and instrumentation enable sampling at annual and even subannual resolution if needed. Many instruments have been used for elemental analysis of tree rings. Inductively Coupled Plasma Mass Spectrometer (ICPMS; Guyette *et al.* 1991), Neutron Activation Analysis (NAA; Guyette *et al.* 1989), Proton Induced X-ray Emission (PIXE; Hall 1987), and Proton Induced Gamma Ray Emission (PIGE; Hall 1987) are some of the more commonly used methods of elemental analysis in tree rings.

In the past, analysis would be conducted on clusters of tree rings because enough wood could not be extracted from a single year of growth. Instrument detection levels are consistently improving, thereby enabling researchers to use smaller samples for analysis. Also, some tools,

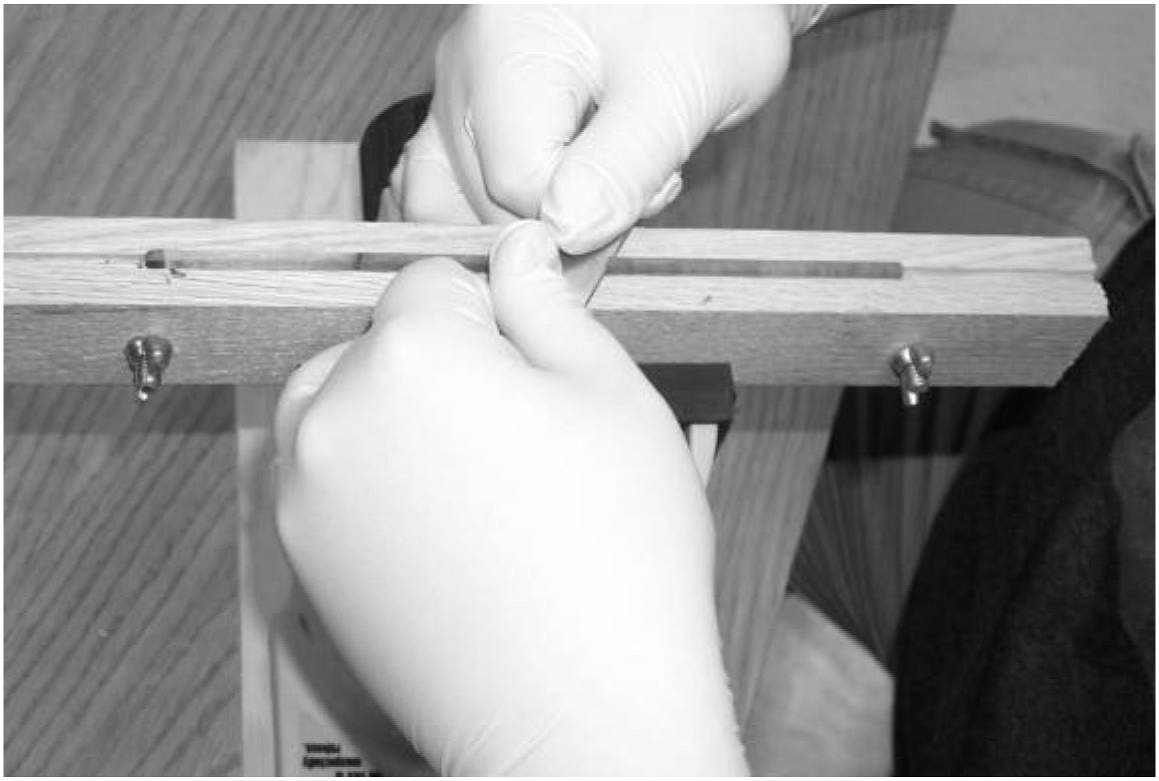


Figure 11. 1 A dendrochemistry sample in a core clamp. The clamp is constructed from two pieces of wood that are grooved on the top center to hold the core. They are drilled through the center of the two boards in three places and a bolt with a wing nut is inserted through each hole to clamp down the core. In this picture, note that the researcher wears gloves to avoid contamination of the sample and uses a razor blade instead of sandpaper to surface the sample prior to dating (photo by Jim Speer).

such as a 12mm borer, have been used to obtain a larger wood sample in each year. Although, because of radial transport within the sapwood, annual resolution is not always expected.

Radial Translocation. **Radial Translocation** is the movement of elements across ring boundaries; this transfer is problematic for dendrochronologists because the resultant signal of an element does not necessarily relate to the time that it was taken up. Whether a given element is translocated seems to be a function of both species and environment (Cutter and Guyette 1993). Tom Yanosky has suggested that translocation may act as a "pressure valve" that helps maintain physiologically favorable element concentrations within living parenchyma, especially near the cambium (Yanosky personal communication). When concentrations exceed some threshold, an element may be translocated away from the cambium, whereas at more typical concentrations the same element may not be particularly mobile (Vroblesky *et al.* 2005). Trees growing over parts of the aquifer contaminated by large concentrations of potassium (from chemical munitions) showed large heartwood concentrations of potassium and sapwood concentrations that increased from outer to inner rings, whereas trees growing over uncontaminated reaches showed smaller concentrations of potassium in heartwood and an increasing gradient from inner to outer sapwood rings. Translocation is an issue for a number of species and for many elements, but the salinet issue is whether there remains a usable environmental signal (Yanosky personal communication).

Hall (1987) examined translocation of 90 elements in pitch pine from New Jersey and found that calcium (Ca), sodium (Na), and potassium (K) were all translocated, while titanium (Ti), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), phosphorous (P), nitrogen (N), fluorine (F), magnesium (Mg), aluminum (Al), strontium (Sr), and rubidium (Rb) were not. Lead (Pb) is a toxic but common contaminant in which many researchers, public health inspectors, and politicians have reason to be interested. Some studies indicate that lead is an element that trees translocate across ring boundaries, complicating any conclusions about the timing of lead contamination in the past (Ault *et al*. 1970, Bindler *et al*. 2004), while others have shown that lead can be accurately recorded in the heartwood of trees with dry heartwood (Guyette *et al.* 1991). Bindler *et al.* (2004) found in a research project that studied $^{206}Pb/^{207}Pb$ in Scots pine in Sweden, that the tree-ring records did not match the timing of other natural records of lead such as peat sequences or soil lead contamination. In one of the first studies of lead uptake by trees in the United States, Ault *et al.* (1970) looked at lead concentrations in tree rings around the New Jersey Turnpike and found that the amount of lead contained in the rings greatly increased towards the outside of the tree. They demonstrated almost a doubling of lead concentration in the rings over a 30-year period, which was greater than the atmospheric increase of lead over the same time. They speculate that the trees might be excluding lead from the inner xylem and therefore are not an accurate record of the environment. However, some tree species with dry heartwood have been shown to be excellent long-term records of changes in lead concentrations in the soil (Guyette *et al.* 1991). This research was able to reconstruct lead for the past 300 years from the heartwood of red cedar (*Juniperus virginiana*) in southeastern Missouri and showed an increase in lead after mining operations started up close to the study site in the late 1800s. Guyette *et al.* (1991) also identified that sites need to have acidic soils for efficient uptake of lead and samples have to be taken from heartwood that is relatively dry. Without these conditions, lead may not be brought into the tree from the soils and it may be translocated in the sapwood.

A tree will often accumulate metabolic wastes and unneeded elements in the heartwood, making it resistant to decay and avoided by insects. Baldcypress in North Carolina was found to compartmentalize excess chloride in its heartwood as a response to salt water intrusion due to dredging and sea-level rise (Yanosky *et al*. 1995). The researchers could estimate the timing of saltwater intrusion because the trees seemed to transport the chloride from the oldest part of the sapwood to the innermost sapwood which then became irrevocably sequestered as the heartwood boundary progressed towards the outside of the tree. From elevated levels of chloride in the heartwood and an estimate of the location of the heartwood/sapwood boundary in the past, they were able to estimate that this contamination may have started around A.D. 1850 (Yanosky *et al.* 1995).

Other Confounding Factors. The solubility of elements is often controlled by other environmental conditions such as pH (Guyette *et al.* 1992). Guyette *et al.* (1992) used mangense (Mn) concentrations in tree rings as a measure of soil pH in red cedars on four sites in the eastern Missouri Ozark Mountains. They were able to document changes in soil pH back to A.D. 1700 and to use soil chemistry and historical records to demonstrate the validity of their record. They suggest that this technique may be useful on other sites to document changes in soil pH due too acid deposition, climate change, or ecological disturbances. Elemental concentrations in trees may be dependent on more factors than the simple levels of that element in the environment, so that soil pH needs to be considered in dendrochemical reconstructions. Although, this also means that soil pH itself can be measured from tree rings under the right circumstances.

Event Reconstructions. Ring width is often adversely affected by the availability of toxic or highly concentrated metals. A suppression in ring width has been observed when certain elements in the surrounding area reach toxic levels. For example, a decrease in the size of tree rings of shortleaf pine (*Pinus echinata*) at Cades Cove, Tennessee in the early 1900s corresponded with peak levels of Fe and Ti in those same rings (Baes and McLaughlin 1984). Further research showed that the probable source of the metal was the nearby Copperhill smelter that was active at the turn of the century. In another example, Yanoksy *et al.* (2001) found an increase in chloride in the rings of oak trees that had access to water contaminated with chlorinated hydrocarbons and they also observed a decrease in ring width in these same affected trees, demonstrating the timing of contamination. This use of multiple lines of information from the same cores, helps to corroborate the timing and cause of injury in dendrochronological records.

*Elements that are useful in dendrochemistry***.** Guyette and McGinnes (1987) found elevated levels of Al, Fe, Zn, Cu, Sr, boron (B), and Mn in red cedar (*Juniperus virginiana*) trees in Missouri that matched smelting activity in nearby mining areas. Al, Fe, and Zn showed the greatest change in concentration in conjunction with smelting and are suggested as possible indicators to track the timing and influence of smelting on sites with unknown exposure. As mentioned earlier, Hall (1987) found that Ti, Mn, Fe, Cu, Zn, P, N, F, Mg, Al, Sr, and Rb did not translocate in pitch pine from New Jersey, suggesting that they may be reliable measures of the timing of their introduction to the environment. Vroblesky and Yanosky (1990) measured Fe and chloride (Cl) on the Aberdeen Proving Grounds in Maryland and found that both elements demonstrated an increase in concentration in the tree rings of tulip popolar when historical activity would have caused an increase in deposition or mobilization of these elements.

Conclusions on Dendrochemistry

Trees can be used as environmental indicators that provide the timing and spatial extent of contamination events (Vroblesky *et al.* 2005). An excellent knowledge of soil chemistry is required in dendrochemistry because most metals enter the tree through root uptake. Dendrochemical work is complicated by translocation of elements and how well the trees will take up certain elements, but it shows potential for future work in dendrochronology. The tree-species being selected for analysis is an important consideration in dendrochemstiry. The ability of a tree to become a recorded of environmental chemistry is based on habitat-based factors, xylem-based factors, and element-based factors; all of which need to be carefully considered when choosing where and how to conduct a dendrochemical analysis (Cutter and Guyette 1993).

Radiometric Isotopes

One of the earliest applications of dendrochronology involving isotopes was the calibration of the ^{14}C dating curve. Radiocarbon, like all radiometric isotopes, decay at a regular rate known as its half-life. This decay rate enables researchers to determine how much time has passed since the isotope was incorporated in the organism. With ^{14}C, plants take in carbon from the atmosphere as long as they are alive, remaining in equilibrium with atmospheric levels of carbon. However, the natural production of ^{14}C in the atmosphere varies slightly through time as affected by solar activity and the Earth's magnetic field, which contribute to variable differences in calendar and radiocarbon ages in the past. Thus, ^{14}C dates needed to be calibrated to account for these differences and to ensure the most reliable ages on samples. Wood samples from giant sequoia (*Sequoiadendron giganteum*) and bristlecone pine (*Pinus longaeva*) were taken for the length of each chronology and submitted to various radiocarbon labs (Ferguson 1968). The labs were able to verify each other's dates and the measurements from the two species also confirmed the temporal drift in the radiocarbon record, so that at 10,000 years before present the radiocarbon curve is off by 2,000 years. This means that a 10,000 year BP date with radiocarbon is really a 12,000 calendar year old sample. This distinction is important when comparing ^{14}C production in the atmosphere to absolutely dated sunspot records for the purpose of determining what drives ^{14}C production.

The current, widely accepted radiocarbon calibration curve is based on the European oak tree-ring chronology (from Ireland and Germany) going back about 10,000 calendar years, which has been extended back nearly an additional 2000 years with a European preboreal pine chronology (Becker 1993; Friedrich *et al.* 1999).

Stable Isotopes

Stable isotope analysis of tree rings is becoming one of the fastest growing applications of dendrochronology (Long 1982, Epstein and Krishnamurthy 1990, Leavitt 1992, McCarroll and Loader 2004) (Table 11.1). This technique analyzes isotope ratios (usually $^{2}H/^{1}H$, $^{13}C/^{12}C$, and $^{18}O/^{16}O$), with the carbon coming from CO_2 in the atmosphere and the hydrogen and oxygen signatures deriving from soil moisture (McCarroll and Loader 2004). Other stable isotope ratios such as $^{15}N/^{14}N$ (Bukata and Kyser 2005), $^{34}S/^{32}S$ (Yang *et al.* 1996), and $^{87}Sr/^{86}Sr$ (English *et al.*

Table 11.1 A summary of the tree-ring isotope studies for paleoenvironmental research (modified from McCarroll and Loader 2004).

Reference	Species	Site	Age-range	Wood component	Isotopes	Data treatment	Environmental or other signal
Anderson et al. (1998)	4 *A. alba*	C Switzerland	1913–1995	Pooled wholewood a-cell.	d13C, d18O	First difference	Temp, prec, and RH
Anderson et al. (2002)	4Fir *A. alba*	C Switzerland	1913–1995	Pooled wholewood a-cell.	d18O	None	Prec and RH
Becker et al. (1991)	*Quercus* sp. and *Pinus sylvestris*	S central Europe	Lateglacial–Holocene	10-year blocks. Cellulose	d13C, dD	None	Qualitative to Lateglacial–Holocene
Bert et al. (1997)	10 *A. alba*	France	1860–1980	5-year blocks. Holocellulose	d13C	Discrimination	Possible age related trend
Buhay and Edwards (1995)	Elm, pine, maple	Ontario Canada	1610–1990	10-year blocks. Cellulose	d18O, dD	None	Modelled d^{18}O of prec. and air RH,
Burk and Stuiver (1981)	Various	N America	Spatial	3 years+blocks. Cellulose	d18O	None	RH and temp.
Craig (1954)	*Sequoiadendron giganteum*	N America	1027 BC–AD 1649	Wholewood	d13C	None	Link to ^{13}C in wood and the atmo
Dubois (1984)	*Pinus sylvestris*	United Kingdom	Recent and ancient	Bulk cellulose	dD	None	Prec and RH
Dupouey et al. (1993)	*F. sylv*.	France	1950–1990	Cellulose annual	d13C	Ci calculated	Extractable soil moisture (July) and CO2
Duquesnay et al. (1998)	*F. sylv*.	NE France	1850–1990	Pooled 10-year cellulose	d13C	D, Ci and WUE	Age effects and long-term trends
Edwards et al. (2000)	19 Fir *A. alba*	S Germany	1004–1980	LW cellulose	d13C, dD	Detrended and shifted	RH and temp.
Epstein and Krishnamurthy (1990)	1 *P. aristata* (+22 sp)	California and global	990–1990	3–5-year blocks. Cellulose	d13C, dD	25-year moving average	Qualitative link to temperature
Epstein and Yapp (1976)	Various (incl. *P. aristata*)	Scotland and N America	1841–1970, 970-1974	Wholewood 10-year blocks	dD	40-year running mean	Winter temperature.
Farmer and Baxter (1974)	*Q. robur, Larix decidua*	United Kingdom	1892–1972	Wholewood	d13C	10-year running mean	Atmospheric C
February and Stock (1999)	6 *Widdringtonia cedarb*	S Africa	1900–1976	Whole ring cellulose	d13C	Corrected not detrended	Air d^{13}C, not prec.
Feng et al. (1999)	2 *Picea*	NE China	1967–1996, 10,040BP	5-year blocks. Cell.	dD	None	Monsoon influence
Feng and Epstein (1995a)	Pine, juniper, oak	N America	1840–1990	5-year blocks. Cell.	d13C	Polynom, 15-yr run ave.	High freq=precip. Low freq = Atmo C
Feng and Epstein (1995b)	7 various	N America	1840–1990	5-year blocks. Cell.	dD	25-year running average	+5.3%/°C to +17%/°C
Freyer (1979a)	26 various	N Hemisphere	1850–1975	2–5-year blocks. Cellulose	d13C	None	Trends in atmospheric C
Freyer (1979b)	10 various	Germany	1890–1975	2-year blocks	d13C	None	Influence of pollution on d^{13}C
Freyer and Belacy (1983)	12 *Q. robur* and *Pinus sylvestris*	Germany and Sweden	1480–1979	1-yr and 10-year, cellulose	d13C	First difference	“Industrial effect", temp, prec.
Gray and Se (1984)	3 *Picea glauca*	Canada	1883–1975	5-year blocks. Cell.	dD	None	Temperature and source water;
Gray and Thompson (1976)	1 *Picea glauca*	Canada	1880–1969	5-year blocks. Cellulose	d18O	None	1.370.1%/°C
Gray and Thompson (1977)	*Picea glauca*	Canada	1882–1969	5-yr blocks WW, cell, lignin	d18O	None	Signal strength with temperature
Hemming et al. (1998)	*F. sylv., Pin. sylv., Q. rob*	United Kingdom	1900–1994	Various	d13C, d18O, dD	Corrected and first diff	RH>temp.>prec.>sunshine

Jedrysek et al. (1998)	2 *Quercus*+fragments	Poland	1850–1970, 10th-20th cent.	1-and 5-year LW celluslose	d13C, dD	5-yr Running average	^{13}C May–July prec.
Kitagawa and Matsumoto (1995)	12 *Cryptomeria japonica*	S Japan	1862–1991, 1846 years	5-and 10-year blocks, a-cellulose	d13C	None	Temp MWP and LIA
Krishnamurthy (1996)	1 *Juniperus phoenica*	Sinai Peninsula	1550–1950	5-year wood blocks	d13C	Ratio internal to ambient CO2	Air d^{13}C and climate, possible moisture
Krishnamurthy and Epstein (1985)	1 *Juniperus procera*	Kenya	1834–1979	5-year blocks. Cellulose	dD	None	Lake levels and water stress
Lawrence and White (1984)	2 *Pinus strobus*	N America	1960–1980	Annual (C-bound H)	dD	None	May–August precipitation amount
Leavitt (1993)	56 *Pinus edulis*	N America	1780–1990	5-year blocks	d13C	None	Moisture stress
Leavitt and Lara (1994)	5 *Fitzroya cupressoides*	Chile	1700–1900	5-year block, holocellulose	d13C	Corrected and ci= ca	"Anthropogenic effect'' in S Hemisphere
Leavitt and Long (1985)	10 *Juniperus* sp.	N America	1930–1979	5-year blocks. Cellulose	d13C	None	Temp and Precip
Libby and Pandolfi (1974)	*Quercus petraea*	Germany	1712–1954, 1530-1800	3–4-year blocks. Wholewood	d13C, d18O, dD	13C corrected for Suess, 9yr running ave	Temperature
Libby et al. (1976)	*Q. pet., A. alba, Cryptomeria japonica*	Germany, Japan	1350–1950, 1660-1950, 137-1950	5-year blocks.	d18O, dD	Smoothed by eye	Temperature
Lipp and Trimborn (1991)	*Picea abies, A. alba*	Southern Germany	1004–1980	LW cellulose	d13C, dD	Unclear	d^{13}C 0.48%/°C dD 2.2%/°C
Lipp et al. (1991)	*A. alba*	Germany	1004–1980	LW cell. nit.	d13C, dD	Detrended and shifted	d^{13}C August temperature, dD no Signal
Liu et al. (1996)	4 *P. tabulaeformis*	N China	1885–1990	Annual pooled multi radii	d13C	Discrimination calculated	June temperature and May-June Prec
Loader and Switsur (1996)	3 *Pinus sylvestris*	United Kingdom	1760–1991	1–10-year cellulose	d13C	First difference	Correlation with summer temp
McCarroll and Pawellek (2001)	36 *Pinus sylvestris*	N Finland, 4 sites	1961–1995	LW cellulose	d13C	Corrected and detrended	Summer sun or precipitation
McCormack et al. (1994)	360 *Q. robur* & *Q. patraea*	United Kingdom	4890 BC–AD 1980	10–20-year, holocellulose	d13C	None	Difference between land and bog oaks
Okada et al. (1995)	3 *Chamae-cyparis*	Japan	1680–1989	4 radii, 5-year blocks. Cellulose	d13C	None	No direct external forcing identified
Pearman et al. (1976)	*Athrotaxis selaginodies*	Australia	1895–1970	Wholewood 5-year blocks	d13C	Running mean	February max. temp.
Pendall (2000)	*P. edulis*	SW USA	1989–1996	E and L wood a-cell.	dD	None	RH dominates. LW more sensitive than E
Ramesh et al. (1985)	*Abies pindrow*	India	1903–1932	Cell. and cell. nit.	d13C, dD, d18O	None	Identified common forcing between radii
Ramesh et al. (1986)	*Abies pindrow*	India	1903–1932	Cell. and cell. nit.	d13C, dD, d18O	None	RH, temp, prec.
Robertson et al. (1997a, b)	10 oak *Q. robur*	SW Finland	1895–1995	LW a-cell.	d13C	Standardised by filtering	Prec.>RH>temp.
Robertson et al. (2001)	4 oak *Q. robur*	E England	1895–1994	LW a-cell.	d18O	No detrending	d^{18}O of winter prec. and summer RH
Saurer and Siegenthaler (1989)	4 *F. sylv.*	C Switzerland	1935–1986	3-year block. Cellulose	d13C	None	d^{13}C temp. and prec.
Saurer et al. (1995)	12 *F. sylv.*	C Switzerland	1934–1989	3-year block. Cellulose	d13C	None	d^{13}C soil moisture status, total prec.
Saurer et al. (1998a, b)	*F. sylv.*	C Switzerland	1935–1990	3-year block. Cellulose	d13C, d18O	Standardised,	d^{13}C temp. and prec. d^{18}O of source
Saurer et al. (2002)	*Larix, Picea, Pinus*	Eurasia	1861–1890, 1961-1990	30-year blocks wholewood	d18O	None	Precipitation

Schiegl (1974)	*Picea*	Germany	1785–1970	5-year blocks wholewood	dD	None	Correlation with summer temperature.
Schleser et al. (1999)	5 *Picea abies*	Germany	1957–1992	EW and LW, Cell. and WW	d13C	None	July temp, mean annual temp.
Sheu et al. (1996)	*Abies kawakamii*	Taiwan	1873–1992	Annual (cellulose)	d13C	None	May–October temp.
Sonninen and Jungner (1995)	1 *Pinus sylvestris*	Finland	1841–1990	Annual (cellulose)	d13C	None	July temp. 0.1%°C
Stuiver and Braziunas (1987)	19 conifers	N America	1100–1850	10-year cellulose	d13C	Standardised	Latitudinal trend. RH>temp. (0.32%/°C)
Switsur et al. (1994)	*Quercus robur*	United Kingdom	1890–1990	Annual, EW, and LW cell	d13C, d18O, dD	None	$d^{13}C$ Jul T and RH $d^{18}O$ Jul T, Jul/Aug RH
Switsur et al. (1996)	1 *Quercus robur*	E England, UK	1869–1993	LW a-cell.	d13C, d18O, dD	None	Temp. (D, $^{13}C^{18}O$), RH (^{13}C, ^{18}O), Prec. (^{1}
Tang et al. (1999)	*Pinus longaeva*	California, USA	1795–1993	Every 5th ring, cellulose	d13C	Detrended, WUE	WUE increases with CO_2
Tang et al. (2000)	*Pseudotsuga menziesii*	NW USA	1934–1996	Annual cellulose nitrate	dD	None	Source-water signal
Tans and Mook (1980)	3 oak, 1 beech	Netherlands	1855–1977	Annual wood, cellulose.	d13C	Corrected for d13C	Mean summer temp. and ann temp.
Treydte et al. (2001)	Spruce *Picea abies*	Swiss Alps	1946–1995	Pooled LW a-cell.	d13C	Corrected for d13C	Late summer temp., prec. and RH
Treydte et al. (2006)	*Junpiperus* sp.	Northern Pakistan	950 - 2006	Annual wood, cellulose	d18O	Corrected to VSMOW	Precipitation
Waterhouse et al. (2000)	5 *Pinus sylvestris*	N Russia	1898–1990	Annual LW a-cell.	d13C	3-year running mean	Correlation with flow of river Ob
Yapp and Epstein (1982)	Various (25)	N America	1961–1975	Cellulose nitrate	dD	Corrected for outliers	Correlation with mean annual temp.
Zimmermann et al. (1997)	*Juniperus* cf. *tibetica*	Tibetan Plateau	1200–1994	5-year blocks	d13C	Corrected for d13C	Inferred soil moisture status

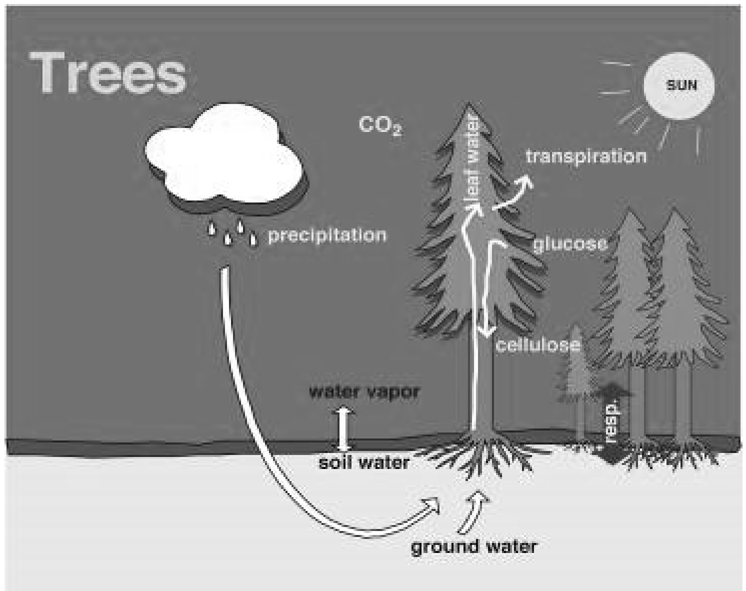
Abbreviations: Q=Quercus (oak); Q. pet=Qiercis petraea (oak); A. alba=Abies alba (fir); F. sylv.=Fagus sylvatica (Beech); LW=latewood; EW=earlywood; a-cell.=a-cellulose; cell. nit.=cellulose nitrate; NiTP=nickel tube pyrolysis; D=discrimination; C_i=internal CO2 concentration; C_a=ambient CO2 concentration; WUE=water use efficiency; T or temp.=temperature; prec.=precipitation; RH=relative humidity; WW = Wholewood

2001) have been examined but not as extensively as hydrogen, carbon, and oxygen. The biological pathways that control how trees fractionate stable isotopes and then incorporate them into their tree rings are fairly well understood, enabling researchers to reconstruct atmospheric temperature, humidity, and water source from which precipitation came (McCarrol and Loader 2004). Most trees take up surface water, which comes directly from precipitation. If a tree is taking up a significant amount of ground water from deeper underground (like mesquite trees that can have a 200 foot deep tap root in the American Southwest) the isotopic composition could be much different. Uncertainties arise because of the variety of factors that control the concentration of these isotopes in the atmosphere and how the plant incorporates them. Oxygen isotopes are controlled by the amount and source of precipitation, temperature, atmospheric humidity, and transpiration of the plant while carbon isotopes are controlled by the CO_2 source, water stress, temperature, humidity, transpiration, and abundance of the isotopes (Figure 11.2).

For example, $\delta^{18}O$ analysis was used to develop a 1000 year-long precipitation reconstruction from juniper trees in the Karakorum Mountains of northern Pakistan (Treydte *et al*. 2006). $\delta^{18}O$ was used instead of ring width because the precipitation signal was enhanced due to the multiple effects of atmospheric humidity on tree physiology. The dendrochronologists demonstrated that the 20th century was the wettest period throughout the record and that this wet interval diverged from normal cycles but matched predictions associated with anthropogenic warming for this region. This research demonstrates the good replication of stable isotopic records over long time periods with relatively few samples, and it highlights the relevance of the science of dendrochronology in helping to understand modern issues.

Oxygen

- Precipitation
- Temp.
- humidity
- transpiration
- source water



Carbon

- CO_2 source
- water stress
- Temp.
- humidity
- transpiration
- limitation

Figure 11. 2 Controls on the isotopic signature in plants (from Anderson *et al.* 2003).

One of the more recent applications of stable isotopes in tree rings, are reconstructions of past hurricane events by the variation of $\delta^{18}O$ in wood cellulose (Mora *et al.* 2006). During normal evaporation of ocean water, more $H_2{}^{16}O$ evaporates from the ocean surface than $H_2{}^{18}O$ such that rainwater is relatively depleted in ^{18}O. During hurricanes, a massive amount of water is evaporated from the ocean surface resulting in even lower $^{18}O/^{16}O$ ratios in precipitation, which is conveyed to tree rings formed during these events.

Limitations

One of the main limitations of isotopic analysis is that multiple environmental factors can cause a change in fractionation of the various stable isotopes (McCarroll and Pawellek 2001). To overcome this limitation, assumptions have to be made about the site from which a sample is collected and how the tree is interacting with the environment as it ages. These assumptions become more tenuous the further back in time our reconstructions run. The best solution for circumventing this problem is the use of multiple proxies, for example using three stable isotopes (like ^{2}H, ^{13}C, and ^{18}O) from the same tree samples to constrain the possible temperature variation in a paleoclimatic study (McCarroll and Loader 2004) or using tree-ring width, density, and stable isotopes in combination as repeated measures of temperature variation (Gagen *et al.* 2006). When multiple proxies are used to make independent estimates of temperature, for example, those resultant estimates can be averaged together. As long as the signal (e.g. atmospheric temperature) is the same between the multiple proxies, but the noise is from different sources, the noise will average out leaving a clearer picture of past temperature fluctuations (McCarroll and Loader 2004).

Standard Procedures

In angiosperms, the earlywood vessels may have some isotopic input from the previous year's stored photosynthates, although the overall affect of stored reserves from the previous year's growth is still a contested issue. Therefore, working only with the latewood from each year is likely to provide the best record of an individual year's isotopic composition (McCarroll and Loader 2004).

Most analysis of tree rings for stable isotopes starts with the extraction of holocellulose or cellulose. This is a useful starting point for stable isotopic analysis because cellulose has a well defined composition compared to whole wood, it is structurally bound in each year, and it does not suffer from possible translocation (Leavitt and Danzer 1993). McCarroll and Loader (2004) suggest, however, that whole wood analysis should be reexamined in greater detail because the time constraints of cellulose extraction slow the processing of multiple samples in automated analysis and the isotopic variability in whole wood seems to be comparable to that in the cellulose.

Holocellulose is the total cellulose, containing cellulose and hemicellulose (non-glucose celluloses), and is a product that is obtained after removal of lignin from the wood. **Cellulose** $(C_6H_{10}O_5)_n$ is a structural polymer of glucose ($C_6H_{12}O_6$) which is the basic sugar that is developed during photosynthesis. The typical cellulose polymer is a linear chain consisting of thousands of glucose building blocks. Cellulose can naturally be found bundled together as microfibrils (a bundle of approximately 50 cellulose molecules). Cellulose can be broken down into three main components: alpha cellulose, beta cellulose, and gamma cellulose. The different types of cellulose are defined by how they behave during a sodium hydroxide NaOH extraction. **Alpha cellulose** is insoluble in strong NaOH (17.5%) and can be removed as a solid; **Beta cellulose** is soluble in strong NaOH but precipitates after neutralization; **Gamma cellulose** remains in solution after neutralization. **Hemicellulose** is another product from wood which is made up of polysaccharides that coat the surface of cellulose microfibrils, running parallel with their structure.

To isolate cellulose for analysis of carbon or oxygen stable isotopes, lignin is removed through oxidation in acidified sodium chlorite ($NaClO_2$) yielding holocellulose. The hemicellulose is then removed by reaction with sodium hydroxide (NaOH) producing alpha-cellulose (Leavitt and Danzer 1993, McCarroll and Loader 2004). Different procedures have been perfected for different species, for example, resins need to be removed from pine trees prior to cellulose extraction and can be done with a Soxhlet apparatus and a solvent of toluene:ethanol in a 2:1 mixture (McCarroll and Loader 2004). See the individual papers cited in the references section for specific methods for each stable isotope.

Once the appropriate wood extraction has been accomplished, the sample is usually converted to a gaseous form through combustion. The ionized particles are then driven down a flight tube by high voltage electric charge and through a magnetic field of a mass spectrometer. The different isotopes are separated by the pull of the magnet and are collected in Faraday cup detectors. I like to think of this like a prism separating out the different wavelengths of white light into a rainbow. The heavier ions follow an arc with a greater radius of curvature than the lighter elements. The Faraday cup detector is a series of metal cups which build up charge depending upon how many ions come in contact with the cup. Once this charge is measured, the mass spectrometer can report how many isotopes were in each weight category and therefore the isotopic composition of the sample.

Results from stable isotope analyses are reported as deviations from a known standard, which is why most stable isotopes are reported as a δ (delta) value. For example, analysis of stable carbon ratios might be reported as -20‰ $\delta^{13}C$, where the sample is 20 part per thousand more depleted in ^{13}C than the standard. Thus, the ‰ (permil) symbol means per 1000 units, just as a % (percent) symbol means per 100 units. Concentrations of many of these stable isotopes are fairly low so they are reported as number of atoms of the stable isotopes for every 1000 atoms in the standard. The standard to which hydrogen and oxygen samples are compared is the standard mean ocean water (**SMOW**). For carbon isotopes, the standard is a calcium carbonate fossil belemnite from the Pee Dee formation in South Carolina and is thus called **PDB** (for Pee Dee Belemnite) (Leavitt 1992, McCarroll and Loader 2004). The fossil carbonate that was originally used as the PDB standard has since been used up and was replaced by the Vienna-PDB (VPDB) standard. Likewise, the SMOW has been replaced by a Vienna-SMOW (VSMOW) (Coplen 1995).

Fractionation

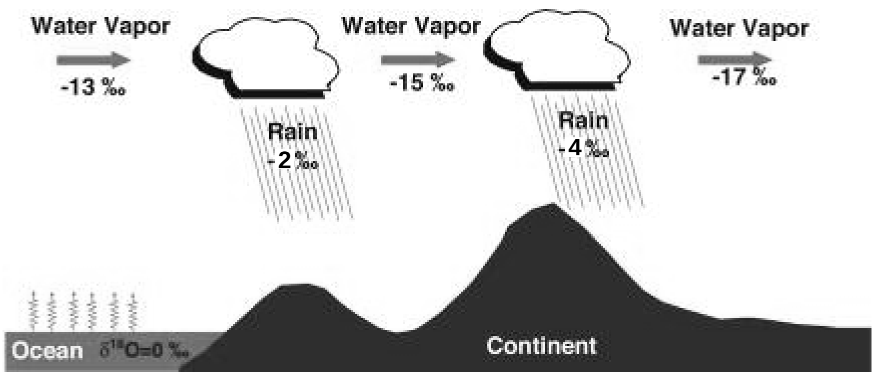
The process of fractionation is how any ratio of stable isotopes changes from its source to where it is later sampled or stored. When examining $^{18}O/^{16}O$, SMOW is the standard or baseline and therefore $\delta^{18}O$ of standard sea water will be 0‰. But when water evaporates off of the ocean, more ^{16}O is likely to go into the atmosphere because it is lighter, producing a lighter fraction in the atmosphere compared to the standard (i.e. -13‰ in the initial water vapor shown in Figure 11.3). As this water moves over land and rain precipitates out of the air mass, more ^{18}O is lost, creating an even lighter isotopic composition of the water remaining in atmospheric vapor. In this example, if everything else is held constant, one can tell the distance to the water source based on the $^{18}O/^{16}O$ in an air mass. The $^{18}O/^{16}O$ ratio in sea water also changes as a result of this evaporation and storage on land, so that marine sediments will become enriched in ^{18}O at the same time glaciers expand with the ^{18}O-depleted water (snow) derived from ocean evaporation.

Further fractionation occurs in the plant itself. Diffusion of carbon isotopes from the atmosphere into the leaf of the plant causes a -4.4‰ reduction in $\delta^{13}C$, because the lighter ^{12}C isotope diffuses more rapidly into the leaves (Figure 11.4). The process of carboxylation (the addition of a COOH group to a molecule) within the plant further fractionates the $\delta^{13}C$ of air, about -27‰ on average. Again, many things can control how carbon isotopes fractionate in the plant, such as leaf morphology, irradiance, air humidity, root to leaf distance, root depth, temperature, amount and seasonality of precipitation (Figure 11.4; Lambers *et al.* 1998, Anderson *et al.* 2003).

Feedback mechanisms also exist, where the plant changes its environment through taking up certain isotopes more so than others. By removing more $^{12}CO_2$ from the atmosphere during photosynthesis, for example, the $^{13}CO_2$ concentration in ambient air will increase, changing the chemistry of the air around the plant. Also, evaporation of water on the ground or in the atmosphere, temperature, humidity, and the amount of circulation in the atmosphere around the

Fractionation

Example $^{18}O/^{16}O$ in Precipitation



Controls

- **Rain-out**
- **Temperature**
- **Amount**
- **Source Area**

Figure 11. 3 An example of fractionation of 18O/16O from sea water to an inland site with two rain events. Evaporation from the ocean causes the main fractionation event with more ^{16}O evaporating off of the ocean so that the ratio is -13‰. Each rain event removes more ^{18}O so that the isotopic ratio drops by -2‰ for each event (from Anderson *et al.* 2003 after Siegenthaler, 1979).

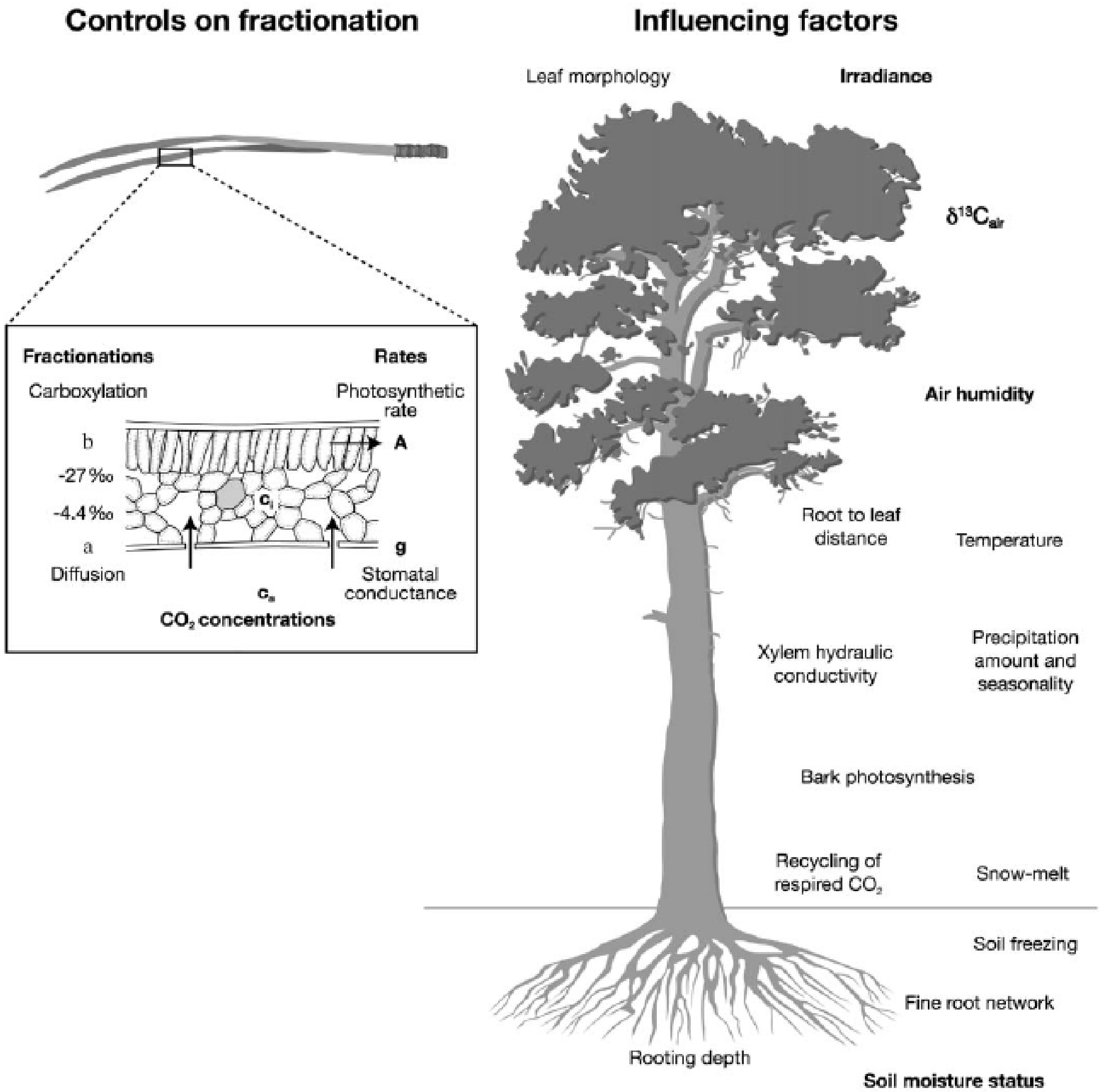


Figure 11. 4 Factors that control fractionation in a pine tree (from McCarroll and Loader 2004).

leaves will all affect the availability of H and O isotopes for assimilation into the plant (Figure 11.5; Lambers *et al.* 1998, Anderson *et al.* 2003).

Different tree species will take up stable isotopes in different concentrations. Because conifer trees transport water much less efficiently than hardwoods resulting in more fractionation from soil water, the gymnosperms will have heavier fractionations of O and H values than angiosperms (McCarroll and Loader 2004). Leaf shape and size in angiosperms also controls how trees fractionate stable isotopes as does the number of stomata on a leaf, which can change through time. One evolutionary consequence of broader leaves is more area for evaporative cooling, and therefore broadleaf trees are less coupled to atmospheric temperature than the needles of a conifer. Rooting depth will control the source of water that trees take up; a shallow rooted tree, for example, will have a greater inter-annual variability in its isotopic composition because of its dependence on rainwater, as opposed to a tree with a deep taproot that can access groundwater. Canopy dominance also controls isotopic fractionation because dominant trees have more direct contact with moving air, which increases the coupling with open atmospheric temperature, humidity, and sunlight, which in turn increases rates of photosynthesis. (McCarroll and Loader 2004). Trees growing in the understory of a forest will experience lower temperatures, high humidity, and less direct sunlight.

Because of isotopic variation within a single ring of a tree, Leavitt and Long (1984) suggest pooling the wood from four radii from four trees (for a total of 16 cores) to obtain accurate values of atmospheric $\delta^{13}C$ for the site. McCarroll and Pawellek (1998) argued against this method stating that it would be better to quantify the $\delta^{13}C$ differences from one core to another

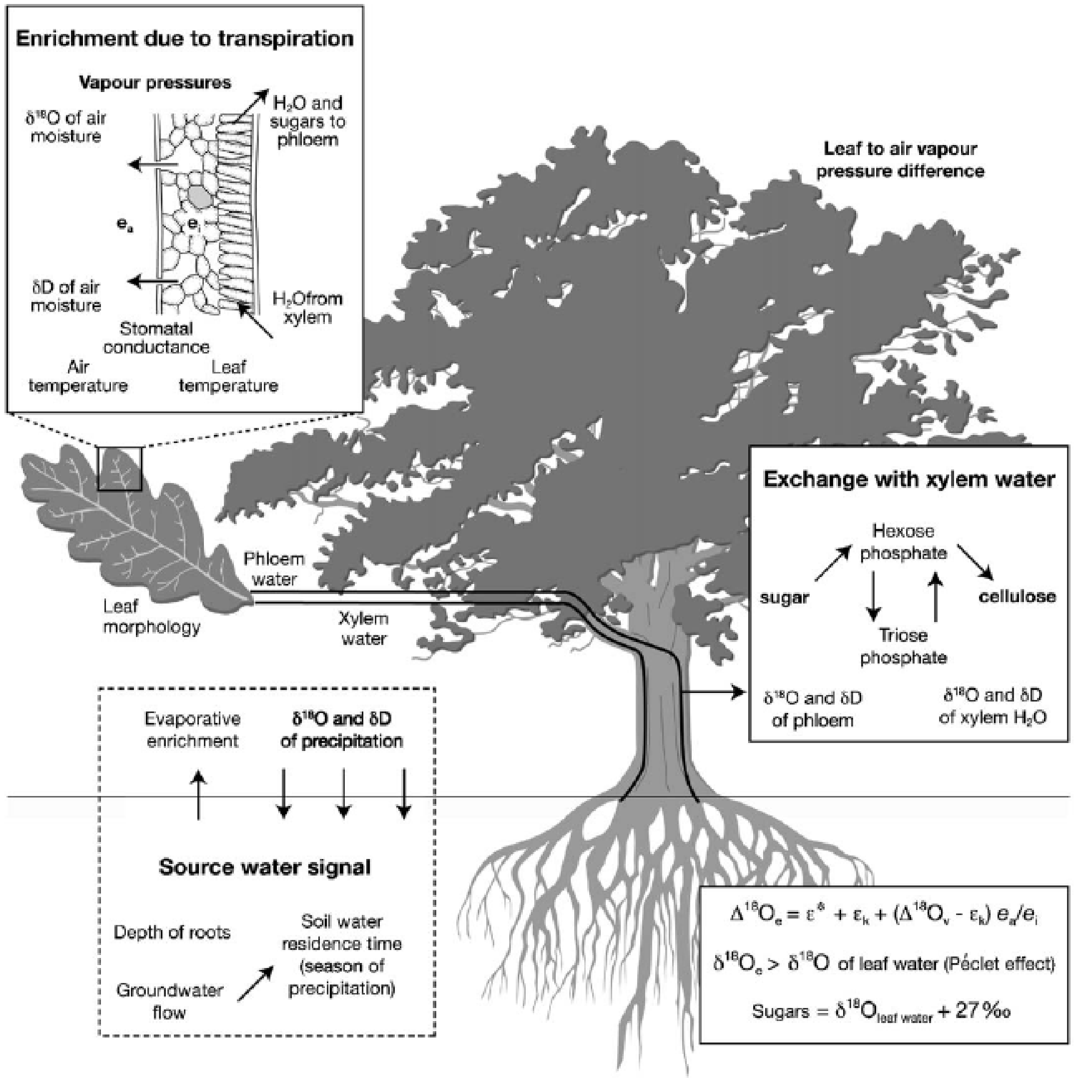


Figure 11. 5 Feedback mechanisms affecting fractionation in an oak tree (from McCarroll and Loader 2004).

by keeping the individual samples separate. They noted that variability between trees was much greater than the variation within a ring, and therefore recommend taking samples from more trees rather than more cores from one tree to average for a more precise measure of the atmospheric isotopic concentrations. They also outlined statistical measures on latewood $\delta^{13}C$ to quantify the error within and between sites and suggested that developing individual tree isotope records was a better way to understand the noise in a chronology rather than pooling wood from multiple trees. The cost and time it takes to process samples in an isotopic study often constrains the number of replicate samples that can be obtained as well as the temporal and spatial resolution and extent.

Other Usable Elements

Trees can be used as a measure of change in the nitrogen cycle due to alteration of land-use by examining variations in ^{15}N, according to a study by Bukata and Kyser (2005). They observed an increase in ^{15}N in white and red oak trees growing on the margin of sites that were clear cut and experienced a permanent change in land-use. The timing and the magnitude of the events was recorded in the nitrogen signal in the trees, although the event seemed to last longer (19 years) than previous studies of disturbance to the nitrogen cycle when foliage alone was sampled would suggest. After 19 years, the nitrogen levels in the tree rings returned to pre-disturbance levels. The authors did note that transport of fluids in the sapwood tended to skew the signal so that some minor translocation likely occurred.

Yang *et al.* (1996) found that trees and shrubs in Death Valley, California accurately recorded variations in soil sulfur. The authors measured levels of ^{34}S in the wood of the plants and examined variations in growth rings of *Tamarix aphylla*. They found that sulfur levels in the plants varied along with sulfur levels in the source water and root growth.

English *et al.* (2001) used $^{87}Sr/^{86}Sr$ to determine the source area of wooden beams in structures from Chaco Canyon, New Mexico that were built around A.D. 1000. They examined the ratio of ^{87}Sr to ^{86}Sr in spruce and fir logs from the archaeological site and examined the strontium ratio in the soil from three surrounding mountains at the spruce/fir zone. The authors determined that the logs came from two of the mountains both approximately 75 km away, while a third mountain source was avoided even though the mountain was the same distance. This example shows the use of stable isotopes as a marker to determine where wood has come from on the landscape.

Conclusions

Stable isotopes provide another record that can be drawn from tree rings and give more information about the environment such as paleo-humidity, summer rainfall, or drought frequency (McCarroll and Pawellek 1998). The application of dendrochronology to isotopic analysis is growing as the methodology becomes automated, reducing the time-consuming attention that was needed in the past by a geochemistry expert. Smaller sample sizes are being analyzed which enables greater replication, finer sampling resolution, and longer time series. Dendrochemistry and stable isotopes are applications of dendrochronology that have recently grown the most out of all dendrochronological applications, changing the face of contemporary tree-ring research. In the next chapter, “Frontiers in Dendrochronology”, I explore new applications, techniques, and methodologies of dendrochronology that are on the cutting edge of research questions today.

Chapter 12: Frontiers in Dendrochronology

Introduction

Although people have long recognized the annual nature of temperate tree rings, dendrochronology as a discipline remains a young science, less than a century old, with its first laboratory founded in 1937 at the University of Arizona. It is growing quickly with 55 major laboratories located around the world today according to Dr. Henri Grissino-Mayer's Ultimate Tree-Ring Webpages. Four large laboratories exist in the U.S. (Laboratory of Tree Ring Research in Tucson, Arizona; Tree-Ring Laboratory at the Lamont-Doherty Earth Observatory New Jersey; Tree-Ring Laboratory at University of Arkansas; Laboratory of Tree-Ring Science at the University of Tennessee) with many smaller ones scattered throughout other American states. Canada has many active laboratories and almost every country in the European Union has at least one dendrochronology laboratory. Russia has many active researchers and China, Australia, and Thailand all of active research programs. South America joined in dendrochronology research about 30 years ago with some of the first research on that continent conducted by researchers at the Laboratory of Tree-Ring Research in Arizona in the 1970s (Lamarche *et al.* 1979c, 1979d). New applications of old techniques are being explored (such as the identification of different insect outbreak systems) and new techniques are being perfected (such as stable isotopic analysis and image analysis). Geographic frontiers still exist in dendrochronology with the use of wood anatomy to explore and examine tropical trees; a greater number of usable tropical species have been identified in the last 10 years than anyone had anticipated. Some researchers are also extending dendrochronological techniques to perennial weeds, shrubs and even to other organisms, such as fish, clams, and turtles. Dendrochronology is a vibrant field with many active researchers contributing to important societal concerns (such as climate change) and pushing the frontiers of our knowledge of the natural world.

Dendrochronologists continue to explore interrelationships between different organisms and trees as they are recorded in tree rings, such as pandora moth (*Coloradia pandora*; Speer *et al.* 2001) or Dothistroma needle blight (*Dothistroma septosporum*; Welsh 2007). What used to be considered "noise" in a tree-ring signal is now understood to be additional biological information that can be isolated as data layers are peeled away. For example, synchronous fruiting history (masting; Speer 2001) has recently been identified in five oak species. Dean *et al.* (1985) continues to push the human behavioral interpretations that can be made from tree-ring data, resulting in the field of dendrochronology being more widely used with greater importance to human society. Along those lines, Speer and Hansen-Speer (2007) have outlined the dendroecological records that can be applied to understand more about anthropogenic ecology and resource availability for native cultures through food resource reconstructions, such as mast and insects, and landscape modification, such as fire history and vegetation change.

Stable Isotopes

Stable isotopes are probably the application in dendrochronology that is most quickly adding to our knowledge of past environments. In the last decade, isotope dendrochronologists have overcome many of the hurdles of the time-consuming sample preparation and wet chemical processing steps in their technique. Now, as these methods become streamlined and analytical equipment improves, isotopic dendrochronologists are able to process hundreds of samples a day in a laboratory, making annual resolution on long chronologies with good sample replication a readily achievable goal (McCarroll and Loader 2004).

New techniques are being developed such as automated laser ablation of whole samples connected directly to an inductively coupled plasma mass spectrometer (LAS ICP-MS) so that sampling can be conducted much more quickly and whole core surveys can be quickly accomplished. Furthermore, LAS ICP-MS removes small amounts of the wood such that the technique does not completely destroy cores, enabling researchers to archive their samples for future reanalysis if necessary (Watmough *et al.* 1998, Schulze *et al.* 2004). Another procedural advance has been the achievement of subannual resolution by using robotic micromilling to mill small sample aliquots from a core or slab (Wurster *et al.* 1999, Dodd *et al.* 2007). The masses needed for analysis have also decreased with improvements made to mass spectrometers; previously, samples as small as 0.3-0.15 micrograms (mg) depending on the isotope system have been routinely analyzed and now the technology is pushing a useful sample size of only 0.02-0.06 mg, again depending on the isotope of interest (Patterson personal communication). By decreasing sample sizes and increasing our ability to isolate tiny aliquots of cellulose we can achieve sample resolutions that represent a week or less for fast growing trees. Newer laser-robotic coupled systems envisioned for the near future should reduce the time-resolution to days or less (Patterson personal communication). The quick processing of whole samples will move isotope dendrochronologists beyond single tree analysis to the investigation of many trees, such that replication between years can be completed from stands of trees with good sample depth back through time.

Isotope dendrochronology truly remains one of the new frontiers in dendrochronology as many environments have not been examined to determine the trees' response to climatic forcing factors that affect stable isotopic fractionation. For example, in the first stable ^{13}C analysis from a subalpine zone, Treydte *et al.* (2001) found that the spruce trees were responding to late summer temperature, precipitation, and relative humidity. The study of climatic responses at extreme environments, such as mountain top sites, is important in the current condition of warming, because many of the mountain top species may be stressed by warmer conditions yet restrained from moving to higher elevations because they are already located at the peak of the mountain.

Multiple Proxies

Stable isotopes provide a wonderful new set of information from tree rings that have expanded the information dendrochronologists can extract from tree rings. But, as was discussed in Chapter 11, isotopic studies are limited by the many mechanisms that can control the concentrations of a single isotope in the tree-ring record (McCarroll and Pawellek 2001). The use of multiple proxies such as ring width, density, and a variety of stable isotopes, helps dendrochronologists narrow down the main driving factors that control these variables in tree rings making climatic reconstructions more accurate (Gagen *et al.* 2006).

Beyond the use of multiple proxies to examine the climatic records of the past, we can use proxies of multiple disturbances to understand the interactions between climate, fire, and insect outbreaks (Kulakowski and Veblen 2002, Kulakowski *et al.* 2003). Historically, each disturbance would be examined in isolation to determine its influence on tree growth. Now we are embracing the complexity of the natural system by examining all of the disturbances that may occur on a site and determining how they influence each other.

Image Analysis of Reflected Light

Students new to dendrochronology often ask if there is an automated technique for measuring and dating dendrochronological samples. Many attempts have been made to automate the process, but in the end, none of them today are equal to manual observation of the tree rings through a good microscope, although a few tools have been developed that do allow scanning and automated ring boundary detection. So far, these techniques are still limited to non-porous wood species (such as pine trees) that have clear ring boundaries and are not hindered by false ring and micro ring structures. Some of these automated techniques such as Windendro (Guay *et al.* 1992, Sheppard and Graumlich 1996) and LignoVision (Rinntech, Heidelberg, Germany) can provide good results, but the automated technique are no substitution to quality controlled crossdating and direct observation of the wood with a good quality binocular microscope. These automated systems work from a scanned sample of wood and optical light reflectance to determine ring boundaries. Both Windendro and Ligno Vision are expensive and limited by the resolution of the image, but some laboratories have had regular success dating samples with these systems.

Potentially, image analysis from reflected light has the capability to quickly provide many different measures of a ring, such as whole ring width, earlywood width, latewood width, cell lumen area, double wall thickness, and circularity index (of individual cells). These latter measurements actually provide a measure of density throughout the tree rings, based on cell lumen area and cell wall thickness (Jagels and Telewski 1990). Image analysis of tree-ring samples started with the work of Telewski *et al.* (1983) and went through a series of advances with the work of Jagels and Telewski (1990), Park and Telewski (1993), Munro *et al*. (1996), Sheppard *et al.* (1996), and Sheppard and Wiedenhoeft (2007). Methodological issues such as removing variations in color that do not relate to ring boundaries have hindered the widespread applicability of this technique to tree-ring analysis. Recent advances, however, have been able to correct for this color difference in the pine heartwood-to-sapwood transition, moving the technique closer to general use (Sheppard and Wiedenhoeft 2007).

Wood Anatomy

Wood anatomy has been studied for hundreds of year, but it is taking on new energy in regards to the applications of dendrochronology. Gärtner (2007b) demonstrates the usefulness of root wood anatomy to determine burial depth of roots and how geomorphological events change that burial depth. Dietz and Schweingruber (2001) are examining root wood anatomy in dicotyledonous perennial herbs of genera never before considered by dendrochronologists to determine the timing of past ecological events.

Efforts are being made to tease apart finer scale effects of climate on tree growth by examing different climate responses from weekly and daily climate records and determining the effect on the growth of individual cells in tree rings. Rossi *et al.* (2006) examined the effect of day length and temperature on weekly xylem cell production in *Picea*, *Pinus*, *Abies*, and *Larix*, finding that the trees were more likely to respond to day length than they were to temperature.

Vessel size in angiosperms is being used as another response to environmental factors. Fonti and Garcia-Gonzolez (2004) used vessel size in a European chestnut (*Castanea sativa*) and found that although variability was not great, earlywood vessel size responded to temperature at the end of the growing season when carbon reserves are put aside for the following year's growth and at the beginning of the growing season. These are periods of time that are not usually recorded in ring width or density and can provide a wider range of climatic data from a tree-ring series.

Fichtler *et al.* (2003) demonstrated the use of wood anatomy combined with radiocarbon dating to determine the oldest age of a number of tropical tree species from Costa Rica, finding the most ancient tree to be 530 years old based on a ring count. Close examination of the wood anatomy enables researchers to recognize cell types that can be used to identify ring boundaries, especially in angiosperm wood, that have complex wood structures. These early attempts at ring identification need to be cross checked with other methods to determine their accuracy; in this case radiocarbon dating was used to help verify the age of these trees. This study is the first step to recognizing the annual rings in some of these tropical tree species through wood anatomy and further work should be able to crossdate these genera to develop absolutely dated chronologies for more extensive regions of the tropics.

Tropical Dendrochronology

Although dendrochronolgy in tropical environments had been conducted in the 19th century, it had long been avoided by dendrochronologists during the 20th century, because conventional wisdom said that there was not enough seasonality in temperature or precipitation to cause trees to shut down on a regular basis forcing annual rings to form (Worbes 2007). Today however, many locations have been found in the tropics where the annual seasonality is great enough or trees are sensitive enough to even slight climatic variations to cause the cambium to form different wood anatomical structures that become visible as rings and many genera of trees are being investigated that do produce annual rings in the tropics (Worbes 1995, 2002, Fichtler *et al.* 2003, Fichtler *et al.* 2004). Through this work, dendrochronologists are pushing the geographic frontiers of dendrochronology and covering the globe with a more uniform distribution of tree-ring chronologies as can be seen by the holdings of the International Tree Ring Databank (ITRDB; Figure 12.1).

Early dendrochronological research in new geographic locations generally starts with a close examination of the wood anatomy of multiple species to demonstrate that these trees produce annual rings (*e.g.* Villalba *et al.* 1985, Boninsegna *et al.* 1989). The next step is to test the annual nature of the chronology and the reliability of ring development through crossdating (Villalba and Boninsegna 1989, Stahle 1999, Speer *et al.* 2004). Stahle (1999) suggests a series of tests to determine if trees have annual rings, based on the ability to crossdate the samples between trees and across multiple sites, their correlation to climate, and through blind crossdating tests of samples with known ages. By following these methods, researchers have been able to document seasonal production of tree rings in Africa (Gourlay 1995, February and Stock 1998, Stahle 1999, Fichtler *et al.* 2004), India (Bhattacharyya *et al.* 1992), Indonesia (D'Arrigo *et al.* 1994), Java (Pumijumnong *et al.* 1995), Mexico (Stahle 1999), Brazilian Amazon region (Worbes 1989, Vetter and Botosso 1989, Schöngart *et al.* 2004), Honduras (Johnson 1980), and the Dominican Republic (Speer *et al.* 2004).

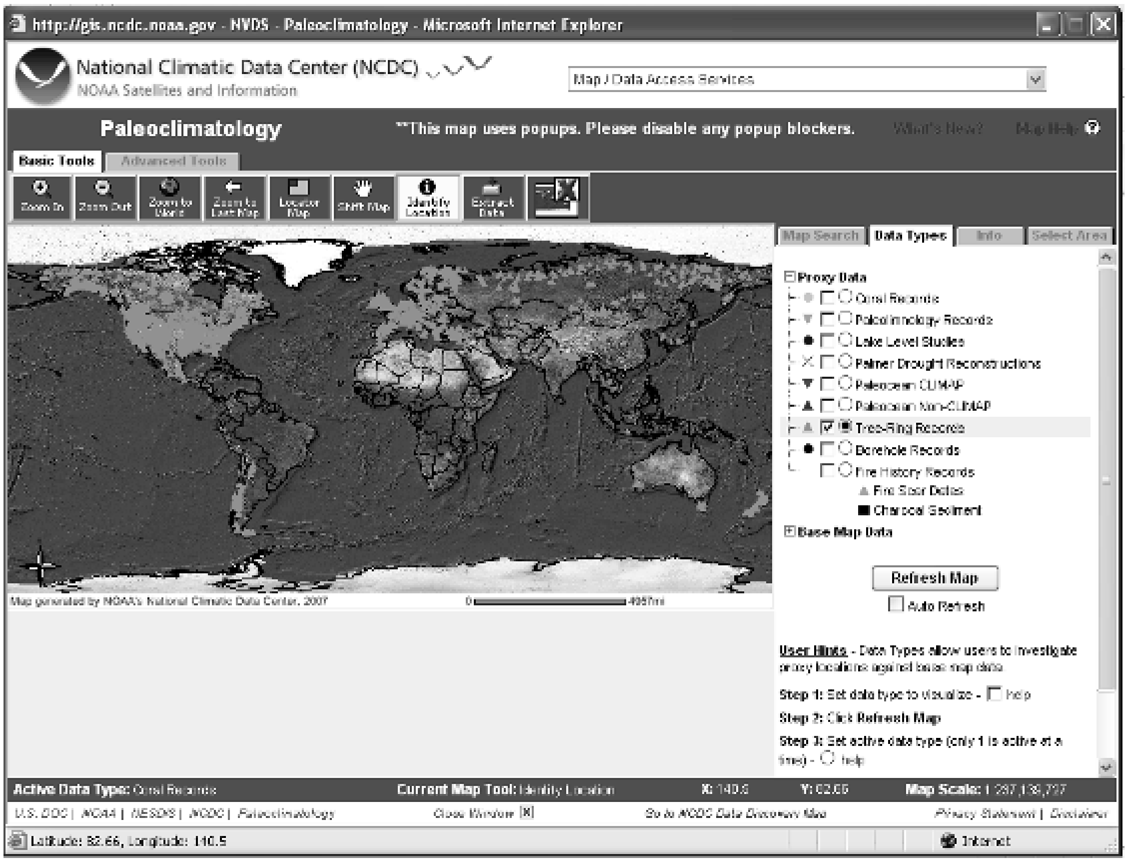


Figure 12. 1 The National Climatic Data Center (NCDC) runs the World Data Center (WDC) for paleoclimatology which houses the tree-ring chronologies of the International Tree Ring Databank (ITRDB). Note the prevalence of chronologies across North America, Europe, and Siberia. There are a growing number of chronologies coming from South America and New Zealand, but a lack of chronologies from Africa and the tropics.

Until the 21st century, the continent of Africa was largely unexplored for the occurrence of tree species that develop annual rings. Gourlay (1995) was able to demonstrate that trees in the genus *Acacia* did develop rings that were bounded by marginal parenchyma cells and that were highly correlated with annual rainfall. February and Stock (1998) examined the potential of two *Podocarpus* species in South Africa but were unable to date the rings due to poor circuit uniformity and locally absent rings. Stahle *et al.* (1999) developed chronologies from *Pterocarpus angolensis* in Zimbabwe at 18 degrees south latitude enabling the researchers to inform the forest managers about the growth rates for this valuable timber species in tropical Africa. Research throughout Africa continues to find older and datable species that can contribute to the data gap on this continent (Eshete and Stahl 1999, Trouet *et al.* 2001, Worbes *et al.* 2003, Fichtler *et al.* 2004, Schöngart *et al.* 2004, Verheyden *et al.* 2004, Couralet *et al.* 2005, Schöngart *et al.* 2005, Verheyden 2005, Trouet *et al.* 2006, Therrell *et al.* 2006).

Unique techniques have also been used to determine the growth of tropical trees and to test for the annual nature of tree rings in some locations. The artificial increase in ^{14}C in the atmosphere from atomic weapons testing caused what is known as the "Bomb Spike" which is an elevated level of ^{14}C that peaks in 1962 in all trees in the world (Worbes and Junk 1989). The Bomb Spike can be used to find the 1962 ring and determine how much growth has occurred in the intervening years. This information may be useful for forest managers so that they can, at least roughly, determine the growth rate of tropical trees that are being harvested. Mariaux (1981) developed an original way for determining the growth rate and ring production in tropical trees by wounding the cambium and returning to see if rings were produced annually.

Unique Environments

Many forests in North America are limited in long-term tree-ring chronologies by extensive logging that occurred around A.D. 1900 and removed many of the old trees, especially in the eastern United States. Many sites have well-preserved old trees on sites that the loggers avoided because the wood was not merchantable such as old lava flows, barrens, or swampy sites. This can be overcome by finding unique sites to which loggers did not have access (Larson *et al.* 1999). For example, the Niagara Escarpment in southern Ontario has Eastern White Cedar (*Thuja occidentalis*) growing on cliffs that obtain ages in excess of 1,000 years (Kelly *et al.* 1992). Research in an environment such as this requires a dendrochronologist who is also skilled at rock climbing.

Submerged logs in anoxic environments (without oxygen) can be preserved for centuries, millennia, and much more rarely, tens of millions of years. These trees have the potential to produce long tree-ring chronologies (Larson and Melville 1996). Places such as the Great Lakes, bog environments, lakes in Siberia, and debris piles at the base of cliffs have all produced preserved logs. Sampling for submerged wood requires dendrochronologists that are interested in scuba diving or have connections with scuba professionals. Submerged environments are great preservation sites that have not yet been explored to their full potential.

Extremely long chronologies are now being developed from **subfossil** wood (usually buried wood that has been preserved but not yet fossilized by the replacement of cellulose by minerals such as quartz) that is being mined from stream banks on tributaries of the Missouri River (Guyette and Stambaugh 2003). This wood has the potential to form the longest tree-ring chronology in the world, extending back some 15,000 years, but work is slow and expensive. Target dates for the samples are determined by the density of the wood (because the longer a specimen is buried the more mass it loses even in anoxic conditions) and radiocarbon dates. Once the sample is placed into a broad period of history, crossdating attempts can be more productive when trying to date the sample against floating chronologies from that time period. As in any tree-ring chronology, adequate sample depth throughout the series is necessary in order to make reliable interpretations from the data; for this project, the task becomes significant because of the length of the chronology.

Sclerochronology

Sclerochronology is the use of boney structures in a variety of organisms to determine the age of the organism and to develop long term histories of the environment from those structures. Sclerochronology has been applied to fish otoliths ("earstones" in the head of fish used for balance and other sensory information), shells of clams, shells of turtles, and even in dinosaur bones. Counting these increments to determine a best guess of the age of the organisms has been done for some time. For example, Aristoltle discussed determination of a fishes age by counting rings in an otolith. Dendrochronologists are now bringing the tool of crossdating to their field to provide quality control and verification of these ages. With the benefit of crossdating, longer chronologies with annual resolution can now be developed (Guyette and Rabeni 1995, Black *et al.* 2005, Helama *et al.* 2006). During the North American Dendroecological Fieldweek in 2006 held at the Hatfield Marine Science Center, Bryan Black led a group that dated geoduck clams from the Vancouver Island area. They found that the clams had better series intercorrelations (~0.716) than any other chronology developed during the fieldweek and also had a significant correlation (r=0.6) with January to March sea-surface temperature (Black *et al.* 2006). Black *et al.* (2005) examined 50 rock fish (*Sebastes diploproa*) otoliths and found that they ranged from 30-84 years in age. The otoliths' growth was significantly correlated with the Northern Oscillation Index (r=0.51, p=0.0001), an upwelling index (r=0.40, p=0.002), and the Pacific Decadal Oscillation (r=-0.29, p=0.007) (Black *et al.* 2005). These results have implications for fisheries management, because many of these fish live much longer than previously expected thereby reducing their rate of replacement. Perhaps the most tragic example of species depletion relates to the age estimate of orange roughy to be an average of 15 years of age, when in reality they were 150 years old. With longer lives and slower development rates, fish would have to be taken less frequently to maintain viable populations.

Conclusion

I hope you have gleaned from this book that dendrochronology is a vibrant field of science that is growing quickly today with many frontiers remaining to be explored. Researchers throughout our discipline are investigating most areas of the natural sciences and touching on a wide variety of fields. Science as a whole is becoming more interdisciplinary and dendrochronology is a tool that can be applied to questions in ecology, archaeology, climatology, geology, hydrology, and atmospheric sciences. These varied uses of the same basic skills make dendrochronology a useful field of study which contributes to our knowledge of the natural world. It is a tool that can be used by practitioners in different fields and is also a science with its own theories.

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Appendix A: Tree and Shrub Species that have been used by dendrochronologists

How to use this list

The table has four columns: CDI (Crossdating Index), Species Code, Genus, Species, and Common name(s).

- The CDI is the Crossdating Index, where
  - "0" indicates the species does not crossdate, or no crossdating information is available
  - "1" indicates a species known to crossdate within and between trees (minor importance to dendrochronology)
  - "2" indicates a species known to crossdate across a region (major importance to dendrochronology).
- The "Code" is the standard four-letter abbreviation assigned by the International Tree-Ring Data Bank for archiving purposes.
- An asterisk (*) beside the four-letter code indicates this species has tree-ring measurements and chronologies held in the International Tree-Ring Data Bank.
- The common names are compiled from various sources.

From Ultimate Tree Ring Webpages http://web.utk.edu/~grissino/species.htm

CDI Code	Species ID	Genus	Species	Common Name
2	ABAL*	Abies	alba	silver fir, European fir
1	ABAM*	Abies	amabilis	Pacific silver fir
2	ABBA	Abies	balsamea	balsam fir
1	ABBO*	Abies	borisii-regis	Bulgarian fir, King Boris fir
0	ABBN	Abies	bornmuelleriana	Bornmueller's fir
0	ABBR	Abies	bracteata	bristlecone fir
1	ABCE*	Abies	cephalonica	Greek fir
0	ABCH	Abies	chensiensis	Chensien fir
1	ABCI	Abies	cilicica	Cilician fir
2	ABCO*	Abies	concolor	white fir
0	ABEQ	Abies	equi-trojani	
0	ABFX	Abies	faxoniana	Faxon fir
0	ABFI	Abies	firma	Japanese fir, Momi fir
1	ABFO	Abies	forestii	Chinese fir
1	ABFR	Abies	fraseri	Fraser fir
1	ABGR	Abies	grandis	grand fir, giant fir
0	ABHO	Abies	holophylla	Manchurian fir
1	ABKA	Abies	kawakamii	Taiwan fir

1	ABKO	Abies	koreana	Korean fir
2	ABLA*	Abies	lasiocarpa	subalpine fir, corkbark fir
1	ABMA*	Abies	magnifica	California red fir
1	ABMR	Abies	mariessi	Marie's fir
1	ABMC	Abies	marocana	Moroccan fir
0	ABNB	Abies	nebrodensis	Sicilian fir
0	ABNE	Abies	nephrolepis	East Siberian fir
1	ABNO*	Abies	nordmanniana	Caucasian fir
1	ABNU	Abies	numidica	Algerian fir
1	ABPI*	Abies	pindrow	Himalayan silver fir
1	ABPN*	Abies	pinsapo	Spanish fir
1	ABPR*	Abies	procera	noble fir
1	ABRC	Abies	recurvata	Min fir
0	ABRE	Abies	religiosa	Mexican fir, sacred fir
0	ABSA	Abies	sachalinensis	Sachalin fir, todo
0	ABSI	Abies	sibirica	Siberian fir
1	ABSB*	Abies	spectabilis	silver fir, East Himalayan fir
0	ABSQ	Abies	squamata	flaky fir
0	ABVI	Abies	vietchii	Vietch's silver fir
0	ACAL	Acacia	alpina	
0	ACCA	Acacia	catechu	cutch, Indian acacia
0	ACGI	Acacia	giraffae	camel thorn
0	ACHO	Acacia	hotwittii	
0	ACME	Acacia	melanoxylon	blackwood
0	ACNI	Acacia	nilotica	gum arabic tree
0	ACRA	Acacia	raddiana	Israelian acacia
1	ACCA	Acer	campestre	hedge maple, field maple
0	ACNE	Acer	negundo	boxelder, ash-leaved maple
0	ACMO	Acer	mono	maple
1	ACOP	Acer	opalus	Italian maple
0	ACPE	Acer	pensylvanicum	striped maple
1	ACPL	Acer	platanoides	Norway maple
1	ACPS	Acer	pseudoplatanus	sycamore maple, plane tree
1	ACRU	Acer	rubrum	red maple
0	ACSA*	Acer	saccharinum	silver maple
2	ACSH*	Acer	saccharum	sugar maple
0	ACSC	Acer	spicatum	mountain maple
0	ACTU	Acer	turkestanica	
0	ADDI	Adansonia	digitata	baobab, monkey bread tree
0	ADFA	Adenostoma	fasciculatum	chamise, greasewood
1	ADHO*	Adesmia	horrida	
1	ADUS*	Adesmia	uspallatensis	
0	AEHI	Aesculus	hippocastanum	horse chestnut
0	AEPU	Aextoxicon	punctatum	olivillo, tique
0	AFAF	Afzelia	africana	afzelia, apa, doussie, alinga, papao
0	AFQU	Afzelia	quanzensis	afzelia, mambokofi, chanfuta
2	AGAU*	Agathis	australis	kauri pine
0	AGMA	Agathis	macrophylla	Fijian kauri
0	AGMO	Agathis	moorei	kauri
0	AGOV	Agathis	ovata	kauri

0	AGPA	Agathis	palmerstoni	North Queensland kauri
2	AGRO	Agathis	robusta	kauri pine, Queensland kauri
0	AGVI	Agathis	vitiensis	
0	AIAL	Ailanthus	altissima	Tree of Heaven
0	ALVE	Allocasuarina	verticillata	
1	ALGL	Alnus	glutinosa	common alder, European alder
0	ALHI	Alnus	hirsuta	
1	ALIN	Alnus	incana	grey alder, white alder
0	ALMA	Alnus	maximowiczii	
0	ALRH	Alnus	rhombifolia	white alder
0	ALRU	Alnus	rubra	red alder
0	ALRG	Alnus	rugosa	speckled alder, rough alder
0	ALSE	Alnus	serrulata	hazel alder
0	ALSI	Alnus	sinuata	Sitka alder
1	ALVI	Alnus	viridis	green alder
0	ALCR	Alnus	viridis	American green alder
1	AMSP	Amelanchier	Medik.	serviceberry
0	AMOV	Amelanchier	ovalis	
0	AMLU	Amomyrtus	luma	luma
0	ANCO	Andira	coriacea	Saint Martin rouge
1	ANSP	Annona	spraguei	araucaria
1	ARAN	Araucaria	angustifolia	Parana araucaria, Parana pine
2	ARAR*	Araucaria	araucana	monkey puzzle, araucaria, pehuen
0	ARBI	Araucaria	bidwilli	bunya pine, bunya
0	ARCU	Araucaria	cunninghamii	hoop pine, Moreton bay pine
0	ARHE	Araucaria	heterophylla	Norfolk Island pine
0	ARHU	Araucaria	hunsteinii	pine
0	ARGL	Arctostaphylos	glauca	bigberry manzanita
1	ARTR	Artemisia	tridentata	big sagebrush
2	ATCU*	Athrotaxis	cupressoides	pencil pine, smooth Tasmanian cedar
2	ATSE*	Athrotaxis	selaginoides	King Billy pine
0	AUKL	Aucoumea	klaineana	okoume
2	AUCH*	Austrocedrus	chilensis	Chilean cedar, cipres de la cordillera,
0	BAAE	Balanites	aegyptiaca	Jericho balsam, heglig
0	BLTA	Beilschmiedia	tawa	Kirk tawa
0	BBVU	Berberis	vulgaria	common barberry
0	BTEX	Bertholletia	excelsa	Brazil nut, yuvia, turury, para nut tree
0	BEAB	Betula	albosinensis	Chinese birch
1	BEAL	Betula	alleghaniensis	yellow birch
0	BEER	Betula	ermanii	Japanese birch, dakekaba
0	BEGL	Betula	glandulosa	bog birch, dwarf birch
1	BEGR	Betula	grossa	Japanese cherry birch
0	BELE	Betula	lenta	sweet birch, black birch
0	BENI	Betula	nigra	river birch
1	BEPA	Betula	papyrifera	paper birch
0	BEAK	Betula	papyrifera	
1	BEPE	Betula	pendula	silver birch, European white birch
0	BEPL	Betula	platyphylla	jagjag-namu, Japanese birch
0	BEPO	Betula	populifolia	gray birch
1	BEPU	Betula	pubescens	downy birch, mountain birch

1	BEUT	Betula	utilis	Himalayan birch
1	BEVE	Betula	verrucosa	silver birch, European white birch
0	BOQU	Bombacopsis	quinata	
0	BOMA	Bombax	malabaricum	semul, ngiu, ngiew, gon run do
1	BUGR	Bursera	graveolens	palo santo
0	BUSI	Bursera	simaruba	gumbo-limbo, West-Indian birch
1	BUSE	Buxus	sempervirens	common box, boxwood
0	CACO	Callitris	columellaris	cypress pine
0	CAIN	Callitris	intratropica	cypress pine
0	CAMA	Callitris	macleayana	brush cypress pine
1	CAPR*	Callitris	preissii	Rottnest Island pine
1	CARO*	Callitris	robusta	
1	CADE	Calocedrus	decurrens	California incense cedar
1	CABU*	Canthium	burttii	canthium
0	CASC	Capparis	scabrida	sapote
0	CAPC	Carapa	procera	carapa
0	CPBE	Carpinus	betulus	hornbeam
0	CYCO	Carya	cordoformis	bitternut hickory
1	CYGL	Carya	glabra	pignut hickory
1	CYIL	Carya	illinoensis	pecan
0	CYOV	Carya	ovata	shagbark hickory
0	CYTO	Carya	tomentosa	mockernut hickory
0	CAGL	Caryocar	glabrum	chawari
0	CACR	Castanea	crenata	Japanese chestnut
1	CADN	Castanea	dentata	American chestnut
1	CASA	Castanea	sativa	sweet chestnut, European chestnut
0	CSLI	Casuarina	litoralis	black she-oak
0	CTSP	Catalpa	speciosa	northern catalpa
0	CNCR	Ceanothus	crassifolius	hoaryleaf ceanothus
1	CEAN*	Cedrela	angustifolia	cedro salteno
0	CEFI	Cedrela	fissilis	central American cedar
1	CELI*	Cedrela	lilloi	cedro salteno
0	CEOD	Cedrela	odorata	
0	CETO	Cedrela	toona	Harms red cedar, Australian cedar,
2	CDAT	Cedrus	atlantica	Atlantic cedar, Atlas cedar
1	CDBR*	Cedrus	brevifolia	
1	CDDE	Cedrus	deodara	deodar cedar, Himalayan cedar
1	CDLI*	Cedrus	libani	Cedar of Lebanon
1	CLAU	Celtis	australis	southern nettle tree, hackberry
0	CLCA	Celtis	caucasica	Caucasian nettle tree
0	CLLA	Celtis	laevigata	sugarberry
1	CLOC	Celtis	occidentalis	hackberry
1	CLRE	Celtis	reticulata	netleaf hackberry
0	CEOC	Cephalanthus	occidentalis	buttonbush
0	CEMI	Cercidium	microphyllum	yellow paloverde
0	CRBE	Cercocarpus	betuloides	birchleaf mountain-mahogany
0	CRLE	Cercocarpus	ledifolius	curlleaf mountain-mahogany
1	CRMO	Cercocarpus	montanus	alderleaf cercocarpus
1	CHFO	Chamaecyparis	formosensis	Formosan false cypress
2	CHNO	Chamaecyparis	nootkatensis	Alaska yellow-cedar, Nootka cypress

1	CHOB	Chamaecyparis	obtusa	hinoki cypress, Formosan cypress
1	CHPI	Chamaecyparis	pisifera	sawara cypress
0	CHTH	Chamaecyparis	thyoides	Atlantic white-cedar
0	CLEX	Chlorophora	excelsa	iroko, kambala, mvule
0	CHSP	Chorisia	speciosa	paneira
0	CIFR	Citharexylum	fruticosum	Florida fiddlewood
0	COCO	Copaifera	coleosperma	Rhodesian copalwood, mehibi
1	COAL	Cordia	alliodora	laurel corriente, lauro amarillo, ajo ajo
0	COAP	Cordia	apurensis	
0	COBI	Cordia	bicolor	
0	COEL	Cordia	elaeagnoides	
0	COTR	Cordia	trichotoma	lauro pardo, peterebi
0	COFL	Cornus	florida	flowering dogwood
0	COSA	Cornus	sanguinea	
0	COAV	Corylus	avellana	common hazel
0	COSI	Corylus	sieboldiana	blume hazel
0	CTCO	Cotinus	coggygria	European smoketree
0	CTSP	Cotoneaster	Medik.	cotoneaster
0	CRAZ	Crataegus	azarolus	azarole
0	CRMO	Crataegus	monogyna	
2	CMJA*	Cryptomeria	japonica	Japanese cedar, sugi, cryptomeria
1	CUAZ	Cupressus	arizonica	Arizona cypress
0	CUAT	Cupressus	atlantica	Atlas cypress
0	CUDU	Cupressus	dupreziana	
1	CUGI	Cupressus	gigantea	
0	CUGL	Cupressus	glabra	smooth Arizona cypress
0	CULU	Cupressus	lusitanica	Mexican cypress
2	CUSE	Cupressus	sempervirens	Italian cypress, Mediterranean cypress
0	CYRA	Cyrilla	racemiflora	swamp cyrilla, leatherwood
0	DADA	Dacrycarpus	dacrydioides	kahikatea, white pine
1	DABD	Dacrydium	bidwillii	New Zealand mountain pine
1	DABI*	Dacrydium	biforme	
1	DACO*	Dacrydium	colensoi	
2	DACU	Dacrydium	cupressinum	rimu, red pine
1	DAFR	Dacrydium	franklinii	Huon pine
0	DIGU	Dicorynia	guianensis	angelique
0	DSVI	Diospyros	virginiana	common persimmon
0	DITO	Discaria	toumatou	matagouri, tumatu-kuru, wild Irishman
1	DITR	Discaria	trinervis	
0	DRLA	Dracophyllum	latifolium	neinei
0	DRWI	Drimys	winteri	canelo, winter bark
1	DUVI	Duschenkia	viridis	.
0	DYMA	Dysoxylum	malabaricum	Bombay white cedar
0	ELGL	Elaeoluma	glabrascens	rΘv.
1	EMRU	Empetrum	rubrum	murtilla
1	ENCA	Enkianthus	campanulatus	
0	ENAN	Entandrophragma	angolense	gedu nohor, kalungi, tiama, edinam
0	ENCA	Entandrophragma	candollei	kosipo, omu
0	ENCY	Entandrophragma	cylindricum	sapeli, sapele, sapelli, assi
0	ENUT	Entandrophragma	utile	sipo, utile EPSP Ephedra L. ephedra

0	EUCA	Eucalyptus	camaldulensis	river red gum
0	EUDE	Eucalyptus	delegatensis	alpine ash
0	EUGL	Eucalyptus	globulus	Tasmanian bluegum
0	EUMA	Eucalyptus	marginata	jarrah
0	EUMI	Eucalyptus	miniata	Darwin woolybutt
0	EUNE	Eucalyptus	nesophila	Melville Island bloodwood
0	EUOR	Eucalyptus	oreades	Blue Mountains ash
0	EUPA	Eucalyptus	pauciflora	snow gum, cabbage gum
0	EUST	Eucalyptus	stellulata	black salee
0	EUTE	Eucalyptus	tetradonta	Darwin stringybark
0	EUVI	Eucalyptus	viminalis	ribbongum
0	EUCO	Eucryphia	cordifolia	ulmo, muermo
0	EUJA	Eugenia	jambolana	jaman, kelat eugenia
0	EXCU	Exocarpus	cuppressiforme	native cherry
1	FAGR*	Fagus	grandifolia	American beech
1	FAOR	Fagus	orientalis	Oriental beech, eastern beech
2	FASY*	Fagus	sylvatica	European beech, common beech
2	FICU*	Fitzroya	cupressoides	alerce, Patagonian cypress
1	FRAM	Fraxinus	americana	white ash
0	FRCA	Fraxinus	caroliniana	Carolina ash
0	FACR	Fagus	crenata	bunya beech
1	FREX*	Fraxinus	excelsior	European ash, common ash
0	FRMA	Fraxinus	mandshurica	Manchurian ash, yachidamo
1	FRNI*	Fraxinus	nigra	black ash
0	FRPE	Fraxinus	pennsylvanica	green ash, red ash
1	FRSP	Fraxinus	spaethiana	ash
1	FRVE	Fraxinus	velutina	velvet ash
0	GEAV	Gevuina	avellana	avellano
0	GIBI	Gingko	biloba	maidenhair tree, gingko
0	GLTR	Gleditsia	triacanthos	honey locust
0	GMAR	Gmelina	arborea	gumari, gumbar, yemane, gmelina
0	GOLA	Gordonia	lasianthus	loblolly-bay
0	GOGL	Goupia	glabra	goupia
0	GRVI	Grevillea	victoriae	
0	GUCE	Guarea	cedrata	bosse, guarea, white guarea
0	HABD	Halocarpus	bidwillii	bog pine
1	HABI*	Halocarpus	biformis	pink pine
0	HAKI	Halocarpus	kirkii	manoao
0	HAVI	Hamamelis	virginiana	witch hazel
0	HEAN	Hedycaria	angustifolia	native mulberry
0	HEAR	Heteromeles	arbutifolia	toyon
1	HEBR	Hevea	brasiliensis	
0	ILAQ	Ilex	aquifolium	English holly
0	ILCA	Ilex	cassine	dahoon, dahoon holly
0	ILCO	Ilex	coriacea	large gallberry, sweet gallberry
0	ILGL	Ilex	glabra	inkberry, gallberry
0	ILIN	Ilex	inundata	
0	ILOP	Ilex	opaca	American holly
0	JACO	Jacaranda	copaia	copaia, gobaja, futui, caroba
1	JGAU*	Juglans	australis	Argentine walnut

0	JGCI	Juglans	cinerea	butternut
0	JGNI	Juglans	nigra	black walnut
0	JGRE	Juglans	regia	common walnut
0	JUCH	Juniperus	chinensis	Chinese juniper
1	JUCO	Juniperus	communis	common juniper
0	JUDE	Juniperus	deppeana	alligator juniper
1	JUDR	Juniperus	drupacea	Syrian juniper
1	JUEX	Juniperus	excelsa	Greek juniper, Grecian juniper
1	JUFO	Juniperus	foetidissima	stinking juniper
0	JUMA	Juniperus	macropoda	Himalayan pencil pine
0	JUMO	Juniperus	monosperma	one-seed juniper
2	JUOC*	Juniperus	occidentalis	western juniper
1	JUOS	Juniperus	osteosperma	Utah juniper
1	JUOX	Juniperus	oxycedrus	prickly juniper
1	JUPH	Juniperus	phoenicea	Phoenicean juniper
0	JUPI	Juniperus	pinchotii	redberry juniper, Pinchot juniper
0	JUPC	Juniperus	procera	Uganda juniper, African pencil cedar,
1	JUPR	Juniperus	przewalskii	Qilianshan juniper
1	JURE	Juniperus	recurva	drooping juniper
2	JUSC*	Juniperus	scopulorum	Rocky Mountain juniper
1	JUSM	Juniperus	semiglobosa	
1	JUSE	Juniperus	seravschanica	
0	JUTH	Juniperus	thurifera	Spanish juniper
1	JUTU	Juniperus	turkestanica	Turkestan juniper
2	JUVI*	Juniperus	virginiana	eastern red-cedar
0	KHGR	Khaya	grandifolia	acajou, Benin mahogany
0	KRDR	Krenevaja	drevesina	
0	KUER	Kunzea	ericoides	kanuka, white tea tree
0	LBGL	Labatia	glomerata	
0	LBAN	Laburnum	anagyroides	common laburnum
1	LGCO*	Lagarostrobus	colensoi	
1	LGFR	Lagarostrobus	franklinii	huon pine
0	LSFL	Lagerstroemia	flos-reginae	pyinma, banaba, banglang, jarul
0	LSPA	Lagerstroemia	parviflora	lendia
0	LSLA	Lagerstroemia	lanceolata	benteak, nana
2	LADE*	Larix	decidua	European larch
1	LAGM*	Larix	gmelinii	Dahurian larch
1	LAGR	Larix	griffithiana	Himalayan larch
1	LAJA	Larix	japonica	Japanese larch
2	LALA*	Larix	laricina	tamarack, eastern larch
2	LALY*	Larix	lyalli	subalpine larch
2	LAOC*	Larix	occidentalis	western larch
1	LAPO	Larix	potanini	Chinese larch
2	LASI*	Larix	sibirica	Siberian larch
0	LAPH	Laurelia	philippiana	tepa
0	LASE	Laurelia	sempervirens	laurelia, Chilean laurel, huahuan
0	LAHU	Laxopterigium	huasango	haltaco
0	LECO	Lecythis	corrugata	angelique
0	LEIN	Lepidothamnus	intermedius	yellow-silver pine
0	LEFL	Leptospermum	flavescens	tea tree

0	LESC	Leptospermum	scoparium	manuka, red tea tree, black manuka
2	LIBI*	Libocedrus	bidwillii	New Zealand cedar, pahautea
0	LIPL	Libocedrus	plumosa	kawaka, plume incense cedar
0	LGVU	Ligustrum	vulgare	
1	LIST	Liquidambar	styraciflua	sweetgum
1	LITU*	Liriodendron	tulipifera	tuliptree, yellow-poplar, tulip-poplar
0	LOFR	Lomatia	fraseri	silky lomatia, tree lomatia
0	LOHI	Lomatia	hitsuta	radal
0	LOXY	Lonicera	xylosteum	
0	LOTR	Lovoa	trichilioides	dibetou
0	MAAC	Magnolia	accuminata	cucumbertree
0	MAGR	Magnolia	grandiflora	southern magnolia
0	MAVI	Magnolia	virginiana	sweetbay, swampbay
0	MASY	Malus	sylvestris	apple tree
0	MABI	Manilkara	bidentata	balata franc
0	MICH	Michelia	champaca	champak
0	MINI	Michelia	niligirica	pilachampa, champak
0	MOCO	Moronobea	coccinea	manil montagne, mountain manil
0	MOAL	Morus	alba	white mulberry
0	MORU	Morus	rubra	red mulberry
0	MYCE	Myrica	cerifera	southern bayberry, bayberry
0	MYGA	Myrica	gale	sweet gale, bog myrtle
0	NEAM	Nectandra	amazonum	
0	NTLO	Notelaea	longifolia	large mock-olive
0	NOAL	Nothofagus	alpina	rauli
1	NOAN	Nothofagus	antarctica	Antarctic beech, nirre
1	NOBE*	Nothofagus	betuloides	coihue de Magallanes, guindo
0	NOCU	Nothofagus	cunninghamii	Australian nothofagus, myrtle beech
0	NODO	Nothofagus	dombeyi	coihue, Dombey's southern beech
0	NOFU	Nothofagus	fusca	red beech, New Zealand red beech
1	NOGU*	Nothofagus	gunnii	tanglefoot beech
2	NOME*	Nothofagus	menziesii	silver beech, Menzies's red beech
0	NONE	Nothofagus	nervosa	rauli
0	NONI	Nothofagus	nitida	roble chicote
1	NOOB	Nothofagus	obliqua	southern beech, roble
1	NOPU*	Nothofagus	pumilio	lenga
2	NOSO*	Nothofagus	solandri	mountain beech, black beech
0	NYOG	Nyssa	ogechee	Ogeechee tupelo
0	NYSY	Nyssa	sylvatica	black tupelo, blackgum
0	OCUS	Ocotea	usambarensis	ocotea, camphor
0	OSCA	Ostrya	carpinifolia	hop hornbeam
0	OXAR	Oxydendrum	arboreum	sourwood
0	PARI	Parapiptadenia	rigida	
0	PAAU	Parkia	auriculata	
0	PATO	Paulownia	tomentosa	empress tree
0	PECA	Peronema	canescens	sunkai, koeroes
0	PEBO	Persea	borbonia	redbay, shorebay
0	PELI	Persea	lingue	lingue
0	PELN	Petrophile	linearis	pixie mops
0	PBPO	Phoebe	porfiria	

1	PHAL*	Phyllocladus	alpinus	mountain toatoa, alpine celery top pine
1	PHAS*	Phyllocladus	aspleniifolius	
1	PHGL*	Phyllocladus	glaucus	toatoa
1	PHTR*	Phyllocladus	trichomanoides	tanekaha, celery pine
2	PCAB*	Picea	abies	Norway spruce
0	PCAS	Picea	asperata	dragon spruce
1	PCBA	Picea	balfouriana	
1	PCBR	Picea	brachytyla	
1	PCCA	Picea	cajanensis	
1	PCCH	Picea	chihuahuana	chihuahua spruce
2	PCEN*	Picea	engelmannii	Engelmann spruce
2	PCGL*	Picea	glauca	white spruce
1	PCGN	Picea	glehnii	Sakhalin spruce
0	PCJE	Picea	jezoensis	Yezo spruce, Hondo spruce
1	PCLI	Picea	likiangensis	Likiang spruce
2	PCMA*	Picea	mariana	
1	PCOM*	Picea	omorika	Serbian spruce, Pancic spruce
1	PCOR*	Picea	orientalis	eastern spruce, Oriental spruce
2	PCPU*	Picea	pungens	blue spruce, Colorado spruce
1	PCPR	Picea	purpurea	
2	PCRU*	Picea	rubens	red spruce
1	PCSH	Picea	shrenkiana	Shrenk's spruce
2	PCSI*	Picea	sitchensis	Sitka spruce
1	PCSM	Picea	smithiana	Himalayan spruce
1	PCTI	Picea	tienschanica	Tien-shan spruce
2	PLUV*	Pilgerodendron	uviferum	cipres de las Guaytecas
2	PIAL*	Pinus	albicaulis	whitebark pine
2	PIAR*	Pinus	aristata	Rocky Mountain bristlecone pine
1	PIAM*	Pinus	armandii	David's pine, Armand's pine
2	PIBA*	Pinus	balfouriana	foxtail pine
2	PIBN*	Pinus	banksiana	jack pine
1	PIBR*	Pinus	brutia	Calabrian pine, brutia pine, see kiefer
0	PIBU	Pinus	bungeana	lacebark pine
0	PICN	Pinus	canariensis	Canary Island pine
0	PICA	Pinus	caribaea	Caribbean pine, Cuban pine
2	PICE*	Pinus	cembra	Swiss stone pine, Arolla pine
2	PICM*	Pinus	cembroides	Mexican pinyon, Mexican nut pine
1	PICH	Pinus	chihuahuana	chihuahua pine
2	PICO*	Pinus	contorta	lodgepole pine
0	PICL	Pinus	coulteri	Coulter pine, bigcone pine
1	PIDN	Pinus	densata	
1	PIDE*	Pinus	densiflora	Japanese red pine
2	PIEC*	Pinus	echinata	shortleaf pine
2	PIED*	Pinus	edulis	pinyon, Colorado pinyon
1	PIEL	Pinus	elliottii	slash pine
1	PIEN	Pinus	engelmannii	Apache pine
2	PIFL*	Pinus	flexilis	
1	PIGE	Pinus	gerardiana	chilgoza pine, Gerard's pine
2	PIHA*	Pinus	halepensis	Aleppo pine, Jerusalem pine
1	PIHE	Pinus	heldreichii	Heldreich's pine, panzer fohre

2	PIJE*	Pinus	jeffreyi	Jeffrey pine
1	PIKE	Pinus	kesiya	Khasi pine
1	PIKO	Pinus	koraiensis	Korean pine
1	PILG	Pinus	lagunae	laguna pinyon
2	PILA*	Pinus	lambertiana	sugar pine
2	PILE*	Pinus	leucodermis	Bosnian pine, greybark pine
2	PILO*	Pinus	longaeva	Intermountain bristlecone pine
1	PIMA	Pinus	massoniana	Masson pine
1	PIMK	Pinus	merkusii	Merkus pine, mindoro pine
1	PIME	Pinus	mesogeensis	cluster pine
2	PIMO*	Pinus	monophylla	singleleaf pinyon
1	PIMZ	Pinus	montezumae	Montezuma pine
1	PIMC	Pinus	monticola	western white pine
1	PIMU*	Pinus	mughus	krummholz pine
1	PIMG	Pinus	mugo	mountain pine, stone pine
0	PIMR	Pinus	muricata	bishop pine
2	PINI*	Pinus	nigra	Austrian pine, black pine
0	PIOC*	Pinus	occidentalis	West Indian pine
0	PIOO	Pinus	oocarpa	Nicaraguan pitch pine, ocote pine
1	PIPA*	Pinus	palustris	longleaf pine
0	PIPT	Pinus	patula	Mexican weeping pine
1	PIPE*	Pinus	peuce	Macedonian pine, Balkan pine
1	PIPI*	Pinus	pinaster	maritime pine, cluster pine
2	PIPN*	Pinus	pinea	Italian stone pine, umbrella pine
2	PIPO*	Pinus	ponderosa	ponderosa pine, western yellow pine
1	PIPM	Pinus	pumila	dwarf Siberian pine
1	PIPU*	Pinus	pungens	Table Mountain pine
1	PIQU	Pinus	quadrifolia	Parry pinyon
1	PIRA	Pinus	radiata	Monterrey pine
2	PIRE*	Pinus	resinosa	red pine
1	PIRI*	Pinus	rigida	pitch pine
1	PIRO	Pinus	roxburghii	chir pine
1	PISI	Pinus	sibirica	Siberian stone pine
2	PISF*	Pinus	strobiformis	southwestern white pine
2	PIST*	Pinus	strobus	eastern white pine, Weymouth pine
2	PISY*	Pinus	sylvestris	Scots pine, Scotch pine
1	PITB	Pinus	tabulaeformis	Chinese pine
2	PITA*	Pinus	taeda	loblolly pine
0	PITH	Pinus	thunbergii	Japanese black pine
1	PITO	Pinus	torreyana	Torrey pine
2	PIUN	Pinus	uncinata	mountain pine
1	PIVI	Pinus	virginiana	Virginia pine, scrub pine
1	PIWA	Pinus	wallichiana	Himalayan pine, kail pine, blue pine
0	PSGR	Pisonia	grandis	
0	PTAT	Pistacia	atlantica	Atlas pistache, betoum
0	PTKH	Pistacia	khinjuk	kakkar
0	PTPA	Pistacia	palaestina	Israelian pistache
0	PTVE	Pistacia	vera	green mastic, real mastictree
0	PLAC	Platanus	acerifolia	London plane tree
1	PLOC	Platanus	occidentalis	American sycamore

0	PLOR	Platanus	orientalis	Oriental plane tree
0	PLIN	Platonia	insignis	parcouri
1	PLOR	Platyeladus	orientalis	Chinese pine
0	PYSA	Polyscias	sambucifolius	elderberry panax, elderberry ash
0	POFA	Podocarpus	falcatus	yellowwood, oteniqua
0	POHA	Podocarpus	hallii	Hall's totara
0	POLA	Podocarpus	lawrencei	Tasmanian podocarpus
1	PONE	Podocarpus	neriifolius	thitmin
0	PONI	Podocarpus	nivalis	snow totara
1	PONU	Podocarpus	nubigensus	manio de hojas punzantes
0	POPA	Podocarpus	parlatorei	
0	POTO	Podocarpus	totara	totara
1	PPAL	Populus	alba	white poplar
0	PPAN	Populus	angustifolia	narrowleaf cottonwood
1	PPBA	Populus	balsamifera	balsam poplar
0	PPDE	Populus	deltoides	eastern cottonwood
1	PPEU	Populus	euphratica	charab poplar, Indian poplar
0	PPFA	Populus	fastigiata	
1	PPFR	Populus	fremontii	Fremont cottonwood
1	PPGR	Populus	grandidentata	bigtooth aspen
1	PPNI	Populus	nigra	lombardy poplar, black poplar
1	PPSI	Populus	sieboldii	Japanese aspen
1	PPTR	Populus	tremuloides	quaking aspen
0	PPTC	Populus	trichocarpa	black cottonwood
1	PRMX*	Premna	maxima	muchichio
1	PRFL	Prosopis	flexuosa	
0	PRGL	Prosopis	glandulosa	honey mesquite
0	PMAN	Prumnopitys	andina	lleuque
0	PMFE	Prumnopitys	ferruginea	miro
0	PMTA	Prumnopitys	taxifolia	matai, black pine
0	PNAM	Prunus	americana	American plum
0	PNAV	Prunus	avium	wild cherry
0	PNIL	Prunus	ilicifolia	
0	PNMA	Prunus	mahaleb	
0	PNPE	Prunus	pennsylvanica	pin cherry
1	PNSE	Prunus	serotina	black cherry
0	PNSP	Prunus	spinosa	
0	PSMU	Pseudobombax	munguba	muguba, huira
1	PSSE	Pseudobombax	septenatum	
1	PSJA	Pseudotsuga	japonica	Japanese Douglas-fir
1	PSMA*	Pseudotsuga	macrocarpa	bigcone Douglas-fir
2	PSME*	Pseudotsuga	menziesii	Douglas-fir
0	PSAX	Pseudowintera	axillaris	
0	PSCO	Pseudowintera	colorata	mountain horopito, pepper tree
0	PSXA	Pseudoxandra	polyphleba	
0	PTAN*	Pterocarpus	angolensis	Muninga, bloodwood
0	PTVE	Pterocarpus	vernalis	
0	PTRH	Pterocarya	rhoifolia	Japanese wing nut
0	PTPA	Pteronia	pallens	
1	PUTR	Purshia	tridentata	bitter brush

0	QUAC	Quercus	acutissima	
0	QUAF	Quercus	afares	
2	QUAL*	Quercus	alba	white oak
0	QUBI	Quercus	bicolor	swamp white oak
0	QUBO	Quercus	boissieri	Israelian oak
1	QUBR	Quercus	brantii	
0	QUCL	Quercus	calliprinos	Kermes oak, Israelian oak
1	QUCA	Quercus	canariensis	Mirbeck's oak, Algerian oak
1	QUCE	Quercus	cerris	Turkey oak, Austrian oak
1	QUCO	Quercus	coccinea	scarlet oak
0	QUCP	Quercus	copeyensis	
0	QUCR	Quercus	costaricensis	
1	QUDE	Quercus	dentata	kashiwa oak, Daimio oak
1	QUDG*	Quercus	douglasii	blue oak
1	QUDS	Quercus	dschoruchensis	
1	QUEL	Quercus	ellipsoidalis	northern pin oak
0	QUEM	Quercus	emoryi	Emory oak
0	QUEN	Quercus	engelmannii	Engelmann oak
1	QUFG	Quercus	faginea	Portuguese oak
1	QUFA	Quercus	falcata	southern red oak
1*	QUFR	Quercus	frainetto	Hungarian oak
2	QUGA	Quercus	gambelii	Gambel oak
0	QUGY	Quercus	garryana	Oregon white oak
1	QUGR	Quercus	grisea	gray oak
1	QUHA	Quercus	hartwissiana	
0	QUIL	Quercus	ilex	holm oak, holly oak
0	QUIT	Quercus	ithaburensis	Mt. Tabor oak
0	QUKE	Quercus	kelloggii	California black oak
1	QULA	Quercus	laurifolia	laurel oak
1	QULO	Quercus	lobata	valley oak
0	QULU	Quercus	lusitanica	oak
1	QULY*	Quercus	lyrata	overcup oak
1	QUMA*	Quercus	macrocarpa	bur oak
0	QUMC	Quercus	macrolepis	Valonia oak
0	QUML	Quercus	marilandica	blackjack oak
0	QUMI	Quercus	michauxii	swamp chestnut oak
0	QUMO	Quercus	mongolica	Mongolian oak
0	QUGS	Quercus	mongolica	
0	QUMU	Quercus	muehlenbergii	chinkapin oak
1	QUNI	Quercus	nigra	water oak
0	QUPA	Quercus	palustris	pin oak
2	QUPE*	Quercus	petraea	durmast oak, sessile oak
1	QUPO	Quercus	pontica	Armenian oak
1	QUPR*	Quercus	prinus	chestnut oak
2	QUPU	Quercus	pubescens	downy oak, pubescent oak
0	QUPY	Quercus	pyrenaica	Pyrenean oak
2	QURO*	Quercus	robur	English oak
1	QURU*	Quercus	rubra	red oak
1	QUSH	Quercus	shumardii	Shumard oak
2	QUST*	Quercus	stellata	post oak

0	QUSU	Quercus	suber	cork oak, cork tree
1	QUVE*	Quercus	velutina	black oak
0	QUAC	Quintinia	acutifolia	Westland quintinia
0	RAGU	Rapanea	guianensis	guiana rapanea
0	RESP	Recordoxylon	speciosum	wacapou guitin
0	RHCA	Rhamnus	caroliniana	Carolina buckthorn
0	RHCT	Rhamnus	cathartica	
0	RHCR	Rhamnus	crocea	hollyleaf buckthorn
0	RHOV	Rhus	ovata	sugar sumac
1	RONE	Robinia	neomexicana	New Mexico locust
0	ROPS	Robinia	pseudoacacia	black locust
0	SBPI	Sabina	pingu	
0	SBRE	Sabina	recurva	
1	SBSA	Sabina	saltuaria	
1	SBTI	Sabina	tibetica	
1	SBWA	Sabina	wallichiana	
0	SAAC	Salix	acutifolia	pointed-leaved willow
1	SAAL	Salix	alba	white willow
0	SAAM	Salix	amygdalina	almond-leaved willow
0	SAAD	Salix	amygdaloides	peachleaf willow
0	SAAR	Salix	arbusculoides	littletree willow
0	SAAT	Salix	arctica	Arctic willow
0	SABA	Salix	babylonica	weeping willow
0	SACN	Salix	candida	sage-leaf willow, silver willow
0	SACA	Salix	caprea	pussy willow, goat willow
0	SACR	Salix	caroliniana	Coastal Plain willow
0	SADI	Salix	discolor	pussy willow, glaucous willow
0	SAEL	Salix	elaeagnos	hoary willow
0	SAEX	Salix	exigua	sandbar willow
0	SAGL	Salix	glauca	grayleaf willow
0	SALA	Salix	lanata	Richardson's willow
0	SALS	Salix	lasiolepis	arroyo willow, white willow
0	SAMY	Salix	myrsinifolia	
0	SAPH	Salix	phylicifolia	tea-leaf willow
0	SAPL	Salix	planifolia	sandbar willow, lakeshore willow,
0	SAPU	Salix	purpurea	purple willow, purple osier
0	SAVI	Salix	viminalis	basket willow, common osier
0	SNAL	Santalum	album	sandalwood, santalin, chandal
0	SSAL	Sassafras	albinum	sassafras
0	SSAL	Sapium	styllare	
1	SACO	Saxegothaea	conspicua	Prince Albert's yew
0	SCTR	Schleichera	trijuga	ta-kro, kusum, kusamo
0	SCMI	Schleronema	micranthum	cordeiro, scleronema
1	SCVE	Sciadopitys	verticillata	
1	SESE	Sequoia	sempervirens	coast redwood
2	SEGI	Sequoiadendron	giganteum	giant sequoia
0	SHRO	Shorea	robusta	sal
0	SIAM	Simarouba	amara	simarouba
0	SOAM	Sorbus	americana	mountain ash
0	SOAR	Sorbus	aria	whitebeam

0	SOAU	Sorbus	aucuparia	mountain ash, rowan
1	SOTE	Sorbus	torminalis	chequer tree, wild service tree
0	SODU	Sorocea	duckei	
0	SWLA	Swartzia	laevicarpa	saboarana
0	SWMC	Swietenia	macrophylla	
0	SWMA	Swietenia	mahagoni	West Indies mahogany
0	SYGL	Symphonia	globulifera	manil
0	TABA	Tabebuia	barbata	Igapo-tree
0	TMAP	Tamarix	aphylla	dur
1	TMCH	Tamarix	chinensis	tamarisk, salt cedar
0	TMJO	Tamarix	jordanis	
0	TPGU	Tapirira	guianensis	tapirira, cedroi, jobo
0	TMXE	Tasmannia	xerophila	
0	TAAS	Taxodium	ascendens	pond cypress
2	TADI*	Taxodium	distichum	baldcypress
2	TAMU*	Taxodium	mucronatum	Montezuma cypress
1	TABA	Taxus	baccata	common yew, English yew
1	TACU	Taxus	cuspidata	Japanese yew
1	TEGR	Tectona	grandis	teak
0	TEBR	Terminalia	brownii	
0	TEGU	Terminalia	guianensis	
0	TETO	Terminalia	tomentosa	Indian laurel, taukkyan, sain
1	TEAR	Tetraclinis	articulata	Arar tree, African thuya
2	THOC*	Thuja	occidentalis	northern white-cedar
0	THOR	Thuja	orientalis	Chinese arborvitae, Oriental arborvitae
1	THPL*	Thuja	plicata	western redcedar, giant arborvitae
1	THST	Thuja	standishii	Japanese arborvitae
1	THDO	Thujopsis	dolabrata	hiba arborvitae
1	THHO	Thujopsis	dolabrata	asunaro arborvitae
1	TIAM	Tilia	americana	American basswood
1	TICO	Tilia	cordata	littleleaf linden, winter linden,
1	TIPL	Tilia	platyphyllos	broad-leaved linden, summer linden
1	TOCA	Torreya	californica	California nutmeg
0	TRSC	Triplochiton	schleroxylon	abachi, obeche, wawa, arere
0	TRCO	Tristania	conferta	Queensland box tree
2	TSCA*	Tsuga	canadensis	eastern hemlock
1	TSCR*	Tsuga	caroliniana	Carolina hemlock
0	TSCH	Tsuga	chinensis	Chinese hemlock
0	TSDI	Tsuga	diversifolia	Japanese hemlock
1	TSDU	Tsuga	dumosa	East Himalayan hemlock
2	TSHE*	Tsuga	heterophylla	western hemlock
2	TSME*	Tsuga	mertensiana	mountain hemlock
0	TSSI	Tsuga	sieboldii	southern Japanese hemlock
1	ULGL	Ulmus	glabra	Wych elm, Scots elm, mountain elm
1	ULLA	Ulmus	laevis	European white elm
1	ULMI	Ulmus	minor	smooth-leaved elm, field elm
0	ULPU	Ulmus	pumila	Siberian elm
1	ULRU	Ulmus	rubra	slippery elm
0	VBLA	Vibernum	lantana	
0	VIME	Virola	melinonii	mountain yayamadou

1	VIKE*	Vitex	keniensis	moru, moru oak
0	VOAM	Vouacapoua	americana	wacapou
0	WERA	Weinmannia	racemosa	kamahi
0	WETR	Weinmannia	trichosperma	tineo, tenio, palo santo
1	WICE*	Widdringtonia	cedarbergensis	Clanwilliam cedar
0	ZISP	Ziziphus	spina-christi	Judas tree, Christ thorn
0	ZYDU	Zygophyllum	dumosum	

Appendix B: Age of the oldest trees per species.

This list is a compilation of Peter Brown's OLDLIST and Neil Pederson's Eastern OLDLIST for the eastern United States. Those two lists have been combined here, organized by the oldest age of the trees, and filtered so that only the oldest individual is represented for each species.

The table includes genus, species, age, type (see below), sample identification number, location of the sample, and the collector's information or a reference where the tree is mentioned.

Four types of ages are recognized in the database:

XD: crossdated
RC: ring counted
EX: extrapolations (based on ring measurements usually)
HI: historic record

Brown, P. 1996. Oldlist: A Database of Maximum. In: Dean, J.S., Meko, D.M., and Swetnam, T.W. (eds.) Proceedings of the International Conference on Tree Ages. Tree Rings, Environment, and Humanity: Relationships and Processes, 17-21 May, 1994, Tucson, Arizona. Radiocarbon 1996: 727-731.

Genus	Species	Age	Type	ID	Location	Collector(s), Dater(s), Reference
Pinus	longaeva	4844	RC	WPN-114	Wheeler Peak, Nevada, USA	Currey 1965
Fitzroya	cupressoides	3622	XD		Chile	Lara and Villalba 1993
Sequoiadendron	giganteum	3266	XD	CBR26	Sierra Nevada, California, USA	M. Hughes, R. Touchan, E. Wright
Juniperus	occidentalis	2675	XD	Scofield juniper	Sierra Nevada, California, USA	Miles and Worthington 1998

Pinus	aristata	2435	XD	CB-90-11	Central Colorado, USA	Brunstein and Yamaguchi 1992
Ficus	religiosa	2217	HI		Sri Lanka	Anonymous
Sequoia	sempervirens	2200	RC		Northern California, USA	E. Fritz
Pinus	balfouriana	2110	XD	SHP 7	Sierra Nevada, California, USA	A. Caprio
Larix	lyalli	1917	EX		Kananaskis, Alberta, Canada	Worrall 1990
Juniperus	scopulorum	1889	XD	CRE 175	Northern New Mexico, USA	H. Grissino-Mayer, R. Warren
Pinus	flexilis	1670	XD	ERE	Northern New Mexico, USA	T. Swetnam, T. Harlan
Pinus	balfouriana	1666	XD	RCR 1	Sierra Nevada, California, USA	A. Caprio
Thuja	occidentalis	1653	XD	FL117	Ontario, Canada	Kelly and Larson 1997
Chamaecyparis	nootkatensis	1636	RC?		Vancouver Island, Canada	L. Jozsa

Taxodium	distichum	1622	XD	BLK 69	Bladen County, North Carolina, USA	Stahle, Cleaveland, Hehr 1988
Psuedotsuga	menziesii	1275	XD	BIC 63	Northern New Mexico, USA	H. Grissino-Mayer
Pinus	albicaulis	1267	XD	RRR15	Central Idaho, USA	Perkins and Swetnam 1996
Lagarostrobus	franklinii	1089	XD		Tasmania, Australia	Cook et al. 1991
Pinus	edulis	973	XD	SUN 2522	Northeast Utah, USA	Schulman 1956
Pinus	ponderosa	929	XD		Wah Wah Mtns, Utah, USA	S. Kitchen
Picea	engelmannii	911	XD	FCC 23	Central Colorado, USA	Brown et al. 1995
Pinus	monophylla	888	XD	PGH-02	Pine Grove Hills, Nevada, USA	F. Biondi, S. Strachan
Juniperus	virginiana	860	XD	--	MO	R. Guyette
Larix	siberica	750	XD	OVL-5N	Ovoont, Mongolia	Nachin, B. Buckley, N. Pederson

Nyssa	sylvatica	679	XD	--	NH	Dan Sperduto P. Krusic
Picea	glauca	668	XD		Klauane Lake, Yukon, Canada	Luckman 2003 (B. Luckman, R. van Dorp, D. Youngblut, M. Masiokas)
Pinus	siberica	629	XD	TPX-16	Tarvagatay Pass, Mongolia	G. Jacoby, Nachin, D. Frank
Pinus	jeffreyi	626	XD	TGS-02	Truckee, California, USA	F. Biondi, S. Strachan
Pinus	strobiformis	599	XD	VPK02	San Mateo Mtns, New Mexico, USA	H. Grissino-Mayer, J. Speer, K. Morino
Tsuga	canadensis	555	XD	39021	Tionesta, PA	E. Cook; Cook and Cole, 1991
Fagus	sylvatica	503	XD	1012306F	Abruzzi Nat'l Park, Italy	Piovesan et al. 2005
Abies	lasiocarpa	501	XD		Southern Yukon, Canada	Luckman 2003 (B. Luckman, M. Kenigsberg)
Pinus	resinosa	500	RC	--	Granite Lake, Kenora, Ontario Canada	S. St. George; Ontario's Old Trees
Picea	abies	468	XD	LBG	Bavarian Forest, Germany	R. Wilson

Quercus	alba	464	XD	85141	Buena Vista, VA	E. Cook; N. Pederson
Torreya	californica	455	XD		Sierra Nevada, California, USA	A. Caprio
Picea	rubens	445	RC	05BCL901a	Fundy Escarpment, New Brunswick, Canada	B. Phillips
Picea	rubens	445	XD	05BCL901a	Fundy Escarpment, NB, Cana.	B. Phillips
Liriodendron	tulipifera	434	RC	--	Great Smoky Mountains National Park	W. Blozan
Quercus	muehlenbergii	429	XD	PSC23	Guadalupe Mtns. Nat. Park, TX	D.Stahle, M.Therrell, D.Griffin, D.(Daniel)Stahle
Quercus	montana	427	XD	LBC25	Uttertown, NJ	E. Cook; N. Pederson; Pederson et al., 2004
Platanus	occidentalis	412	RC	BHY001	MO	R. Guyette, M. Stambaugh
Pinus	strobus	408	XD	sww51	Swan Lake, Algonquin Park, Ont. Canada	R.P. Guyette & B. Cole; ITRDB
Quercus	gambelli	401	XD		North central Arizona, USA	F. Biondi

Quercus	stellata	395	XD	KEY13	Osage County, OK	D. Stahle; ITRDB
Betula	alleghaniensis	387	RC	--	Algonquin Park, Ontario, Canada	Vasiliauskas, S. A.,; Ontario's Old Trees
Pinus	rigida	375	XD	--	Mohonk Lake, NY	E. Cook; ITRDB
Betula	lenta	361	XD	STE03	New Paltz, NY	E. Cook; N. Pederson & H.M. Hopton; Pederson et al. in press
Carya	ovata	354	XD	WFS08a	Fiddler's Green, VA	N. Pederson; A. Curtis; Pederson et al. in press
Pinus	palustris	354	XD	SPB35	Sprewell Bluff Wildlife Management Area, Meriwether County, GA (on the Piedmont)	T. Knight
Magnolia	acuminata	348	XD	MDC02b	Fiddler's Green, VA	N. Pederson; H.M. Hopton; Pederson et al. in press
Quercus	macrocarpa	343	XD	BHY002	MO	R. Guyette, M. Stambaugh
Picea	mariana	330	XD	--	Sleeping Giant Prov. Park, Ontario, Canada	Girardin et. al, 2006
Quercus	rubra	326	XD	hem79	Wachusett Mountain, Massachusetts, USA	Orwig et al. 2001

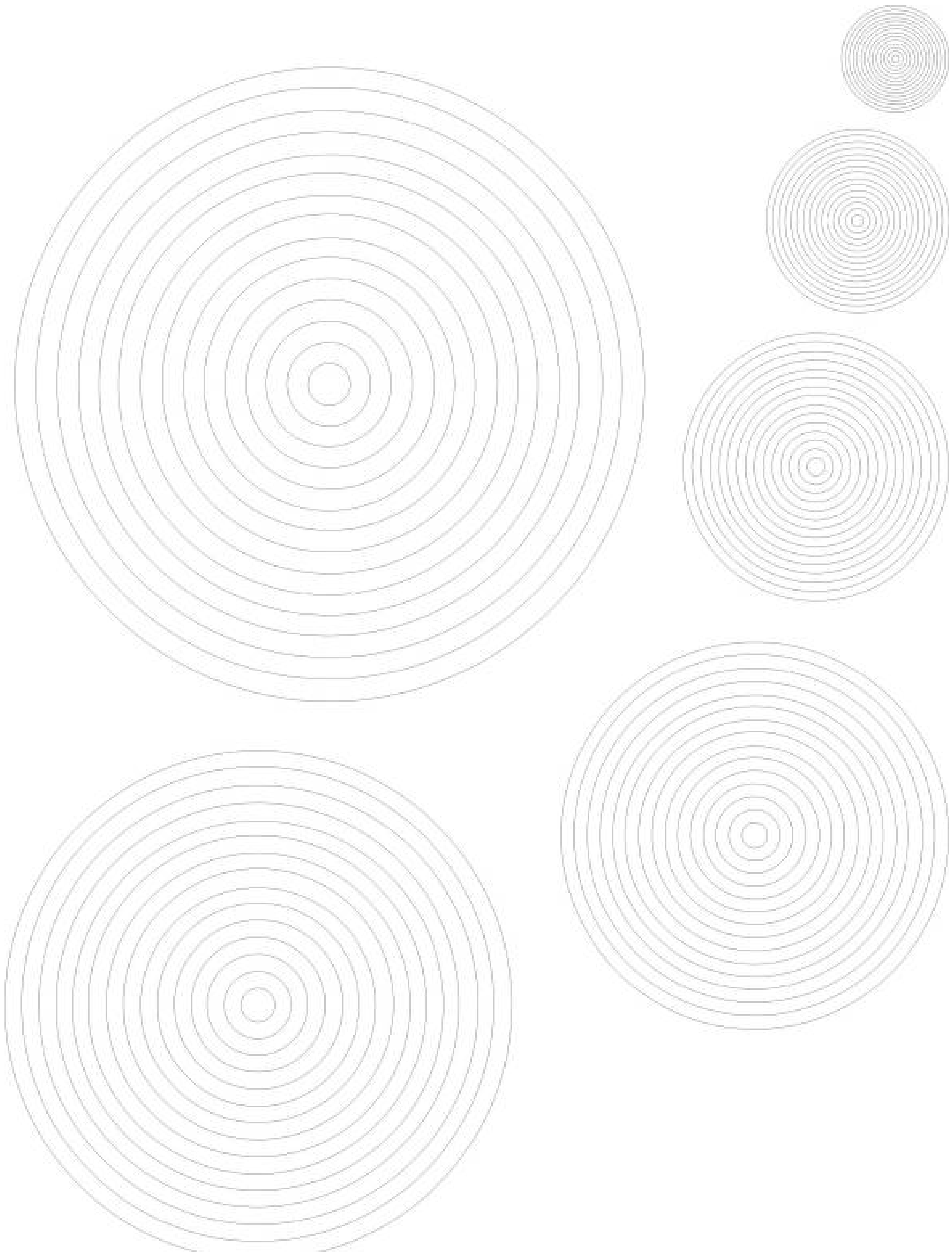
Fraxinus	nigra	319	XD	--	Lac Duparquet, Quebec	Tardif & Bergeron, 1999
Pinus	echinata	315	XD	LAW38	Saline County, Arkansas, USA	D. Stahle
Tsuga	caroliniana	307	XD	101231	Kelsey Tract, NC	E. Cook; Cook and Cole, 1991
Acer	rubrum	300	XD	CATB142	Catskill Mtns, NY	P. Sheppard & C. Canham; P. Sheppard; Pederson et al. in press
Quercus	bicolor	285	XD	RHS01a	Catkill, New York, USA	D & N. Pederson, M. Hopton
Acer	saccharum	280	RC	--	Peter's Woods, Ontario, Canada	Martion & Martin,; Ontario's Old Trees
Castanea	dentata	270	XD	GB204B	Greenbriar, Great Smoky Mountains, TN	J. Young, W. Blozan; ITRDB
Carya	glabra	265	XD	BCV16a	Mohonk Preserve, NY	N. Pederson; Pederson et al., 2004
Quercus	prinus	265	XD	GL18	Pisgah Nat'l Forest, North Carolina, USA	Speer 2001
Acer	nigrum	247	RC	BHY038	MO	R. Guyette, M. Stambaugh

Pinus	banksiana	246	XD	--	Blue Lake, Ontario, Canada	Girardin et. al, 2006
Abies	balsamea	245	XD	--	Lac Liberal, Canada	C. Krause, H. Morin; ITRDB
Pinus	taeda	241	XD	--	Congaree Swamp National Park, SC	N. Pederson; T. Doyle; Pederson et al., 1997
Betula	papyrifera	240	XD	--	Rainbow falls Prov. Park, Ontario, Canada	Girardin et. al, 2006
Quecus	margaretta	234	XD	RCP41	Rambulette Creek, Taylor County, GA	T. Knight
Pinus	pungens	232	XD	GKA111	Griffith Knob, Virginia, USA	G. DeWeese, H. Grissino-Mayer, C. Lafon
Ostrya	virginiana	230	RC	--	Algonquin Park, Ontario, Canada	Vasiliauskas, S. A.,; Ontario's Old Trees
Cotinus	obovatus	221	RC	--	Arkansas	R. Guyette
Quercus	velutina	219	XD	293503	Alley Spring, Shannon County, Missouri	S. Voelker
Quercus	lyrata	218	XD	SNA7	Desha County Arkansas, USA	D. Stahle

Populus	tremuloides	213	RC	--	Lake Abitibi Model Forest, Ontario, Canada	Lefort, P.; Ontario's Old Trees
Populus	balsamifera	207	RC	--	Ontario, Canada	Vasiliauskas, S. A.,; Ontario's Old Trees
Fagus	grandifolia	204	RC	--	Backus Woods, Ontario, Canada	B. Larson; Ontario's Old Trees
Xanthorrhoea	preissii	200	XD	Tree 41	Western Australia	D. Ward
Fraxinus	quadrangulata	194	RC	BHY012	MO	R. Guyette, M. Stambaugh
Ulmus	alata	186	RC	--	Rocky Creek, Shannon County, Missouri	S. Voelker
Carya	tomentosa	169	XD	PCT2025	Fentress Co., TN	J. Hart
Quercus	falcata	141	XD	--	Knox County, TN	J. Hart and S. van de Gevel
Fraxinus	americana	136	XD	--	Coweeta Hyrdologic Laboratory, NC	S. Butler 2006
Quercus	coccinea	124	XD	511068	MOFEP Site 5, Shannon County Missouri	S. Voelker

Populus	grandidentata	113	XD	83-2	Good Harbor Plains, MI	T.C. Wyse, P.C. Goebel; ITRDB
Dirca	palustris	44	RC	--	MO	M. Stambaugh

Appendix C: Pith Indicators



Appendix D: Field Note Cards

Introduction

Various note cards can be used for efficient data collection in the field. Note cards are useful because they remind the researcher of the variety of information that can be collected from a site for a particular project and the enable uniform data collection for different research projects. The following pages present a variety of useful field note cards that can be photocopied or edited for personal use. I recommend printing these on card stock paper, so that they can stand up to hard use in the field and remain a more permanent collection of that field data. Many of the cards are made to be printed as half page cards with information provided for the front and the back. These cards are meant to be the starting point for your own cards that hold the information that you need for your particular project. The Core Collection chart and Fire History Sample Cards are modified from formats used by the University of Arizona Laboratory of Tree-Ring Research and the Dendrogeomorphology Sample Card is modified from Shroder 1978 and was used at the University of Nebraska.

Core Collections

Site :____________________ **Date :**______________ **Page :** __________________________

Field Crew : ____

Site Description:

Sample ID	X Coord	Y Coord	Coring Height	Species	Notes

Dendrogeomorphology Sample Cards

Species ______________________________

Collection Date ______________________________

Crown Density ______________________________

Lean Direction ______________________________

Lean Degree ______________________________

Lean Characteristics ______________________________

Height of Samples above base

A ____________ B ____________

C ____________ D ____________

Diameter at sample location

A ____________ B ____________

C ____________ D ____________

Section Orientation (azimuth, base side, crown side, etc.) ____________________

Specimen Number ______________________________

Site ID ______________________________

Field ______________________________

Lab ______________________________

Geomorphic Feature ______________________________

Collector ______________________________

Height of Tree ______________________________

Species Density ______________________________

Slope Direction ______________________________

Slope Degree ______________________________

Photo Data ______________________________

____

Drawing of tree (show sample locations and height of measurements).

Core or section data

A

B

C

D

Appendix E: Web Resources.

Please note that web address to frequently change. All attempts were made to make sure that all links in this appendix were operational when this book went to print. When encountering a bad address, please search the site name in a web search engine to find the page.

Site Name	Web Address
Bibliography of Dendrochronology	http://www.wsl.ch/dbdendro/ April 30, 2009
Dencroclim2002 Program	http://dendrolab.org/dendroclim2002.htm April 30, 2009
Eastern OLDLIST	http://people.eku.edu/pedersonn/oldlisteast/ April 30, 2009
Henri Grissino-Mayer's Ultimate Tree Ring Webpages	http://web.utk.edu/~grissino/ April 30, 2009
International Dendroecological Fieldweek	http://www.wsl.ch/fieldevent/ April 30, 2009
North American Dendroecological Fieldweek	http://dendrolab.indstate.edu/nadef/index.htm April 30, 2009
OLDLIST	http://www.rmtrr.org/oldlist.htm April 30, 2009
PRECON Program	http://www.ltrr.arizona.edu/webhome/hal/precon.html April 30, 2009
PRISM Data Set	http://www.prism.oregonstate.edu/ April 30, 2009
Voortech Company	http://www.voortech.com/projectj2x/docs/userGuide.htm April 30, 2009