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ISSN 2047-0371

4.2.8. Dendrochronology

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ABSTRACT: Dendrochronology is a dating technique that utilises the common growth signal in trees of the same species growing in the same area under similar conditions. Cross-dating is achieved by matching ring-width patterns between individual trees. Exact calendric dates can be produced for subfossil material if a temporal overlap exists with modern samples. The death and establishment of trees, as well as ring-widths and anatomical features in the wood, have been used to study past geomorphic episodes including mass movement activity, earthquakes, volcanic eruptions, fire, glacier movement, and flooding. In addition to providing high-precision dates for known disturbances, evidence from tree rings can help identify previously unknown events and be used to study the synchronicity of abrupt environmental changes across space. This paper summarizes the theory and practice of tree-ring dating and reviews its application in dendro-geomorphological research.

KEYWORDS: tree rings, chronology, cross-dating, Common Era, Holocene

Introduction

The growth of trees has attracted scientific interest for thousands of years. Theophrastus, a student of Aristotle, noted that stones forced into a tree became “hidden” with time (Studhalter, 1956), indicating that new wood is formed close to the exterior of the tree. Leonardo da Vinci is said to have discovered the annual nature of tree rings, as well as their connection to climate (Stallings *et al*., 1937). It was not until the early 20th century, however, that dendrochronology and tree rings as a dating method was fully developed into a science, largely through the works of A.E. Douglass (Douglass, 1919; Baillie 1982).

Dendrochronology has been used extensively in a range of scientific fields over the past 100 years, including archaeology (Baillie, 1982), ecology (Schweingruber, 1996), and palaeoclimatology (Fritts 1976). Tree rings provided calibration during the development of the radiocarbon dating because of their ability to record atmospheric carbon fluctuations with high dating resolution (Stuiver and Becker, 1993; Friedrich *et al*., 2004). Prehistoric artefacts have been dated, with annual and sometimes intra-annual precision, using dendrochronology (e.g. Visser, 2015). The relationship between climate variability and tree growth has facilitated continental to hemispheric reconstructions of drought and temperature (Cook *et al*., 1999; Esper *et al*., 2002), and tree rings have provided regional and local perspectives of past ecological and climatic shifts across the world (Swetnam and Betancourt, 1998; Salzer *et al*., 2009; Buckley *et al*., 2010). The high precision dating offered by dendrochronology can also be useful when measuring rates and timing of geomorphic processes (Strunk, 1997; Stoffel and Bollschweiler, 2008; Koprowski *et al*., 2010). Trees can be killed by geomorphic processes and/or become established on recently modified surfaces, and the time of death/germination will therefore serve as a temporal indicator of abrupt landscape change. Surviving trees can also record evidence of these events in the wood they form, and by establishing an absolute chronology for each tree ring it is possible to assign calendric dates to such markers.

Principles of dendrochronology

Trees cover approximately 30% of Earth’s land surface and are found on all continents except for Antarctica (Pan *et al*., 2013). The distribution of any given species is governed by the

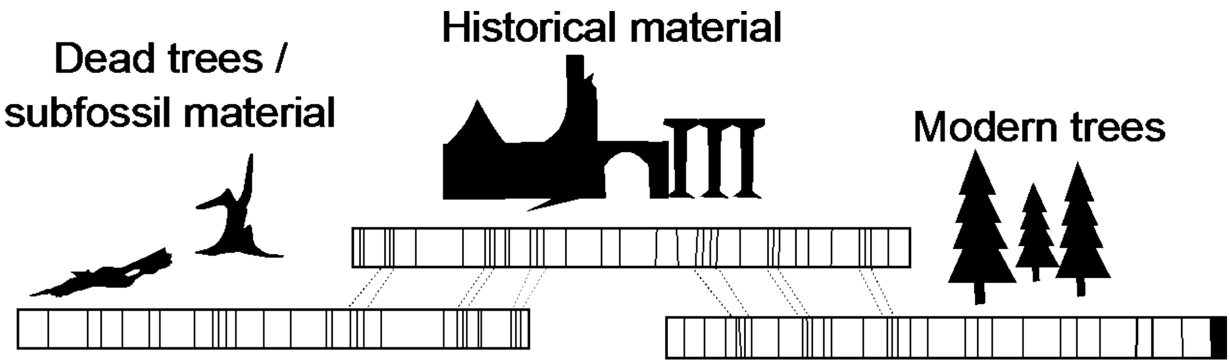

Figure 1: Schematic of matching ring-width patterns in overlapping series from different contexts.

conditions a tree can grow and reproduce under, known as the ecological amplitude of the species (Fritts, 1976). Trees can be divided into two main subgroups: angiosperms (flowering trees that include broad-leafs such as oaks and ashes), and gymnosperms (seed-producing trees that include all conifer species). Angiosperms generally require higher temperatures and precipitation totals than gymnosperms but there is considerable geographical overlap between the two (Woodward *et al*., 2004).

In regions where distinct seasonal climate forces plants into periodic dormancy, trees tend to form annual rings (Fritts, 1976). Radial growth is influenced by a range of factors including climate, soil, topography, and competition for resources with nearby trees (Cook, 1987). Individuals growing at the same site under similar conditions should therefore display similar year-to-year variability in growth. By comparing and matching ring-width patterns between trees it is possible to cross-date each ring in a given set of samples (Stokes and Smiley, 1968). Trees growing at the edge of the species' ecological amplitude show stronger coherence in inter-annual growth and thus have higher potential for dendrochronological dating.

The outermost ring in a living tree represents the most recent growing season (if sampling a Northern Hemisphere tree in January 2015, the outermost ring will correspond to the growth of 2014) and becomes an "anchor" in time for preceding patterns of growth. Cross-dating thus allows for the assignment of absolute calendric dates for every ring in samples recovered from dead trees and timbers (Figure 1), provided that there is a temporal overlap in ring patterns and that the growth forcing common to all sampled is strong enough. In addition to sequences of narrow and wide rings, samples can also be matched by comparing distinctive anatomical features in the wood such as frost damage and light-coloured latewood bands (Filion *et al*., 1986; Schweingruber *et al*., 1990).

Sampling and processing

Field methods

Material collected for dendrochronology can be divided into two main categories: increment cores and cross-sections (or parts of cross-sections) (Stokes and Smiley, 1968). The least destructive method to obtain tree-ring samples is coring the tree with an increment borer, a tool designed to extract a small core (Figure 2) without inflicting significant mechanical injury to the tree (van Mantgem and Stephenson, 2004).

Figure 2. An increment core is extracted from an Abies magnifica *tree at Lassen Volcanic National Park, California.*

In general, coring should be done at a right angle on a section of wood that does not contain distorted growth (Stokes and Smiley, 1968). The borer should be aimed at what is believed to be the pith of the tree in order to maximize the number of rings sampled and to ease the subsequent analysis (Figure 3). More than one core is usually collected because of locally absent rings (LARs, or "missing" rings; St. George *et al*., 2013) and extra "false" rings (Schweingruber, 1996). Depending on the objective of the study, coring close to visible injuries may be appropriate (Stoffel and Bollschweiler, 2008).

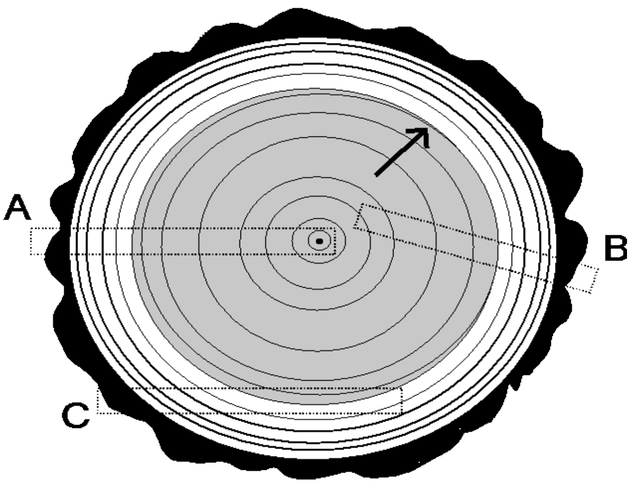

Figure 3: Placement of: (A) an increment core that includes all elements of radial growth (pith, heartwood (grey), sapwood (white), and bark); (B) a core with a locally absent ring (arrow), as well as missing pith; and (C) an off-centred core of little dendrochronological value.

Cross-sections are taken perpendicular to the stem with a manual saw or chainsaw, they provide tree-ring information across the whole circumference of growth. Unless the tree is rotten at the centre, cross-sections also guarantee that the full number of rings (from pith to bark) is present in the sample. However, collecting cross-sections from living trees means killing the tree, and the practice should be reserved for fallen/dead trees. Furthermore, the volume and weight of cross-sections can become an issue when sampling remote locations. Taking a 'wedge' or 'plunge' cut (Arno and Sneck, 1977) is a compromise and frequently done when studying fire history through tree rings (Swetnam, 1996; Kipfmueller and Baker, 2000).

Sample preparation and cross-dating

After collection, samples are air-dried before mounted on wooden platforms for stability. The surface of cores is prepared using a scalpel or sandpaper of progressively finer grade until a fine polish is achieved. The use of a planer and belt-sander can ease preparation of large cross-sections. For subfossil materials, rubbing powdered chalk into prepared surfaces can improve the clarity of ring boundaries (Pilcher *et al*., 1995), and the use of rubbing alcohol can similarly help define rings in burnt samples.

A simple ring count can produce an inaccurate age for individual rings because of the possible presence of LARs and/or "false" rings in a core or cross-section, and checking samples against each other is therefore required to establish true dates. There are several approaches to cross-dating, including skeleton plotting (Stokes and Smiley, 1968), the list method (Yamaguchi, 1991), and the memorization method (Speer, 2010). Common for these techniques is the use of "event" and "pointer" years (or marker rings/years). Event years are those years for which a tree displays abnormal or conspicuous growth in terms of width or structure (Figure 4; Schweingruber *et al*. 1990). A year is labelled a pointer year when a group of trees display event years in the same year, and the pointer years aid in the assignment of dates to samples of unknown age.

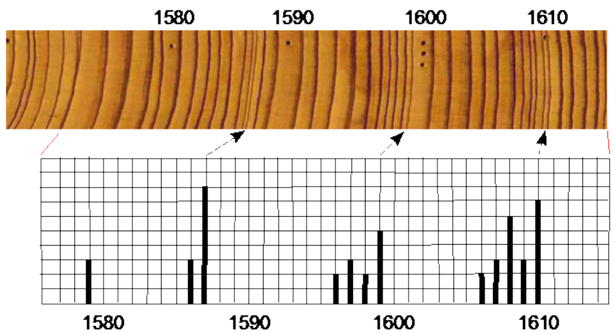

Figure 4: An example of event years (below) in a Taxodium distichum *sample (above) from Blackwater River, Virginia. Note the narrow ring in 1587, and the sequence of five consecutive narrow rings between 1606 and 1610.*

When absolute dates have been assigned to each ring in a sample, ring-widths are measured. A sliding stage paired with a microscope is commonly used, but high-resolution scans of the core or cross-section surface can be used together with computer software such as WinDendro (Regent Instruments Canada Inc., 2009). However, a microscope is recommended when studying species with low growth rates as some finer features of the samples can be missed due to limited scanning resolution (Maxwell *et al*., 2011).

Statistical testing of dates produced by cross-dating can be performed by analysing measurements in COFECHA (Holmes, 1983). The averaging of measurements and construction of a 'master' chronology can be done in ARSTAN (Cook 1985). There are several other computer packages for tree-ring analysis, including dplR for the R language environment (Bunn, 2008) and David Meko's 'Tree-Ring MATLAB Toolbox'. A master chronology can be used to date samples from dead trees (Figure 5). The frequency of LARs varies over space and species boundaries (St. George *et al*., 2013), and for some study regions it is sufficient to count and measure rings and produce absolute dates based on statistical analysis (Baillie, 1982; Holmes, 1983). The minimum number of overlapping years required to provide an absolute date varies depending on species and strength of the common signal (Yamaguchi, 1986), where there are few overlapping rings short sequences of tree rings may cause spurious and incorrect matches (Hillam *et al*., 1987).

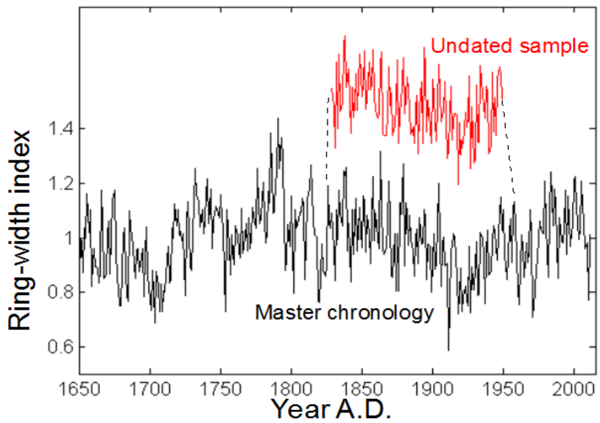

Figure 5: Alignment of a sample of unknown date (a floating chronology) with a local master chronology to produce calendric dates.

The inner-ring date of a sample only provides the age for above where the core was taken, and to identify the total tree age the number of years' growth below the core must be added (Schweingruber, 1996). Hence, coring close to the root crown is recommended in order to minimize the uncertainty of establishment dates (McCarthy *et al*., 1991).

Applications in geomorphology

Landslide and rockfall events

The notion that trees can record evidence of landslides and debris flows dates back to the late 19th century (McGee, 1893). Such events can cause scarring and death, but also create new surfaces for tree establishment (Shroder, 1979; Stoffel *et al*., 2006). Furthermore, mass movements will have direct or indirect effects on the growth rate of nearby trees (Schweingruber, 1996; Stoffel *et al*., 2006). Partial burial, loss of limbs, or decapitation will cause abrupt growth reductions, and the tilting of stems can cause eccentric growth (leading to the formation of reaction wood in the downslope side of conifers and tension wood in the upslope side of broad-leafed trees) on the tree's downslope/upslope side (Panshin and de Zeeuw, 1970; Stoffel, 2008). Trees left unharmed will benefit from the death of neighbouring trees through less competition for resources and their radial growth rate will increase (Schweingruber, 1996). Rockfall activity can have similar effects but unlike debris flows and landslides, during which large masses of material have a uniform impact on a given area, rockfalls will affect the landscape discretely (Stoffel and Perret, 2006). Some tree species respond to mechanical wounding by increased resin flow in the stem (Ruel *et al*., 1998). Traumatic resin ducts (TRDs; Figure 6), often formed in the growth ring near an injury, can provide evidence of past debris flows and rockfall activity (Bollschweiler *et al*., 2008), including events that are not recorded in other proxies (Stoffel, 2008). Because a range of other factors can cause TRDs (Schweingruber, 2007; Sheppard et al., 2008), thresholds may need to be established in order to identify geomorphic events (Stoffel *et al*., 2005).

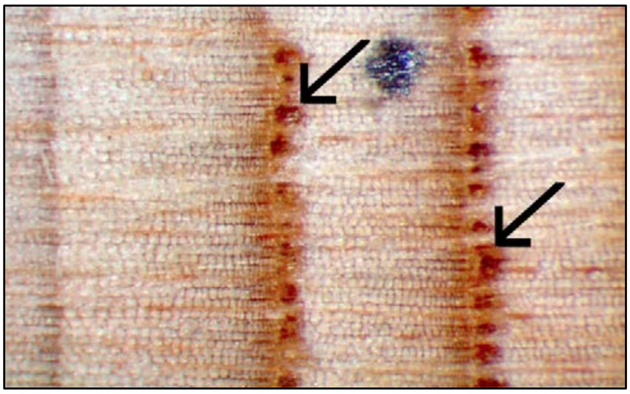

Figure 6: Traumatic resin ducts (arrows) in Abies magnifica *from Crater Lake, Oregon. Growth left-to-right.*

Tree selection and sampling strategies are particularly important for the study of landslides, debris flows, and rockfalls (Trappmann and Stoffel, 2013; Corona *et al*. 2014). Stoffel *et al*.

(2013) present an excellent guide on field sampling for studying mass movements through tree rings. Large sample sizes from a confined area will not only allow for the dating of individual events but can also provide spatial and temporal patterns of rockfall activity over time, which can in turn inform hazard management (Stoffel *et al*., 2005; Corona *et al*., 2014).

Glaciology

The establishment of trees can be used to date moraines and other glacial deposits (Luckman, 1988). Germinating trees from nearby areas will colonize a surface as it becomes ice-free and able to sustain vegetation (Sigafoos and Hendricks, 1969). The pith of the oldest tree on a landform will therefore produce a minimum age for the most recent glacial retreat in that area (Lawrence, 1950). Sampling several locations on a glacial forefield can provide rates for ice front-recession over time (Smith *et al*., 1995; Winchester *et al*., 2014). However, the lag-time between glacial recession and successful tree establishment (or ecesis) must be considered (Lawrence, 1950; McCarthy and Luckman, 1993). If similar changes have occurred during periods for which satellite imagery or historical photographs exist, an ecesis interval can be estimated (McCarthy and Luckman 1993; Winchester *et al*., 2014).

Dating glacial retreats though tree rings is often done in combination with lichenometry to minimize the uncertainties associated with either method (Karlén, 1984; Smith *et al*., 1995; Winchester and Harrison, 2000; Wiles *et al*., 2002; Reyes *et al*., 2006; Trenbirth, 2010).

Together, it is postulated that the two dating methods can provide sufficiently high temporal resolution of glacial activity to allow comparison with paleoclimatic proxies (Luckman, 1993; Mood and Smith, 2015) and to aid reconstruction of past mass-balances (Wood *et al*., 2011). Glacial advances have also been dated through dendrochronology (e.g. Nicolussi and Schlüchter, 2012).

Seismology

The impact of earthquakes on vegetation is multifaceted (Page, 1970). Trees may fall over and/or be buried by rapid sedimentation or landslides activated by the seismic activity (Jacoby, 1997). The apparently sudden death of trees along the West Coast of United States has been linked to a large Cascadia earthquake at A.D. 1700 (Atwater and Yamaguchi, 1991; Jacoby *et al*., 1995). In areas with extensive landslide activity, tree-ring dating can show synchronicity across space, and highlight events of great magnitude. The precision of dendroseismology allowed Filion *et al*. (1991) to attribute two landslides in eastern Canada to a 1663 earthquake.

Abrupt changes in growth rates following an earthquake have been observed in several studies across different forest ecosystem (Jacoby *et al*., 1988; Veblen *et al*., 1992; Bekker, 2004). The ecology and topographic setting of the species studied is of importance because trees can have opposite excursions of growth in response to the same event (Stahle *et al*., 1992).

Volcanic events

Tree rings have been used to date major and minor volcanic eruptions for periods when observations are sparse or non-existent. During large events, gases and dust particles from the volcano will reach the atmosphere and influence climate on a global scale by limiting incoming solar radiation (Rampino and Self, 1982). Subsequent cooling can affect trees either over a full growing season causing low growth over the year or through frost damage caused by a late frost at any point of the growing season (Figure 7).

LaMarche and Hirschboeck (1984) recorded frost rings in *Pinus longaeva* trees in the western United States during years of known eruptions. Using tree-ring density chronologies, Briffa *et al*. (1998) were able to show the impact of major volcanic events on periods of cooling in the Northern Hemisphere since the 1400's. The synchronous effect on high latitude or high altitude trees has since been demonstrated for the past 5000 years, with the tree-ring record displaying high correlation with volcanic events identified in the Greenland ice cores (Salzer and Hughes, 2007).

Eruptions with less pronounced impacts can also be dated if local samples exist (Biondi *et al*., 2003). Subfossil materials from Kamchatka, Russia, have been used to date an eruption of the Shiveluch volcano to 1756-58 (Solomina *et al*., 2008). Pyroclastic surges caused by the 1842-43 eruption of Mount St. Helens, Washington, are thought to explain the anomalous series of narrow rings in nearby trees (Yamaguchi and Lawrence, 1993). In addition to ring-widths, variations in the chemistry of individual growth rings may also contain information on past volcanic activity (Pearson *et al*. 2005). Cinder cone eruptions have shown to increase Na, S, and P in rings of adjacent trees (Sheppard *et al*., 2008; 2009). Thus, the chemical composition of wood can be used to strengthen the interpretation of ring-width anomalies and dating produced by cross-dating, or even to identify the source of eruption (Pearson *et al*., 2009).

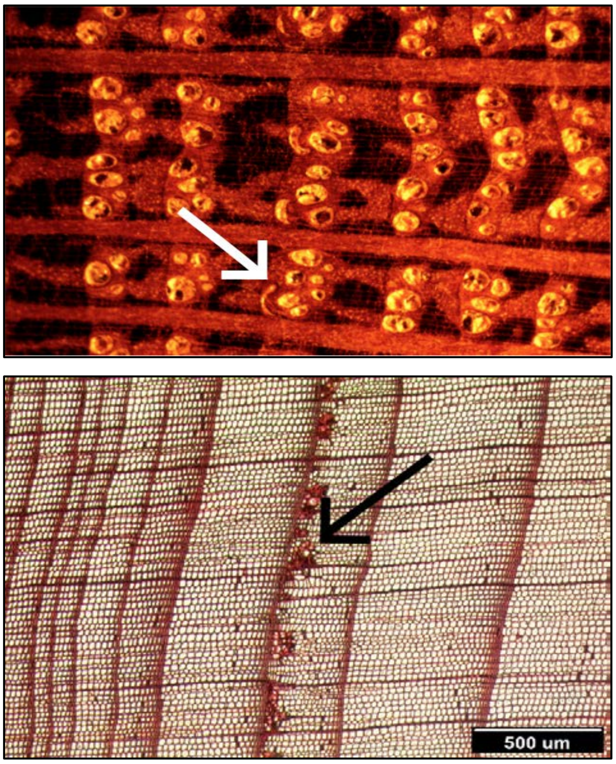

Figure 7: Frost damage (arrows) during the early growing season of year 1826 in Quercus alba *from Arkansas (top), and* Juniperus virginiana *from Oklahoma (bottom). Growth left-to-right. Photos courtesy of the Tree-Ring Laboratory, University of Arkansas*.

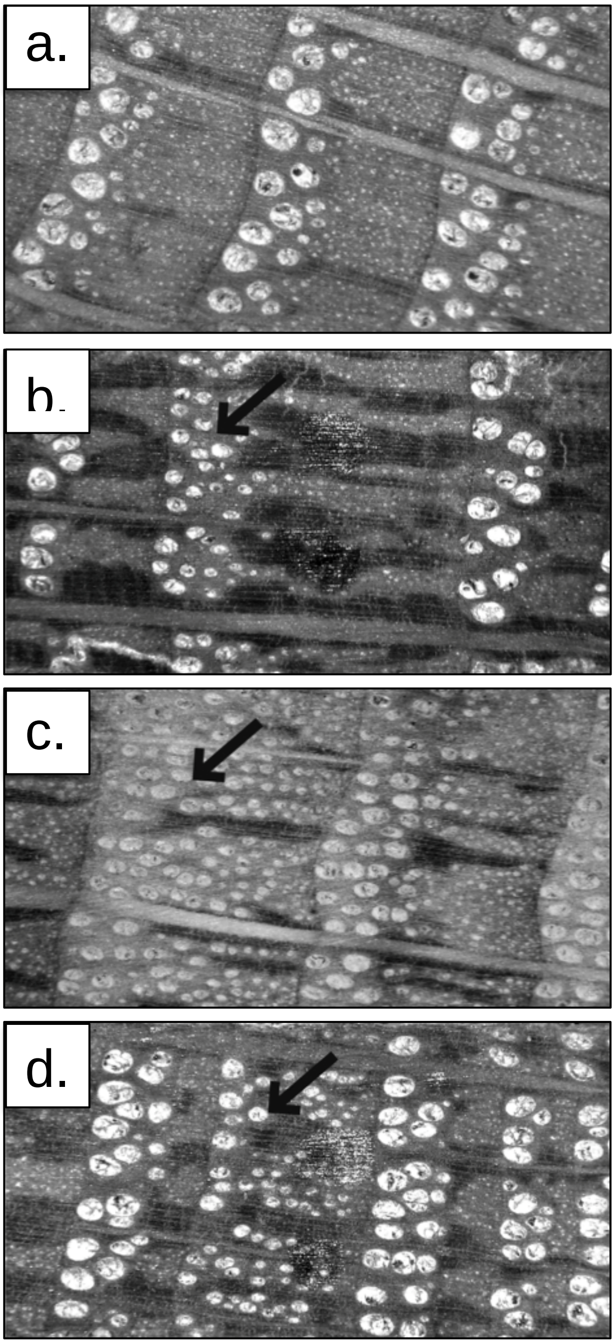

Figure 8. (a) Normal growth rings in Quercus macrocarpa*, with large vessels in the earlywood, (b) shrunken earlywood vessels, (c) earlywood vessels extending into the latewood, and (d) both shrunken and extending vessels. Growth left-to-right. Photos courtesy of Dr. Scott St. George.*

Flooding

Flood events can cause distinct anatomical features in the wood of rings formed during inundation (Schweingruber, 2007). Yanosky (1983; 1984) studied *Fraxinus americana* and *F. pennsylvanica* on the Potomac River, Washington D.C., and noted that there were considerably larger cells in the latewood of 1972 than in any other year. This year coincided with the third largest flood on record, and as Yanosky looked further back in time the growth features occurred in many other known flood years and they were therefore dubbed ‘flood rings’. More recently, anatomical signatures of flood in *Quercus macrocarpa* have been identified, including shrunken earlywood vessels and earlywood vessels extending into the latewood (St. George *et al*., 2002; Wertz *et al*., 2013; Figure 8). The use of older wood material from historical buildings and subfossil deposits has allowed the reconstruction of a flood history for Red River, Manitoba, extending further back in time than observational data (St. George and Nielsen, 2000). Sampling trees from different locations can also produce a spatial reconstruction of flood extent. Although the most successful studies have used ring-porous broad-leaf species, conifer softwoods are also known to exhibit features attributable to floods (Yamamoto *et al*., 1987; Ballesteros *et al*., 2010).

Caveats and considerations

Although the vast majority of tree species outside the tropics form annual rings, not all show coherent inter-annual growth variability across space and these are therefore not suitable for cross-dating exercises. An extensive list of species and their usefulness in dendrochronology is provided by Grissino-Mayer (1993). The temporal range to which trees can be dated also differs depending on species and region. In areas where subfossil or archaeological materials do not exist, the germination date of the oldest living trees becomes the limit to which a sample can be dated. Although the trees of some species can live for several millennia (Brown, 1996), tree-ring chronologies that date back over 1000 years are rare outside the southwestern United States (St. George, 2014). Over 2500 tree-ring chronologies from across the world are publically available through the International Tree-Ring Data Bank (Grissino-Mayer and Fritts, 1997). However, tree rings can still provide valuable chronological information even when there are no possibilities of calendric dates. Cross-dating between samples can indicate synchronicity over space, and samples of annual tree-growth can facilitate the 'wiggle-matching' of radiocarbon dates (Bronk Ramsey, 2009).

Some samples may not contain every ring from pith to bark because of poor preservation or sampling difficulties. This can be detrimental when assigning death and/or germination dates of trees. Where a core does not reach the pith, the curvature of the innermost rings can be used to estimate pith position and the number of rings not present (Applequist, 1958; Wong and Lertzman, 2001). If bark is not present, death dates can be estimated based on the number of sapwood rings still attached to the sample (Baillie, 1982; Hillam *et al*., 1987). Sapwood is more susceptible to decay over time (Panshin and de Zeeuw, 1970), thus the outer rings of trees were sometimes removed from timber used in historic buildings (Baillie, 1982) and in cases where no sapwood is present it is only possible to produce a *terminus post quem*.

Conclusions

Shared year-to-year variability in ring-width allows for the assignment of calendric or cross-dates to sequences of tree rings. Dendrochronology does not only offer the potential of unrivalled dating precision but can also inform researchers about the spatial extent of past landscape change. The temporal range for which trees can be useful varies between study areas but trees grow to be over 200 years old in most regions. When subfossil or historical material is available it is possible to use tree rings for dating on considerably longer timescales. Because signs of geomorphic processes recorded in trees can be caused by several different factors, it is recommended to use multiple lines of evidence, including death and establishment, abrupt changes in growth rate, anatomical features, and in some cases chemical composition. Correctly used and in combination with other sources of information, dendrogeomorphology can be a powerful tool for understanding the processes that form the landscapes around us.

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