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32

An Evaluation of Fire Regime Reconstruction Methods

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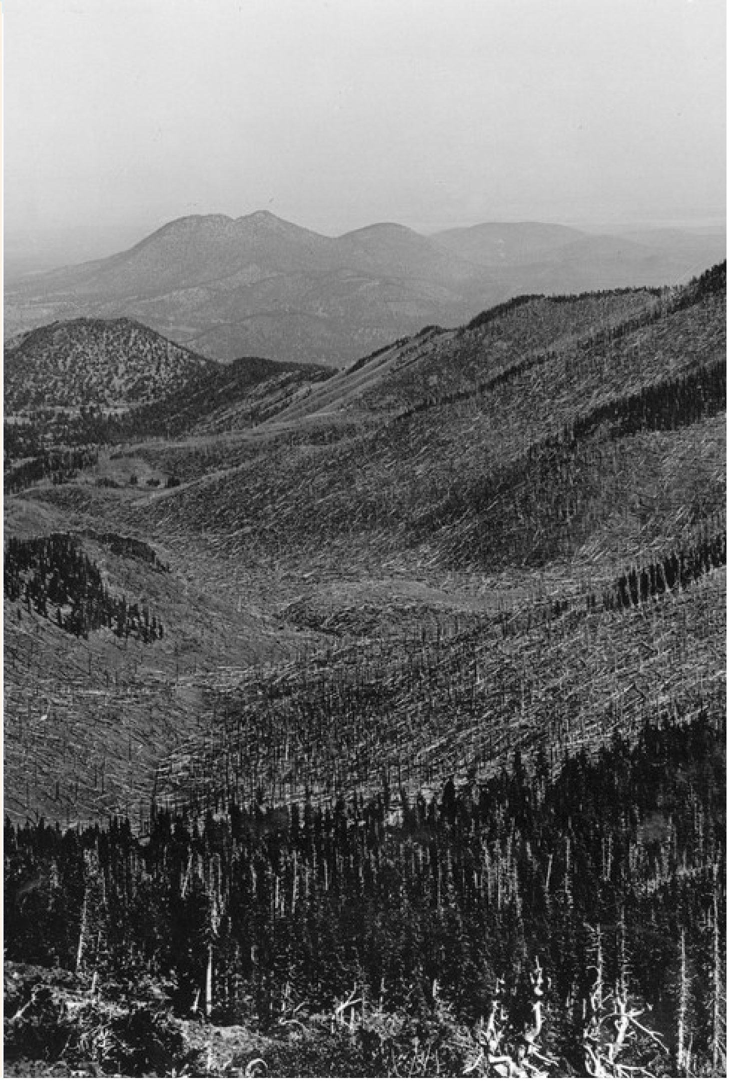

NORTHERN ARIZONA UNIVERSITY

Ecological Restoration Institute

SOUTHWEST FIRE SCIENCE CONSORTIUM

Intermountain West Frequent-Fire Forest Restoration

Ecological restoration is a practice that seeks to heal degraded ecosystems by reestablishing native species, structural characteristics, and ecological processes. The Society for Ecological Restoration International defines ecological restoration as “an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability….Restoration attempts to return an ecosystem to its historic trajectory” (Society for Ecological Restoration International Science and Policy Working Group 2004).

Most frequent-fire forests throughout the Intermountain West have been degraded during the last 150 years. Many of these forests are now dominated by unnaturally dense thickets of small trees, and lack their once diverse understory of grasses, sedges, and forbs. Forests in this condition are highly susceptible to damaging, stand-replacing fires and increased insect and disease epidemics. Restoration of these forests centers on reintroducing frequent, low-severity surface fires—often after thinning dense stands—and reestablishing productive understory plant communities.

The Ecological Restoration Institute at Northern Arizona University is a pioneer in researching, implementing, and monitoring ecological restoration of frequent-fire forests of the Intermountain West. By allowing natural processes, such as low-severity fire, to resume self-sustaining patterns, we hope to reestablish healthy forests that provide ecosystem services, wildlife habitat, and recreational opportunities.

The Southwest Fire Science Consortium (SWFSC) is a way for managers, scientists, and policy makers to interact and share science. SWFSC’s goal is to see the best available science used to make management decisions and scientists working on the questions managers need answered. The SWFSC tries to bring together localized efforts to develop scientific information and to disseminate that to practitioners on the ground through an inclusive and open process.

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Cover Photo: Historical photos like this one, which shows evidence of a large severe fire in spruce and aspen forests on the San Francisco Peaks near Flagstaff, AZ, taken in 1910, can provide rich historical information, but they are typically “snapshot” images, meaning that changes over time are not documented. A combination of methods used together is the strongest approach to reconstructing historical fire regimes. *Photo courtesy of USDA Forest Service, fs.usda.gov*

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Introduction

Reconstruction of Fire Regimes

Fire is a fundamental disturbance process in ecology and has been a powerful agent of change in terrestrial ecosystems for millions of years. Understanding the role of fire on a landscape is critical for managing fire and forests for biodiversity, ecosystem function, and resilience to changes in climate. To better understand the role fire can play in forests today, researchers and managers have found it useful to reconstruct attributes of historical fire regimes before the onset of fire exclusion. Fire exclusion in the southwestern United States often occurred in the late 1800s, when activities such as grazing of domestic animals, logging, and fire suppression began on a widespread scale.

Information about past fire regimes can be a helpful reference to guide and inform land managers about current and future fire regime characteristics, patterns, and forest structure characteristics. Management activities that benefit from understanding past fire regimes include prescribed fire, managed wildfires for resource benefit, and mechanical treatments to reduce fire risk. Six fire regime attributes are often considered:

- Frequency: how often fires occur in a given area or region (see Box 1 for more detailed frequency terminology)
- Seasonality: time of year
- Severity: ecological effects of fire
- Type: surface or crown fire
- Size: area burned
- Spatial complexity: pattern of severity within fire perimeter

Fire intensity, which is a measure of the heat of a fire, is a seventh fire regime attribute that cannot be reconstructed directly but is inferred from fire severity. Fire severity refers to the ecological effects of fire and is often quantified by overstory tree mortality. Each fire regime attribute can be characterized by an average condition (for example, an average fire frequency of 8 years) as well as a measure of variation (for example, a range in fire frequency of 2 to 20 years).

This working paper discusses several methods for reconstructing historical fire regimes:

- Historical documents and photos
- Dendrochronology: fire-scar data
- Dendrochronology: tree age, death and growth data
- Forest structure data
- Plant traits
- Charcoal

Each of these methods will be discussed in terms of advantages, disadvantages, inherent uncertainties, and assumptions as well as temporal and spatial precision. The potential value and limitations for reconstructing historical forest structure and composition with each method are also briefly covered.

Identifying the Best Available Historical Data

Scientific work can be evaluated for quality based on a few key characteristics. Confidence in scientific work can be based on the type, amount, quality, and consistency of evidence, as well as the degree of agreement of the evidence (Mastrandrea et al. 2010). "Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence" (Mastrandrea et al. 2010).

Two kinds of evidence will be discussed in this working paper: direct and indirect evidence. Direct evidence is a measurement of the actual subject of interest. For example, temperature can be measured with a thermometer; therefore a thermometer reading is direct evidence of temperature. Indirect evidence requires an assumption; it is not a measurement of the actual subject of interest but it is a measure of something related. For example, frost-killed tomatoes are indirect evidence of temperature; if the tomatoes have frost damage, we have evidence (we can ***infer***) that temperatures were below freezing.

Assumptions should be considered and a best estimate of the level of confidence should be developed for any assumption. It is particularly important to evaluate assumptions if the overall results of a study rest heavily on those assumptions. Uncertainty levels, both for assumptions and for the results, can be quantitatively or qualitatively assigned (Mastrandrea et al. 2010).

Box 1. How often do fires occur?
Fire frequency definitions (from Agee 1993).

Fire frequency: a general term referring to the recurrence of fire in a given area over time

Fire event (fire occurrence, fire incidence): a single fire or series of fires within an area at a particular time

Fire interval (fire-free interval or fire-return interval): the number of years between two successive fire events in a given area

Mean fire interval (mean fire-return interval): arithmetic average of all fire intervals in a given area over a given time period

Fire rotation (natural fire rotation): the length of time necessary for an area equal in size to the study area to burn

Box 2. For more information about concepts and applications of historical ecology, generally and in the Southwest, see the following sources:

Balee, W. 1998. Advances in historical ecology. Columbia University Press, New York.
Crumley, C. 1994. Historical ecology: Cultural knowledge and changing landscapes. School of American Research Press, Santa Fe, NM.
Egan, D. and E. Howell. 2001. The historical ecology handbook: A restorationist's guide to reference ecosystems. Island Press, Washington, DC.
Friederici, P. 2004. Establishing reference conditions for southwestern ponderosa pine forests. Ecological Restoration Institute Working Paper 7. Ecological Restoration Institute, Flagstaff, AZ.
Kaufmann, M.R., L.S. Huckaby, C.M. Ragan, and J. Popp. 1998. Forest reference conditions for ecosystem management in the Sacramento Mountains, New Mexico. USDA Forest Service, RMRS-GTR-19. USDA Rocky Mountain Research Station, Fort Collins, CO.
Larson, A.J., and D. Churchill. 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. *Forest Ecology and Management* 267: 74–92.
Moore, M.M., W.W. Covington, and P.Z. Fulé. 1999. Reference conditions and ecological restoration: A southwestern ponderosa pine perspective. *Ecological Applications* 9: 1266-1277.
Rackam, O. 1980. Ancient woodland: Its history, vegetation and uses in England. Edward Arnold, London, England.
Sheil, J. 1980. Historical ecology: The documentary evidence. Institute of Terrestrial Ecology, Cambridge, England.
Smith, H.Y. and S.F. Arno. 1999. Eighty-eight years of change in a managed ponderosa pine forest. USDA Forest Service, RMRS-GTR-23. USDA Rocky Mountain Research Station, Ogden, UT.
Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1999. Applied historical ecology: Using the past to manage the future. *Ecological Applications* 9: 1189-1206.

Historical Documents and Photos

Historical photos and documents, including timber company records, personal diaries, and expedition notes, can be valuable for understanding historical fire regimes because they provide written or visual evidence of conditions as people experienced them before the effects of fire exclusion changed forests throughout much of the Southwest. An example is an excerpt written by Lt. Edward Beale in 1857 during an expedition in northern Arizona: "... A vast forest of gigantic pines, intersected frequently with open glades, sprinkled all over with mountains, meadows, and wide savannahs, and covered with the richest grasses, was traversed by our party for many days" (Bell 1870). Example photos are shown in Figure 1. Although historical documents and photos can provide rich historical information about a place, they are typically "snapshot" descriptions or images, meaning that changes over time are not documented. One exception is when repeat photography is available (Webb et al. 2010).

Fire ***frequency***, unless it is directly described in a historical document, must be inferred from descriptions or images of forest structure or fire severity. Old, large, widely-spaced trees, with or without fire-scar catfaces, likely experienced low-severity, high-frequency fire. Even-aged, densely spaced trees or places that were

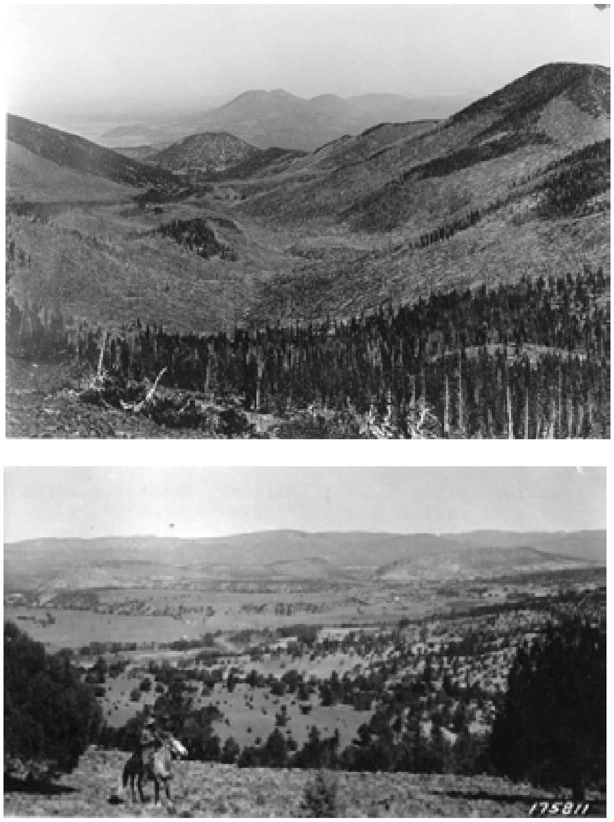

Figure 1. Top: Photo showing evidence of large severe fire in spruce and aspen forests, San Francisco Peaks, near Flagstaff, AZ, 1910. Bottom: Photo showing grasslands and scattered juniper trees, Reserve Valley, Apache National Forest, 1923. *Source of photos: fs.usda.gov.*

photographed after high-severity fire, such as in the top photo in Figure 1, likely experienced infrequent but more high-severity fire. Any inferences about fire frequency from historical documents and photos are likely to have moderate to high degrees of uncertainty.

Most historical documents and photos are unlikely to provide information about historical fire ***seasonality***, unless the season is directly mentioned in the text. Often fire ***type*** or ***severity*** is referred to in a historical document, and fire type and severity can also be seen in some historical photos. Fire type and severity can also sometimes be inferred from forest structure seen or described in historical documents and photos. Fire ***size*** is usually not possible to reconstruct with this method. Photos may not show the extent of a fire, or low-severity fire evidence may not be visible at a distance. Writers rarely explored forested areas thoroughly enough to be able to report fire sizes. A classic exception was F.E. Clements, who, in 1910, wrote a fairly thorough description of recent fires in lodgepole pine in Colorado (Clements 1910). It is also unlikely and rare that ***spatial complexity*** of historical fire regimes can be reconstructed from historical documents and photos.

Length of Reconstruction, Temporal Precision and Spatial Resolution

Historical documents and photos in the Southwest are available from the time when Europeans began exploring and living in the region. Except for documents associated with Spanish colonization, typically the earliest records are from the late 1800s and early 1900s. Temporal precision of fire evidence from historical documents and photos varies widely, from precise dates of fires published in newspapers (Bahre 1991) to descriptions of forests which contain a mention of a fire sometime in the past. For example, charred bark, which may be described in written documents or captured in photos, can last for many years on live trees. In terms of spatial resolution, photos often give a broad, landscape-scale view of a particular place, but detail is difficult to see on landscape-scale photos. Written documents vary in their spatial resolution, from travelers describing a specific place or route to a general description of a region.

Forest Structure and Composition

Written documents as well as photos can provide information about forest density and species. Good information can be found in surveys of early national forests (Leiberg et al. 1904, Lang and Stewart 1910, Woolsey 1911). However, many other historical documents and photos are limited to the places settlers and explorers happened to visit and document, they usually are not quantitative in nature, and qualitative descriptions of forests in historical documents can be interpreted in different ways. In addition, the authors of reports may have had biases or poor skill level in identifying species or characterizing forest density (Edmonds 2001).

Historical photos and documents may be most useful as supporting lines of evidence when combined with other methods of fire regime reconstruction.

Dendrochronology: Fire-scar Data

Fire scars are injuries formed in tree boles by exposure to heat from wildfire (Fig. 2). The injuries are formed when a fire kills a portion of a tree's cambium. Following the formation of a fire scar, the uninjured portion of a tree's cambium continues to grow and can begin to grow over the injury. Fire scars can be used to date exact years of fires and sometimes the seasons of past fires as well. Fire-scarred sections of live trees, stumps, snags or logs are sampled in the field and analyzed in the laboratory to determine precise years of historical fires.

Historical fire ***frequency*** can be easily calculated using fire scars (see Box 1). In a general sense, this is done by determining the specific years that fires scarred trees and then averaging the intervals between the scars. See Swetnam and Baisan (1996) for a good description of fire-scar data compilation and statistical description.

Critiques of fire-scar methods (Johnson and Gutsell 1994, Baker and Ehle 2001) have focused on the way fire frequency statistics are calculated from fire-scar

Figure 2. Top: multiple fire scars seen in a "catface" on a living tree. Bottom: sample showing multiple fire scars recorded in the wood of a tree, datable to the year and sometimes the season of a fire.

dates. Mean fire interval calculations can be strongly influenced by the area sampled (Falk et al. 2007) as well as how many samples are collected. The more area that is searched or the more samples collected, the more fire dates will likely be found, as more small fire dates are picked up. Therefore it is important to understand the area and sample basis for reported mean fire interval statistics, especially when comparing statistics among studies or designing fire and forest management practices. Partially to address these issues, most recent fire-scar-based fire history studies report "filtered" mean fire intervals, which are intervals between more widely represented (widespread) fire dates. For example, researchers often report fire intervals between fire scars represented on at least 10% or 25% of recording samples (Swetnam and Baisan 1996; Fig. 3). This technique usually eliminates fire-scar dates that appear on only one or a few trees, and filtered fire interval statistics are relatively immune to changes in area or sample size (Van Horne and Fulé 2006). Another issue is whether the interval between the pith date of a tree and the date of the first fire scar should be included as a fire-free interval when calculating mean fire interval, with some arguing that small trees do not survive fire well and therefore must not have encountered fire until the first scar was formed (Baker and Ehle 2001). However, most trees are not scarred by surface fires; the lack of a scar on a tree cannot be used to indicate lack of surface fire around the tree. This issue affects the determination of fire frequency, since including the interval between the pith date and the first scar would tend to lengthen the mean fire interval calculated in most cases. Most researchers do not include the interval between pith dates and first scars in their calculations.

Another critique of fire-scar-based methods for reconstructing fire history is that researchers tend to collect samples in areas where fire-scarred trees are abundant. If researchers focus on areas with high numbers of fire-scarred trees, they might be bypassing areas that historically experienced high-intensity stand-replacing fires, which today would have few or no fire scars.

Finally, researchers typically collect samples from trees that have the largest number of fire scars. It has been argued that this "targeted" method of sampling is biased; it may result in a focus on trees or areas that burned more frequently than the average in the region. However, tests of this question in southwestern forests have shown that targeted sampling is the most efficient way to arrive at the same answer that random sampling would provide, with many fewer samples collected (Van Horne and Fulé 2006, Farris et al. 2013).

Using the position of a fire scar within an annual growth ring allows dendrochronologists to determine the approximate ***season*** that a fire occurred. Scars in the early part of an annual ring are formed early in the growing season and scars in the later part of an annual ring are formed late in the growing season.

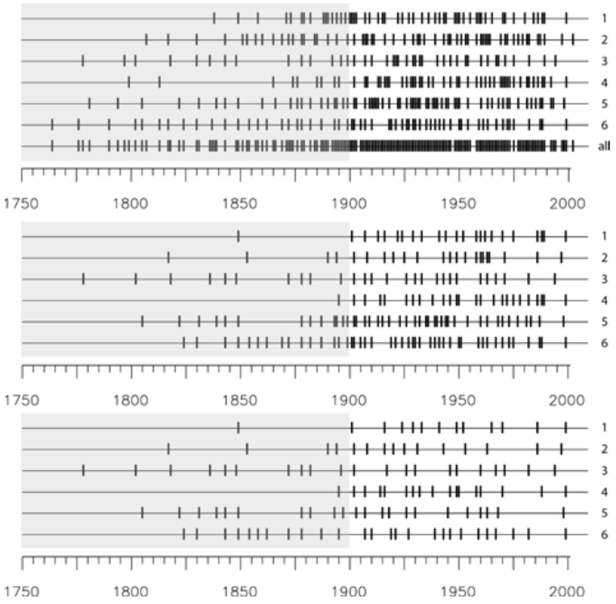

Figure 3. Example of "filtering" to eliminate fire scars represented on one or few samples. Shown are fire charts from six different sites. Horizontal lines represent sites and vertical dashes represent fires. Top: all fires in each site and in all sites combined. Middle: years when a minimum of two samples were scarred in each site. Bottom: years when a minimum of 25% of recording samples and a minimum of two samples were scarred. Filtered fire interval statistics are relatively immune to changes in area or sample size. *From Yocom and Fulé 2012.*

More specific timing of fire scar formation can be reconstructed if the timing of annual growth is known for a given species, region, and elevation. Seasonality often is determined for the majority but not all fire scars in a given study.

Fire scars can be used to reconstruct ***type*** and ***severity*** of fire. They are most often used to reconstruct low-severity surface fire regimes because the presence of a fire scar is an indication of low-severity fire at the scale of a tree; a fire injured but did not kill the tree. Where several trees are scarred by low-severity fire in the same year, it is inferred that a fire was a low-severity fire throughout the area, including in the spaces between the fire-scarred trees. Fire scars can also be used to supplement evidence of stand-replacing fires in crown fire regimes. For example, in Rocky Mountain National Park, fire scars were sampled around the edges of even-aged stands (the result of past stand-replacing fires) to verify the dates of those stand-replacing fires (Sibold et al. 2006).

Fire scars are "point-specific" evidence that a fire in the past occurred exactly where the tree is located (Swetnam and Baisan 1996). Fire scars usually cannot be used to reconstruct with certainty the ***size*** of fires that burned in the past, because "absence of evidence is not evidence of absence"; fires do not scar every tree within a fire perimeter, and some fires may burn few or no trees (Swetnam and Baisan 1996). In addition, fire-scar evidence of past fires can rot away or burn up in

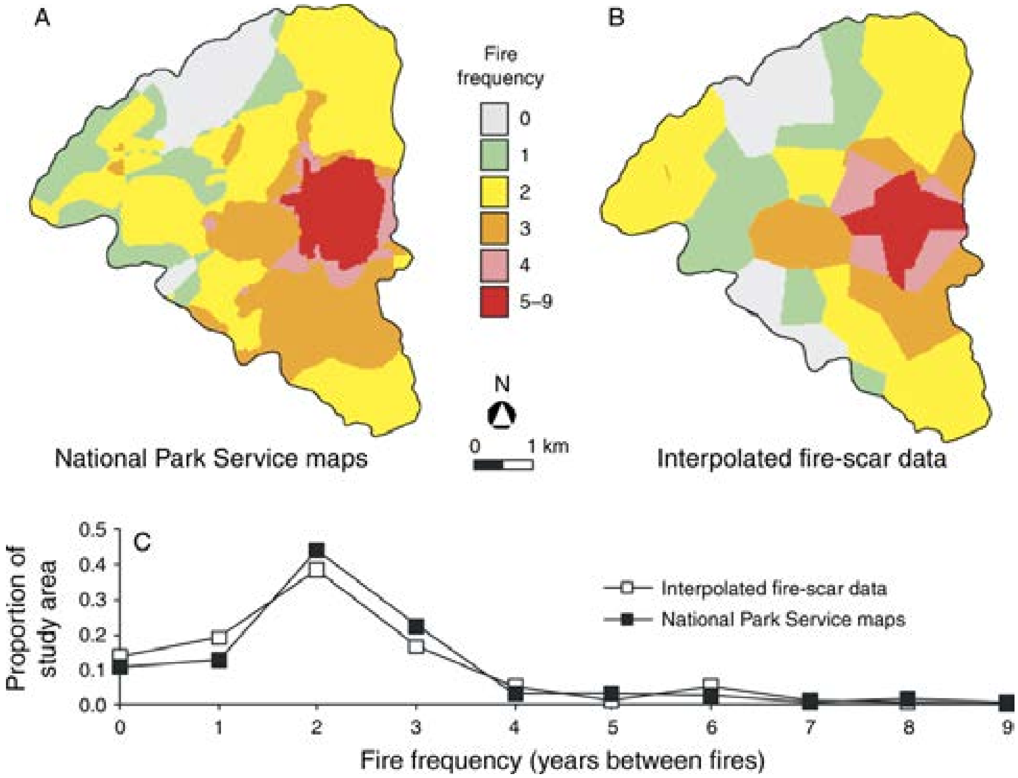

Figure 4. Spatial patterns of fire frequency from 1937 to 2000 calculated from (A) National Park Service Fire Atlas maps and (B) fire-scar data interpolated with Thiessen polygons. (C) The proportion of the study area occupied by each fire frequency class in the two maps (panels A and B). *From Farris et al. (2010).*

subsequent fires. However, there are methods that can be used to estimate past fire perimeters based on fire-scarred trees (Hessl et al. 2007). A study by Farris et al. (2010) compared National Park records with fire scar records and showed that fire scars allowed very accurate reconstruction of spatial patterns of fire (Fig. 4).

The fire-scar method alone is not effective for reconstructing ***spatial complexity*** of past fires. Because fires do not scar every tree, it cannot be known if a fire burned everywhere within a fire perimeter. Also, patches of high-severity fire within a low-severity fire may not be identified using only fire scars.

Length of Reconstruction, Temporal Precision and Spatial Resolution

The fire-scar method can be used to reconstruct the fire history of a site as far back in time as the oldest preserved wood in the site. In western North America, this typically means a fire history can be reconstructed for several hundred years (Grissino-Mayer 1995, Fulé et al. 2003, Brown et al. 2008a). In very long-lived trees, fire history from tree rings can be reconstructed for a much longer time period. The first fire recorded in giant sequoias in a 1993 study was in 1125 BCE and most records in the study went back to ~500 AD (Swetnam 1993). Exact years of historical fires are known with high precision and accuracy using the fire-scar method. In terms of spatial resolution, the fire-scar method has been used at widely varying spatial scales, from <2.5 acres to many thousands of acres.

Forest Structure and Composition

The fire-scar method cannot be used to reconstruct forest structure and composition, although identifying the species from which fire-scarred samples are taken is a common practice. Therefore the presence of particular species is known as far back in time as the tree samples extend.

For further reading on the fire-scar method of reconstructing fire history, see Johnson and Gutsell (1994), Swetnam and Baisan (1996), Minnich et al. (2000), Baker and Ehle (2001), Fulé et al. (2003) and Van Horne and Fulé (2006).

Dendrochronology: Tree Age, Death and Growth Data

Tree-ring data besides fire scars can also be used to obtain information about historical fire regimes (Kipfmueller and Swetnam 2001). In particular, researchers use dendrochronology to look for even-aged stands of trees that presumably initiated after a stand-replacing fire. Other tree-ring approaches for determining past fire regime attributes include examining growth releases and determining the death dates of fire-killed trees (Johnson and Gutsell 1994). Caution must be used to differentiate fire-initiated stand establishment, tree death, or growth release from

establishment, death, or growth release after other high-severity disturbances (see Veblen et al. 1994), but they are useful in conjunction with other methods to reconstruct historical fire regime attributes. One example of using multiple lines of tree-ring evidence to reconstruct fire history in the Southwest is a study of mixed conifer forests in northern New Mexico and southern Colorado (Margolis et al. 2007). This study used inner-ring dates, outer-ring dates, tree-ring width changes and fire scars to show that stand-replacing fires coincided with strong droughts in the region.

Using tree age data, fire ***frequency*** of high-severity fire can be calculated using a statistical method very different from the method for calculating mean fire interval from fire scars. Instead, fire rotation can be estimated. Fire rotation is the time it would take for an area equivalent to the entire study area to burn. Some areas may burn more than once and other areas not at all (see Box 1 and Fig. 5). There are assumptions that go into calculating fire rotation. In the example in Figure 5 from Agee (1993), it is assumed that the first fire event (top right box) burned 100% of the area. However, as little as about 20% may have burned; subsequent high-intensity fires wipe away the original evidence. If only 20% burned in the first event, the natural fire rotation (NFR) would change from 162 years to 286 years.

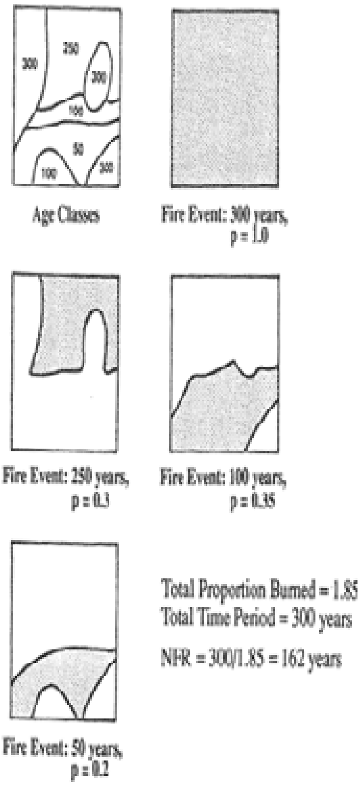

Figure 5. Example of a natural fire rotation (NFR) calculation. From Agee 1993. Tree age classes are shown in the top left box, resulting from 4 fire events. Fires occurred 300, 250, 100, and 50 years ago (other four boxes). The proportion of area burned in each fire was: 1.0, 0.3, 0.35, and 0.2. The total proportion of area burned is 1.85, over a time period of 300 years. The natural fire rotation is therefore 300/1.85, or 162 years.

Seasonality of historical fires cannot be reconstructed using tree age, growth release, or death data. In terms of fire ***type*** and ***severity***, tree age, growth releases, and death dates are most useful in reconstructing high-severity fires. Tree death dates, even-aged germination dates, and tree growth releases all indicate some amount of high-severity historical fire. When tree age can be associated with discrete stands of trees, it is possible to reconstruct, with relatively high confidence, the ***size*** of past fires (e.g., Romme 1982, Margolis et al. 2011). With an intensive sampling design, it is also possible to reconstruct ***spatial complexity*** using a combination of tree ages and fire scars. For example, Brown et al. (2008b) used a combination of fire-scar data and tree age data in the Black Hills of South Dakota to conclude that the historical fire regime was dominated by low-severity surface fire but had patches of high-severity fire at the scale of <250 acres.

Length of Reconstruction, Temporal Precision and Spatial Resolution

One drawback to this method is that many times only the most recent high-severity fire can be reconstructed; often older evidence is lost in subsequent fires. Reconstructions using tree age data range in length from one fire date to several fires over hundreds of years. Precise dates of fires are difficult to obtain with tree age data alone, but precise dates can be obtained by collecting fire-scar samples from the perimeter of a historical high-severity fire (Sibold et al. 2006). The spatial resolution of fire regime reconstructions using dendrochronology data is limited only by the sampling design and the presence of trees with datable rings.

Forest Structure and Composition

Historical forest structure and composition are often reconstructed using tree-ring information. For example, Mast et al. (1999) reconstructed historical forest composition, age structure, and regeneration patterns in an unharvested ponderosa pine forest in northern Arizona. The researchers found a multimodal presettlement age distribution with the oldest tree having a center date of 1333 AD.

Forest Structure Data

Early forest structure data, including data from General Land Office (GLO) surveys and data derived from early aerial photographs, have been used in some cases to infer disturbance history of the forests. These methods are different than tree-age data obtained with dendrochronological methods because they use information like size of trees, tree density, and species composition at the time of sampling to infer disturbance history of forests instead of post-fire tree ages, death dates, or growth releases.

Established by the federal government in the early 1800s, the General Land Office sent surveyors across much of the United States to map the country. Surveyors were required to note "bearing" trees at every mile mark (section corner) and half-mile mark (quarter section corner). Species, diameters, bearings, and distances from the corner were recorded for two or more bearing trees at each corner. In addition, surveyors wrote descriptions of vegetation, soil, and disturbances encountered along the lines between section corners (Whitney and Decant 2001). The GLO Survey data (also called Public Land Survey (PLS) data) have been used extensively to reconstruct historical forest structure, species composition, and forest type (Whitney and Decant 2001). Survey data including tree density, tree sizes, and species composition, have also been used less commonly to infer disturbance history. Examples include studies by Baker (2012) and Williams and Baker (2012a, 2013).

Another method for obtaining information about past forest structure is to use early aerial photographs. For example, Hessburg et al. (2007) used aerial photographs from the 1930s and 1940s in eastern Washington to estimate canopy cover, species composition, size classes of trees, number of canopy layers, and other variables. These variables were then used to infer disturbance history of the forest.

Deriving disturbance history from forest structure information has not been done uniformly across studies. This is likely because of differences in data types and characteristics, forest types, and relationships between fire and forest structure in particular areas. This makes comparisons among studies difficult. However, there are assumptions involved with each set of methods. Three example papers will be presented to illustrate assumptions as well as methods used to infer various fire regime attributes from forest structure data (Taylor and Skinner 1998, Hessburg et al. 2007, and Williams and Baker 2012a). These three papers were chosen because they use tree size, tree species, and/or tree density to infer historical fire history. Other studies that have used survey data have also used surveyor notes about disturbances encountered (e.g., Schulte and Mladenoff 2005, Williams and Baker 2012b) and they are not included as examples. In the first example paper, Taylor and Skinner (1998) used a combination of dendrochronology techniques and stand structure methods to infer historical fire history in the Klamath National Forest in northern California. The second example paper, by Hessburg et al. (2007), is described above. The third example paper, by Williams and Baker (2012a), classified forests in four areas of the western United States into fire severity categories based on reconstructed stand structure from the GLO data. Although the details of the methods in these three papers vary, some assumptions are consistent across the studies and include: 1) forest structure (size class structure) is related to the disturbance history of the forest, 2) the disturbance that led to the documented forest structure was fire rather than another disturbance type such as wind or an insect outbreak, 3) fire exclusion and succession had little effect on the forest structure documented in photographs or surveys, and 4) some measure of tree size is related to tree age.

Because each example study used different methodology to infer historical fire regime information, the methods used in each study are summarized in Table 1.

Severity of historical fires was estimated in different ways by the three studies in Table 1. Hessburg et al. (2007) assumed that lower overstory ***canopy cover*** (<30%) indicated higher fire severity in the past. Williams and Baker (2012a) assumed that a ***lower percentage of large trees and a higher percentage of small trees*** (<20% large trees, >50% small trees, measured by bole size) indicated higher fire severity in the past. Taylor and Skinner (1998) assumed that fewer ***taller trees*** (<10 stems per 2.5 acres) indicated higher fire severity in the past.

The assumption that tree size and tree age are reliably correlated has been questioned (Fulé et al. 2014), given that "the relationship between age and size is frequently not very strong" (Spies 1998, p. 37), especially in shade-tolerant species. Tree size may be limited by site quality, overcrowding, or climate, which would cause trees to remain the same size for decades. Another critique is that even if age and size are reliably correlated, there are other reasons trees could regenerate in cohorts, including bark beetles, wind, climate-induced mortality, climate-induced establishment, or fire exclusion (Fulé et al. 2014). "In some cases, different disturbance histories can produce similar size distributions of trees" (Spies 1998, p. 37). Post-wildfire regeneration is often inconsistent or delayed in dry western forests, with post-fire regeneration being non-existent, delayed, or dense and immediate (Savage and Mast 2005, Roccaforte et al. 2012).

For more on using forest structure to infer disturbance history, see Fulé et al. (2014), Williams and Baker (2014), and the three papers described in Table 1.

Length of Reconstruction, Temporal Precision and Spatial Resolution

The GLO surveys were conducted at around the time European settlers were arriving and altering land use and vegetation at a landscape scale (late 1800s in the Southwest). Aerial photos were taken over some areas in the 1930s and later. In many places, widespread changes had probably not yet occurred at the time of the surveys, and aerial photos also may predate heavy human influence on forests. The surveys and aerial photos, like historical documents and photos, are "snapshots"; changes through time are not captured. In terms of temporal precision, it is not possible to derive specific fire dates from forest structure data. A strength of using GLO survey data to reconstruct fire regimes is that the data cover large landscapes across large portions of the country.

Fire regime attribute	**Hessburg et al. (2007)**	**Williams and Baker (2012a)**	**Taylor and Skinner (1998)**
Frequency	Not reconstructed	Using GLO survey data, "we estimated fire rotation… as the number of years a fire was detectable divided by the percentage of the landscape burned by high-severity fire." "We estimated the time a fire was detectable as the time it took for a tree to grow to the cut-off size for a 'large' tree." For example, "in northern Arizona, an average 40-cm tree is about 120 years old." 120 years is therefore "the maximum length of time a fire could be recognized using this structure-based approach."	Used data from fire-scarred trees (dendrochronology methods)
Seasonality	Not reconstructed	Not reconstructed	Used data from fire-scarred trees (dendrochronology methods)
Severity	Using aerial photos from the 1930s and 1940s: "overstory canopy percentage classes (= overstory canopy remaining classes, ≥80%, 30.1–79.9%, ≤30%)" [were] used to define low, mixed and high severity fires." In some patches, "the fire tolerance of the cover type was also used to predict the most likely fire severity. Cover type was used where overstory canopy percentage exceeded 80%, and where it was impossible to discern from structural attributes alone whether severity was high (stand replacing fire from a long time ago) or low (surface fire maintained)."	Using GLO survey data and forest structure data reconstructed from survey data: "low-severity fire was assigned if: (1) mean tree density was < 178 trees ha^{-1}, (2) the percentage of large trees was > 29.2%, and (3) the percentage of small trees was < 46.9%. … High severity was defined as having a percentage of small trees > 50% and a percentage of large trees < 20%. … Remaining areas … were classified as mixed severity."	At plot level: tree age obtained using dendrochronology. Then "we calculated a measure of fire severity as the average number of 60-year periods in which trees regenerated. Presumably, plots with trees in fewer 60-year age-classes characterize stands that have burned more severely than those with more age-classes." At stand level, using aerial photographs from 1944 to 1975: "Severity patches were mapped using the relative density of short even-aged stems and taller, older trees that survived successive fires. High-severity patches had <10 tall stems ha^{-1}, moderate-severity patches had 10-20 tall stems ha^{-1}, and low-severity patches had >20 tall stems ha^{-1}."
Type	Not specifically reconstructed, although often "low-severity" implies surface fire and "high-severity implies crown fire	Not specifically reconstructed, although often "low-severity" implies surface fire and "high-severity implies crown fire	Not specifically reconstructed, although often "low-severity" implies surface fire and "high-severity implies crown fire
Size	Not reconstructed	Not reconstructed	Used data from fire-scarred trees (dendrochronology methods)
Spatial complexity	Not reconstructed	Not reconstructed	Not reconstructed

Table 1. Summary of methods used by three different studies to infer various fire regime attributes

Forest Structure and Composition

Structure and composition of historical forests has often been reconstructed using GLO data (e.g., Radeloff et al. 1999, Leahy and Pregitzer 2003, Whipple et al. 2010). Critiques of forest reconstructions using GLO data include the possibility of error and ambiguity in tree identification, survey contract fraud, surveyor bias in selection of bearing trees (small and large trees were often avoided), the "snapshot" nature of the survey records, and the underestimation of small features on township maps (Bourdo 1956, Schulte and Mladenoff 2001, Whitney and Decant 2001). However, Williams and Baker (2010) quantified measurement error and selection bias at 384 survey corners in the western United States and concluded that surveyor bias and measurement errors were fairly low. Schulte and Mladenoff (2001) concluded that survey data are most appropriately used over a broad spatial scale and at coarse spatial resolution, and with complementary data from other historical sources. For example, Batek et al. (1999) used survey data to reconstruct vegetation in the Missouri Ozarks and fire-scarred trees to reconstruct fire regimes, which resulted in data that could be compared. They concluded that fire played a large role in influencing vegetation patterns in that region.

Using GLO data to reconstruct forest density can also be done, but caution should be used because, depending on the methods, it may overestimate tree density. Hagmann et al. (2013) compared tree density reconstructed using GLO data with tree density recorded in historical timber inventories on the former Klamath Indian Reservation in Oregon. They found that a GLO-based reconstruction (Baker 2012) resulted in tree densities nearly 2.5 times higher than tree densities recorded in the timber inventories. The authors ruled out differences in diameter limits, timing of the two datasets, and disturbance events between the time of the GLO surveys and the timber inventories as potential reasons for the differences in tree density between the GLO-based methods and the timber inventories, and concluded that tree density was overestimated using GLO data and methods (Hagmann et al. 2013). The results of this study in Oregon have not been replicated in other parts of the western United States.

Plant Traits

Plant traits that give plants increased fitness in particular fire regimes can be used to infer that, over long time periods, those species survived and even thrived in those fire regimes. An example that is often cited is the thick bark of ponderosa pine and some other conifers. Thick bark gives trees a competitive advantage over thin-barked tree species in a low-intensity surface fire regime because they can live through multiple fires with little to no disruption, while trees with thin bark often die. It is inferred that frequent surface fires were part of the "evolutionary environment" for ponderosa pines and many other conifers with thick bark (Covington 2003). He et al. (2012) found that the development of thick bark in pines coincided 126 million years ago with a rise in low-intensity surface fire. On the other hand, many other tree species with thick bark are not associated with low-intensity surface fire (Paine et al. 2010).

The plant trait method must be used with caution because it is difficult to ascertain that plant traits that currently give plants advantages in particular fire regimes were selected for by fire or if they were selected by some other agent. For example, the ability to resprout is often cited as a stand-replacing fire adaptation, but there are other disturbances after which it is advantageous for plants to be able to resprout. Those disturbances include flooding, windstorms, drought, landslides, and herbivory (Bond and Midgley 2001). Therefore, it is possible that resprouting species have not experienced stand-replacing fire over an evolutionary time period. However, it has also been argued that no matter what the original conditions particular traits evolved in, plant traits that increase fitness in particular fire regimes today are important and can be used by managers to predict plant dynamics under alternative fire regime scenarios (Keeley et al. 2011).

Historical fire ***frequency*** can be estimated using the fire frequency in which plants can persist today. For example, increased fire frequency due to an invasion of cheatgrass across western North America has resulted in vastly different species composition in many areas. It was estimated that before the invasion of cheatgrass on the Snake River Plains in Idaho, fire return intervals were several decades long, but with much more frequent fire (<5 years) it was not possible for native plants to persist on the landscape (Whisenant 1990). Therefore, we can infer that fire frequency was historically on the order of decades rather than years where those native plants lived over an evolutionary time scale.

Historical fire ***seasonality*** can also be inferred from how plants respond to fire in different seasons today. For example, in California chaparral, historically fires burned in late summer or fall when soil moisture was low. Spring prescribed burns, when soil moisture is higher, impair the germination of certain native species (Le Fer and Parker 2005). It can be inferred that fires burned in late summer or fall over an evolutionary time span, in at least some locations, for those species to have persisted on the landscape.

Fire ***type*** and ***severity*** can also be inferred from plant traits. Some plants depend on high-severity crown fire to persist. For example, serotinous lodgepole pines have a competitive advantage after high-severity fires. We can infer that, over an evolutionary time frame, serotinous lodgepole pines experienced some high-severity fires. However, many lodgepole pine trees also produce non-serotinous cones, which would be consistent with conditions that did not include only high-severity fires. ***Size*** and ***spatial complexity***

of fires in historical fire regimes cannot be inferred using plant traits.

Inferences from plant traits come with a low degree of certainty because evolution may not have occurred in response to a homogeneous landscape and fire regime.

Length of Reconstruction, Temporal Precision and Spatial Resolution

Plant traits are used to infer fire regimes over thousands to millions of years, rather than at the scale of human history. Plant traits cannot be used specifically to infer fire regimes at the time of fire exclusion in the late 1800s, although the vegetation communities present at that time were shaped in part by the existing fire regimes. Using plant traits gives us zero temporal precision; no particular fire dates can be known by understanding plant traits. Plant traits can be used to understand historical fire attributes at the scale of species distributions. Individual fires, including size or location, cannot be reconstructed.

Forest Structure and Composition

Specific historical forest structure and composition cannot be determined by knowing plant traits, although generalizations can be made. Species that can resprout and species that have serotinous seeds are likely to form even-aged stands, for example.

Charcoal

Charcoal particles formed during wildfires are found in lakes, bogs, wetlands, and in soil. They are extracted for research purposes with sediment cores in wet areas (Whitlock and Larsen 2001) and with soil cores from the soil profile within forest stands (Carcaillet et al. 2002, Fesenmyer and Christensen 2010). Charcoal particles are dated in the laboratory using radiocarbon dating to estimate individual fire dates. Charcoal can be found at the site of a past fire or deposited by overland flow (Gardner and Whitlock 2001).

Fire ***frequency*** can be reconstructed with charcoal, but not with the precision of fire-scar records. ***Seasonality***, fire ***type***, and ***severity*** cannot be reconstructed using charcoal records. Determining the ***size*** of fires using charcoal evidence depends on whether sediment charcoal or soil charcoal is used. With sediment charcoal, a peak in charcoal can mean a fire at the edge of a lake or a fire several kilometers away, depending on wind and other factors (Gardner and Whitlock 2001). However, soil charcoal can be used to reconstruct fire history at or very near the site that the soil charcoal is found (Fesenmyer and Christensen 2010). Finally, ***spatial complexity*** of historical fire regimes cannot be reconstructed using charcoal records.

Length of Reconstruction, Temporal Precision and Spatial Resolution

One strength of the charcoal sediment technique is that it allows the reconstruction of fire history for much longer than the fire-scar method. For example, fire history, vegetation, and paleoclimate were reconstructed for the last 13,500 years on the Kaibab Plateau in northern Arizona (Weng and Jackson 1999), with results indicating dynamic climate, vegetation, and fire regimes over millennia. In terms of temporal precision, historical fires cannot be dated to a precise year using the charcoal method. This method is most useful in areas where the historical fire return interval was on the order of decades rather than years, since with very frequent fires a nearly steady stream of charcoal is deposited, and individual events cannot be identified.

Forest Structure and Composition

Another strength of charcoal studies is that the length of the reconstructions allows the comparison of fire with long-term climate and vegetation changes reconstructed from pollen records (Anderson et al. 2008). Usually charcoal alone is not used to reconstruct forest structure and composition, although wood structure in soil charcoal can be assessed to learn more about forest composition.

Integration of Multiple Lines of Evidence

A combination of methods used together is the strongest approach to reconstructing historical fire regimes (example studies that use two or more lines of evidence include Kaye and Swetnam 1999, Whitlock et al. 2004, and Margolis et al. 2011). Multiple lines of evidence that point in the same direction give managers a stronger basis for inferences about characteristics of a historical fire regime. Researchers in the Southwest are extraordinarily fortunate to have several of these methods available for reconstructing historical fire regimes. This is not the case in many other parts of the world. For example, fire scars do not form in all tree species, wood may be highly susceptible to rot, historical written and photographic evidence may not be available, an area may not be suitable for charcoal sampling, and land surveys may not have been carried out.

	Historical documents and photos	Fire scars	Tree age, death & growth data	Forest structure data	Plant traits	Charcoal
Advantages	Contemporary to time when forests were not altered by a century or more of fire exclusion	Precise to year (and sometimes season) of fire; most utility in reconstructing surface fire regimes; point-specific direct evidence of past fires	Most utility in reconstructing high-severity fire regimes	Can be broad scale across large regions; evidence from time before forests were altered by a century or more of fire exclusion	Plant traits (and lack of traits) indicate success or lack of success in a particular fire regime; trait success implies fairly long-term relationships between plant traits and fire regimes	Long reconstructions; most utility in reconstructing mixed-severity or high-severity fire regimes; can be used to compare with long-term pollen records of vegetation and climate
Disadvantages	Limited to availability of old photos & documents; not available everywhere; recorders could have been biased or poorly skilled	Time period limited by oldest wood; not all fires scar trees; limited to forest types where trees form scars; sampling scheme can result in biases; MFI interpretation influenced by sample size and area sampled	Often can only reconstruct last stand-replacing fire; older evidence is lost in subsequent fires; dating of fires not precise because regeneration may not be immediate after disturbance; small-scale fires difficult to reconstruct	Regeneration uncertain after fire; “snapshot” of forest structure available from the time the surveys were completed or photos taken; in surveys, sampling intensity low (small number of trees per square mile);	Fire regimes can change (and have changed) over millennia; traits can’t be pinned to an evolutionary “reason”- could have evolved for other reasons	Not precise to year of fire; less utility for low-severity fire regimes; cannot reconstruct exact spatial pattern of fire in the watershed (not point-specific) or area burned
Amount of uncertainty	Uncertainty about how applicable photo or description is to larger area; sometimes uncertainty about exact location	No uncertainty at point scale: a fire scar indicates fire happened at that point, but some uncertainty about fire extent between point samples.	Uncertain disturbance event unless accompanied by fire scars; uncertain dating of fires unless accompanied by fire scars	Uncertainty about size/age relationships; uncertain disturbance event unless accompanied by other evidence	Uncertainty about whether traits evolved as an adaptation specifically to fire, even if useful now for fire	Uncertainty about specific years of fires
Direct or indirect evidence of historical fires?	Direct (e.g., photo of burned area) or indirect (e.g., description of open, park-like forest)	Direct (fire scars are evidence of fire) and indirect (infer fire spread between scarred trees)	Indirect (even-aged cohort of trees or growth release) or direct (dates of fire-killed trees)	Indirect (particular forest structures are the result of historical disturbances)	Indirect	Direct (charcoal fragments are evidence of fire)
Assumptions	Photos and written descriptions are representative of the larger area.	Multiple fire-scarred trees in a study site in the same year are the result of a spreading surface fire and not individual fires at each tree	Stand initiated by fire and not some other stand-replacing event	Tree density, tree size, and/or forest species composition can be translated into evidence of historical fire and attributes such as fire severity	Traits adaptive in particular fire regimes represent long-term conditions for plant species	Charcoal is the result of forest fire in the study area
Length of reconstruction	Limited to time when settlers were writing about explorations and settlements; in SW, usually late 1800s	Several hundred years common in SW, longest reconstructions using fire scars are thousands of years long	Can be several hundred years, but often limited to most recent stand-replacing fire (older evidence is lost)	Limited to point in time that surveys were conducted or aerial photos were taken	Evolutionary time scale; not possible to pinpoint fire regime at any particular time	Many thousands of years

	Historical documents and photos	Fire scars	Tree age, death & growth data	Forest structure data	Plant traits	Charcoal
Spatial resolution	Depends on source; usually descriptions of routes or small regions, photos of stands to landscapes	<1 to 1000s of hectares	Usually landscape scale; small fires difficult to detect	Large spatial scale (many thousands of hectares); small fires difficult to detect	Scale of species distribution	Scale of watershed, usually; cannot reconstruct specific fire perimeters or sizes
Temporal precision	Documents and photos are often dated precisely, but dates of fires may not be recorded precisely if they are not directly witnessed	Precise to year of fire and sometimes to season	Cannot precisely date fires with tree germination dates unless accompanied by fire-scar information; can precisely date fires with fire-killed tree death dates	No temporal precision; not possible to determine individual fire years	No temporal precision; not possible to determine individual fire years	Not precise to year; carbon dating estimates are given confidence limits
Forest structure and composition reconstruction?	Can glean some information from documents and photos	Not possible to reconstruct with fire-scar data alone	Useful tool for reconstructing forest structure and composition	Useful tool for reconstructing forest structure and composition	Not possible	Not possible with charcoal alone, but often accompanied by pollen studies, which can be used to understand forest composition over long time scales

Table 2. Summary of advantages and disadvantages, uncertainty, direct/indirect data, assumptions, length of reconstruction possible, spatial and temporal resolution, and whether forest structure and composition can be reconstructed using each of six different reconstruction methods.

	Historical documents and photos	Fire scars	Tree age, death & growth data	Forest structure data	Plant traits	Charcoal
Frequency		Direct	Indirect	Indirect	Indirect	Direct
Seasonality		Direct			Indirect	
Severity	Direct or indirect	Direct	Direct or indirect	Indirect	Indirect	
Fire type	Direct or indirect	Direct	Direct or indirect	Indirect	Indirect	
Size	Direct	Indirect	Indirect			
Spatial complexity	Direct					

Table 3. Fire regime attributes that can be reconstructed by each of six different fire regime reconstruction methods, and an indication of whether the attributes are based on direct or indirect evidence. Boxes that are blank indicate that an attribute is usually not able to be reconstructed using that method.

Conclusion

All the methods discussed in this working paper have strengths and weaknesses, and are most appropriate for reconstructing particular fire regimes and fire regime attributes (Table 2) as well as for particular research or resource goals. While historical documents and photos are usually qualitative in nature, they serve as effective communication tools to teach or introduce fire history to diverse audiences. The fire-scar method provides strong evidence about low-severity historical fire frequency, seasonality, severity, and type. Other dendrochronology methods such as using tree ages, tree death dates, and growth releases, are most appropriate for reconstructing high-severity fire regimes, and can provide evidence of historical fire severity, type, and size. Forest structure data is most useful for reconstructing dominant species composition and tree density, and is valuable because it covers large landscapes. Plant traits can provide information about fire regimes that plants were subjected to over an evolutionary time scale. Fire regime attributes that can be inferred from plant traits include fire frequency, seasonality, severity, and type. Finally, information about charcoal from soil cores is most useful for reconstructing high-severity fire and can be used to gain information about historical fire frequency over thousands of years.

Historical fire regimes are useful to inform current fire and forest management practices. Results of studies using these methods can contribute to prescribed fire programs that may need to measure tradeoffs of ecological benefit with other resources, including threatened and endangered species or human community health. However, it is not advisable to attempt to replicate exactly the historical fire regime in a modern context. Many management variables must be considered, including agency mission and policy, wildlife, smoke, WUI, costs, and climate change. Due to these variables, it is important to think about desired future conditions, which may be very different from historical conditions. As always, it is important to incorporate local data, knowledge, and monitoring in any forest restoration plan.

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For more information about forest restoration, contact the ERI at (928) 523-7182 or **nau.edu/eri**.

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