Multiscale controls of historical forest fire regimes: New insights from fire-scar networks

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Review article, *Frontiers in Ecology and the Environment*

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**Abstract**

Anticipating changes in forest fire regimes with changing climate requires that we understand the factors that control fire regimes at both small and large scales. Fire scars, proxy records of fire that are recorded in the rings of long-lived trees, provide an annually accurate window into past low severity fire regimes. In western North America, the fire-scar record now includes networks of 100s to 1000s of trees sampled across 100s to 10,000s of hectares, spanning centuries to millennia. Development of local and regional networks has created a new data type for ecologists interested in disturbance and climate regulation of ecosystem processes – for example, why forest fires are widespread during certain years but not others. They also provide crucial reference information on fire as a dynamic landscape process for use in ecosystem management, especially when managing for forest structure and resilience to climate change.

In a nutshell:

1. Forest fire is a spatial process regulated by interacting bottom-up and top-down controls.
2. Fire scars record low-severity fires over hundreds to thousands of years with high spatial and temporal accuracy.
3. Fire-scar networks can reveal how fire regimes vary over space and time in relation to fuels, topography, and climate.
4. Understanding past controls of fire allows ecologists and managers to anticipate future fire regimes as forest conditions and climate change.

**Introduction**

Fire is a fundamental Earth system process linking ecosystems, biogeochemical cycles, and climate variability (Bowman et al. 2009). Understanding what controls forest fire regimes is increasingly important as climate changes and the size and severity of wildfires increase. Climate remains an important driver of widespread fire today despite a century of fire exclusion, fuel accumulation, and land use change (Morgan et al. 2008, Littell et al. 2009). Fire regimes – the aggregate properties of multiple fires characteristic of an ecosystem – respond to temperature and rainfall, which are predicted to change in coming decades. However, they are also driven by conditions on the ground, particularly landscape mosaics of fuels. Understanding the interactions of climate and fuels is central to understanding fire today and in the future, and to linking fire to other areas of terrestrial ecology (Parisien and Moritz 2009, Turner 2010).

Fire is a spatial process driven by controls acting across a range of scales. At fine scales, when and where fires start depends on the distribution of ignitions and flammable fuels. Once ignited, the rate and direction of fire spread are controlled by local fuel conditions, weather, and topography. These fine-scale *bottom-up* controls modify fire behavior, and consequently the immediate effects on vegetation and soils. Thus, most fires create mosaics of fire severity, a signature of bottom-up regulation (see mtbs.gov for examples from contemporary fires). This heterogeneity affects other ecological processes, such as forest dynamics, carbon sequestration, insect outbreaks, wildlife habitat, soils, hydrology, and subsequent fires (Collins and Stephens 2008).

At broad scales, *top-down* controls synchronize regional and sub-continental fire occurrence. The dominant top-down control in most ecosystems is climate, which varies across temporal scales from interannual to centennial and longer (Table 1). The signature of top-down control is synchronous fire occurrence among sites beyond the reach of a single fire, compared to the patchy landscape patterns created by bottom-up regulation. Understanding the interplay of bottom-up and top-down controls of fire is central to understanding fire as an ecosystem process, and to managing fire under rapid changes in land use and climate (Heyerdahl et al. 2001, Lertzman et al. 1998, Falk et al. 2007).

Accurate twentieth century records of fire are only 30 to 100 years long – too short to detect the influence of slower processes such as forest succession or multi-decadal climate variation. Fortunately, the paleoecological fire record – including fire scars on trees, forest age structure, and sediment charcoal – provides a longer view (Gavin et al. 2007, Marlon et al. 2008).

We summarize recent insights into three areas of historical forest fire dynamics gained from fire-scar networks in western North America. First, we discuss recent progress in mapping historical fires. Second, we present new knowledge about bottom-up controls of fire and how these varied within and among landscapes. Third, we discuss how regional and continental networks have revealed interactions between bottom-up and top-down controls of fire across scales. We conclude by discussing applications of these insights in ecosystem management.

The North American fire-scar network

In much of North America, contemporary fires reflect a century or more of human-driven fire exclusion and landscape change. Fortunately, fire scars on trees record spatial and temporal patterns of fires that pre-date this time of great change in some forest types (Panel 1). Most fire scars form in forests that historically sustained low-severity surface fires, although trees also scar along the perimeters or in low-severity patches of high- and mixed-severity fires (Kipfmueller and Kupfer 2005).

The fire-scar record on any given tree may be incomplete because fires do not scar every tree within their perimeter, and scars that do form can be consumed by subsequent fires or decay. Consequently, fire-scar dates from several trees in a small area are often combined into a composite fire chronology. In North America, such composite fire chronologies have been generated using dendrochronology since the 1980s (Dieterich and Swetnam 1984). Recently, spatial fire-scar networks have been developed over 100s to 1000s of hectares by sampling fire-scarred trees using a variety of designs (Figure 2). These networks are a new data type for ecologists interested in how disturbance and climate regulate ecosystem processes over large scales of space and time.

In some networks, individual scarred trees are identified in the field, sampled exhaustively and analyzed at spatial scales that are determined *post hoc* (Figure 2.a). In others, trees are sampled systematically to explore variation across environmental gradients such as elevation, vegetation, and microclimate. Fire-scar composites distributed along environmental gradients allow inferences about bottom-up drivers of fire regimes, such as topography (Veblen et al. 2000; Brown et al. 2001, Fulé et al. 2003b, Margolis and Balmat 2009; Figure 2.b). Composites can also be sampled on systematic grids (Fulé and Covington 1994, Heyerdahl et al. 2001; Figure 2.c), which are also useful for determining scale-dependent spatial properties of fire regimes (Falk et al*.* 2007).

As local composites have proliferated across North America, they have been combined into broader-scale networks. These “networks of networks” are especially useful for understanding regional variability in top-down drivers of fire occurrence, including large-scale climate patterns such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) (Swetnam and Betancourt 1998, Kitzberger et al. 2007).

Growing interest in the drivers of fire at continental and global scales led to the creation in 2003 of a public archive of fire chronologies – the International Multiproxy Paleofire Database (IMPD), which now holds more than 474 fire-scar records (*Web Panel*). To assess the full scope of the fire history network, we compiled an additional 150 crossdated and georeferenced fire-scar sites from western North America that have been published but not yet contributed to the IMPD (Figure 3).

Ecological insights from multiscale fire-scar networks

This new sub-continental fire history network provides unprecedented opportunities to examine how climate, vegetation, and landform influence fire over long periods. The potential strength of these inferences derives from the increased statistical power that comes from sampling a large number of trees, as well as from the dispersion of samples along biophysical gradients at multiple scales. Below, we focus on three research areas where the development of multiscale fire-scar networks has enabled significant scientific progress of broad interest to ecologists.

Mapping historical fires  
Fire-scar networks yield basic information about when and where fires occurred (Hessl et al. 2007, Swetnam et al. in press). Fire perimeters reconstructed from scars correspond remarkably well with those mapped from direct observation and remotely-derived data, confirming that they are a reliable source of information about past fires (Shapiro-Miller et al. 2007).

For example, Farris et al. (2010) compared twentieth century fires interpolated from fire scars sampled on grids with those recorded on fire-atlas maps in the Rincon Mountains, Saguaro National Park, Arizona. The fire-scar record captured the perimeter and area burned of all mapped fires larger than 100 ha, and even detected some fires missing from the atlas. Fire scars also captured the spatial pattern of fire frequency accurately, i.e., where fires occurred most commonly. This interpolation can now be applied to pre-twentieth century fire scars to accurately reconstruct the perimeters of historical fires for which there are no maps (Figure 4.a). Similarly, Hessl et al. (2007) used a network of fire-scarred trees in eastern Washington (Figure 2a) to test alternative algorithms for reconstructing fire perimeters (Figure 4.b). Although each approach required assumptions about how to interpolate point data to landscape scales, they showed that fire-scar networks can be used to reconstruct both perimeters and heterogeneity in burn patterns.

Fire-scar networks can also yield valuable information on the extent of large historical fires. Fire-scar networks may not capture every small fire, but they capture large fires reliably, which account for the majority of area burned. Such information could help resolve a current debate about whether contemporary fires are larger and more severe than in the past. Fire-scar networks show that low-severity fires in dry forests and woodlands burned extensive landscapes (often >100s km2) across many areas of the interior West prior to the twentieth century (Everett et al. 2000, Caprio, 2004, Wright and Agee 2004, Farris et al. 2010). The tree-ring record shows clearly that in many low- and mid-elevation forests these fires did not cause widespread overstory tree mortality, suggesting that they burned primarily with low severity (Brown and Wu 2005, Brown et al. 2008, Scholl and Taylor 2010). Low-severity fires are rarely so extensive in North America today except in parts of northern Mexico and some large wilderness areas, because fires of this kind occur under fuel and weather conditions that make them relatively easy to suppress.

Bottom-up controls of fire regimes

Spatial variation in climate and topography controls the distribution of plant communities, and likewise is the dominant bottom-up control of wildland fires (Taylor 2000, Heyerdahl et al. 2007). For example, aspect and elevation strongly affect the strength and duration of solar insolation, which in turn controls dominant vegetation types as well as the amount and moisture of fuel, and the period during which fuels are dry enough to burn (the “fire season”). Fuel type and fuel moisture also vary with elevation, a proxy for temperature and evaporation rate during the fire season. Dry surface fuels consisting of long-needled litter and cured grasses in low-elevation ponderosa pine forests tend to facilitate fire spread, in contrast to more mesic high elevation mixed-conifer and spruce-fir forests, where surface fuel moisture and denser fuel beds derived from short-needled species inhibit fire spread except under extreme weather conditions.

Spatial fire-scar networks frequently reveal how historical fire regimes reflected the biophysical template across which they burned (Veblen et al. 2000, Heyerdahl et al. 2001 and 2007, Taylor and Skinner 2003). Studies in Grand Canyon National Park and the Arizona Sky Islands show that contrasting north versus south aspects led to a mixture of fire frequencies and severity in close proximity (Heyerdahl et al. 2001, 2007, Fulé et al. 2003b, Iniguez et al. 2008). In Sequoia and Kings Canyon National Parks (Caprio 2004), fire frequency varied with aspect at lower, drier elevations, but not at higher elevations where temperatures are lower and fuel moistures higher, regardless of aspect (Figure 5).

Interplay of top-down and bottom-up controls

Fire-scar networks can identify interactions of top-down and bottom-up controls of fire regimes. Some studies examine the interplay of top-down and bottom-up controls by sampling a regional network of local grids. In eastern Oregon and Washington, Heyerdahl et al. (2001; Figure 2.c) found that top-down and bottom-up controls interacted to regulate fire occurrence: a latitudinal climate gradient produced earlier and more frequent fires to the south, consistent with a warmer and drier climate there compared with sites to the north. Fire frequency also varied with aspect, a bottom-up control, but only in watersheds with steep terrain and strong topographic barriers to fire spread.

In a northern California study, Taylor and Skinner (2003) identified persistent similarities in fire chronologies within landscape compartments separated by ridges, streams, and changes in aspect (Figure 6). These bottom-up controls were filters to fire spread, not absolute barriers: during years of extreme fire weather, top-down control created weather and fuel conditions that overrode bottom-up controls, allowing fires to spread past barriers that impeded fire spread under more moderate conditions.

Recent studies of large landscapes where fires burn freely, as well as fire history studies, reveal fire's self-organizing properties across scales (Taylor and Skinner 2003, Collins and Stephens 2008). Reconstructing fire perimeters from fire-scar networks in successive years has shown that each fire modifies the fuel environment for subsequent events, for a period of time that varies with productivity and climate variability. These fuel mosaics create self-limiting landscape behavior of subsequent fires. As spatial fire-scar networks continue to expand, they may reveal such fire-vegetation dynamics at large spatial scales and over decadal to centennial time (Figure 4).

Fire-scar networks have been especially powerful for understanding top-down entrainment of fire regimes by climate at large spatial scales, revealing persistent patterns of intra- and inter-regional synchrony in fire (Swetnam and Betancourt 1998). Kitzberger et al. (2007) used spatial and temporal patterns of fire occurrence in 238 fire-scar chronologies from western North America to infer multicentury continental-scale synchrony in surface fires and large-scale climate drivers. They found that drought and forest fires covaried, depending on the modes of large-scale climate patterns: ENSO and PDO were the main drivers of high-frequency (interannual to decadal) variation in fire, modulated by AMO at multidecadal scales. These insights were possible only because of the extensive fire-scar network in western North America.

Applications to ecosystem management

Fire history has long guided ecosystem management in the West. As early as the 1940s, Harold Weaver (1943) based his recommendations for prescribed burning at the Colville and White Mountain Apache reservations on fire scars. Subsequent reconstruction of fire regimes in southwestern forests confirmed the historical pattern of high-frequency, low-severity surface fires – a point of considerable contention in the early 20th century, when many land managers still considered fire an anomalous and unnatural process.

Spatial fire-scar networks provide managers and scientists a window into how fire functions in ecosystems lacking the pervasive human influences of fire suppression, livestock grazing, and logging that influence modern fire behavior. For example, in Sequoia-Kings Canyon National Parks, decades of fire history research “provided a firm justification and basis for the development of the parks’ prescribed and use of wildland fire management programs” (NPS 2010). This included studies of topographic and climate controls of fire regimes, departures from historic fire intervals, and landscape patterns of fire severity derived from Park-wide fire-scar networks (Caprio 2004).

***Fire severity.*** A key question in forest management today concerns the severity and extent of contemporary fires. Managers can use fire history as a “best available science” standard to evaluate contemporary fires. Because fire scars form only under certain combinations of fire behavior and tree properties (Panel 1), spatial fire-scar networks can be used to bracket the historical range of variability in fire severity in some forest types. Recent landscape studies in ponderosa pine and Sierran dry mixed conifer forests (Brown and Wu 2005, Brown et al. 2008, Scholl and Taylor 2010) have used combinations of fire scars and tree demography to demonstrate differences of past fire regimes from the extensive stand-replacing events that burn these forests today. Other research at higher elevations or along elevation gradients has found a continuum of fire severity, with frequent surface fires at low elevations and infrequent stand-replacing events in higher elevation forests (Veblen et al. 2000, Margolis and Balmat 2009). The Grand Canyon National Park Fire Management Plan (NPS 2010) used maps of historic fire regimes based on fire history research to guide management treatments at sites across gradients of elevation and vegetation.

***Fire size***. The spatial distribution of historical fires also provides a reference by which ecosystem managers can assess fire management in specific vegetation types. In Lassen Volcanic National Park in northern California, most large fires burned historically in the yellow pine and mixed conifer belts, but not in red fir forests at higher elevations, suggesting that fuel type and moisture (snow line) along an elevation gradient limited the upslope spread of fire (Taylor 2000). Historical fires were, on average, 20-fold larger than contemporary prescribed burns, indicating that the spatial scale of contemporary management burns did not fully represent the natural fire regime. This led to a shift by National Park Service managers towards larger burns and use of topographic features such stream courses, ridge tops, and lava flows create natural fire compartments, as reflected in the Park’s wildfire management plan (NPS 2005).

***The role of climate***. The top-down climate drivers of historical fire documented in the fire-scar record still operate today (Morgan et al. 2008, Littell et al. 2009). Consequently, understanding how climate variability – such as periods of extended multi-year drought – has controlled fire regimes in the past can also inform scientists and managers about the drivers of modern fire. Spatial fire-scar networks also provide a long-term perspective for understanding the climatic conditions that lead to regional fire years – conditions that most climate projections indicate will become more common in the future.

Understanding the interactions of top-down and bottom-up controls allows fire-scar networks to complement other spatial arrays of biophysical data, with a broad range of ecological inferences possible across landscapes and regions. The fire-scar network can be coupled with tree-ring width, sediment charcoal, and other proxies, allowing reconstruction of area burned and carbon dynamics over millennial time scales (Girardin 2007, Marlon et al. 2008). The growth of spatial fire-scar networks around the world (Veblen et al. 2003, Yocom et al. 2010) promises to reveal new insights about the range of variability of fire as a keystone ecological process in the earth system.

Panel 1. The fire-scar record

Ecologists have long recognized the potential for fire scars to date past fires. Clements (1910) and Keen (1937) observed fire scars on trees and understood that they captured the record of an ecological process. Pioneering work by Weaver (1943) and Arno (1976) in the inland Northwest, Kilgore (1973) in the Sierra Nevada, and Dieterich and Swetnam (1984) in southwestern US developed the techniques for reconstructing past fires from fire scars.

Using dendrochronological methods, fire scars can be dated to their exact calendar year and their locations mapped precisely. During surface fires, heated combustion gases interact with fine surface fuels to create a region of persistent high temperatures, usually on the uphill side of a tree; smoldering combustion can cause additional damage to the basal cambium (Gutsell and Johnson 1996; Figure 1.a). Heat penetrating the bark kills part of the vascular cambium, causing a lesion, or fire scar, where further radial growth cannot occur. In subsequent years, the tree compartmentalizes the lesion, producing woundwood that scars more readily in a subsequent fire than the remaining bole because it has thinner bark. Some species also partition the wound with protective resins; where these flammable resins exude onto the surface, they increase the likelihood of subsequent scarring. Repeated scarring before the cambium can fully reestablish produces a cavity surrounded by woundwood ribs, termed a catface (Figure 1.b).

In a carefully sanded cross section, xylem cells are visible under moderate magnification (Figure 1.c). To identify the correct calendar year of formation for each ring, dendrochronologists apply a pattern-matching process known as crossdating, which adjusts for growth anomalies such as false or partially absent rings. Fire scars are clearly visible in cross section and can generally be dated to their exact year of occurrence by determining the date of the annual ring in which they occur, even if the tree was dead when sampled (Figure 1.d).

**Panel 2. Interpretation and inference in fire history**

Like all paleoecological records, fire scars require careful interpretation. The presence of a scar indicates heat energy sufficient to wound the tree, but not enough to cause mortality by killing roots, cambium, or crown (Panel 1). Thus, a fire scar (like many ecological legacies) is context-dependent evidence that forms only under a prescribed range of physical and biological conditions. The same may be said of almost any paleoecological evidence; for example, stand origin cohorts and sediment charcoal records predominantly reflect high-severity stand replacing fires.

The *lack* of a scar, however, is more uncertain evidence. Fire-scar formation and retention are dependent on fine-scale variation in bark thickness, heat load at the time of a fire, and subsequent events that may burn off lesions from earlier events (Gutsell and Johnson 1996, Stephens et al. 2010). Thus, whereas a scar is affirmative evidence of fire, the absence of a scar is not necessarily evidence of the absence of fire, at least at the scale of an individual tree.

This simple asymmetry has generated an ongoing debate about interpretation and inference of the fire-scar record (Baker and Ehle 2001). Spatial scale is central to this discussion. For example, what do the point records of wounded trees tell us about the behavior of fire across larger landscapes? Are areas where fire scars are found different in some way from other parts of the landscape? How can we infer properties of mixed- and high-severity regimes from the fire scars that form along their perimeters or in mosaics of varying severity?

Recent work is beginning to shed light on these questions. Sibold et al. (2006) and Margolis et al. (2009) combined fire scars with stand origin dates to reconstruct fire history in subalpine forests in Colorado and New Mexico with mixed-severity fire regimes. They found that fire dates represented by demographic evidence were generally a subset of fires captured by fire scars at lower elevations, suggesting the expression of interacting top-down and bottom-up controls across landscape gradients. Studies combining fire-spread modeling and fire atlases with fire-scar evidence can help to calibrate the historic record (Fulé et al. 2003, Farris et al. 2010). Better understanding of the mechanisms of scar formation will also help explain some of the observed variability in scar formation in real landscapes.

**Table 1.** Fire regimes are governed by the interaction of top-down and bottom-up factors operating over a range of scales of space and time.

|  |  |  |
| --- | --- | --- |
|  | Top-down regulation | Bottom-up regulation |
| Signature | Persistent synchrony over large spatial scales beyond the scale of fire spread, leading to widespread or limited regional fire years | Spatial heterogeneity in fire occurrence and severity across areas receiving similar climate |
| Drivers | Interannual to millennial climate variation | Spatial variation in fuels (mass, condition, and distribution), topography, and fire weather |
| Mechanism | Regional droughts and pluvials regulate fuel production (years to decades) and flammability (years); succession and vegetation types govern fire regime | Variation in factors that control fire behavior leads to variation in fire spread and effects; post-fire landscape legacies |
| Typical Scale | > 104 ha | 10‐4 – 104 ha |

**Figure Captions**

**Figure 1** (In Panel 1). Reconstruction of historical fires begins with processes such as low-severity surface fire that scar a living tree (upper left), often several times during its lifetime (upper right). Scars appear as growth lesions occurring in a specific growth-year ring when viewed in cross-section (lower right). When fully crossdated, scarred trees can provide accurate records of multiple events with annual resolution (lower left).

**Figure 2.** A variety of sampling designs are used to create spatial fire-scar networks in western North America. a. Fire-scarred trees sampled in the Swauk Creek watershed, Washington (Everett *et al.* 2000); points are individual trees. b. Elevation transect in the Santa Fe Watershed, New Mexico (Margolis and Balmat 2009); black triangles are fire-scarred trees, sampled opportunistically; white circles are tree demography plots used to determine age structure. c. Systematic sampling grid in the Blue Mountains, Oregon; points are 1-ha multiple-tree composites (Heyerdahl et al. 2001).

**Figure 3**. The fire-scar network for western North America, includes 475 locations recorded in the IMPD and an additional 150 recent studies compiled for this article.

**Figure 4.** Annual fire areas reconstructed from fire-scar networks. a. Fire perimeters in the Rincon Mountains, Arizona, USA. Upper panels (1954 and 1994): shaded polygons are fire area reconstructed from fire scars; red outline indicates NPS mapped fire perimeter. Lower panels (1822 and 1851): Shaded polygons are fire area reconstructed from fire scars using the same interpolation algorithm. Based on Farris et al. (2010). b. Reconstructed burned likelihood for 1895 in the Swauk Creek, eastern Washington, USA using (a) indicator kriging, (b) inverse distance weighting, and (c) Theissen polygons. Warmer colors indicate higher likelihood that an area burned (Hessl et al. (2007).

**Figure 5.** Relationship between number of fire events recorded at a site and elevation by aspect in the Kaweah River watershed, Sequoia and Kings Canyon National Parks, CA. Fire frequency declines with elevation on south facing slopes, but elevation has little effect on fire frequency on more mesic north slopes. Open triangles in Panel B are from a similar elevation transect near Giant Forest (Caprio 2004.

**Figure 6**. Landscape partitions are reflected in multi-century similarity in fire occurrence. Shaded polygons indicate areas with persistent similarity over many years of fire occurrence, derived by multivariate analysis. Under extreme weather conditions, fire can over-run topographically controlled fire boundaries (Taylor & Skinner 2003).

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