

Multi-scale controls of historical forest-fire regimes: new insights from fire-scar networks

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Anticipating future forest-fire regimes under changing climate requires that scientists and natural resource managers understand the factors that control fire across space and time. Fire scars – proxy records of fires, formed in the growth rings of long-lived trees – provide an annually accurate window into past low-severity fire regimes. In western North America, networks of the fire-scar records spanning centuries to millennia now include hundreds to thousands of trees sampled across hundreds to many thousands of hectares. Development of these local and regional fire-scar networks has created a new data type for ecologists interested in landscape and climate regulation of ecosystem processes – which, for example, may help to explain why forest fires are widespread during certain years but not others. These data also offer 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.

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Fire is a fundamental Earth-system process, linking ecosystems, biogeochemical cycles, and climate variability (Bowman *et al.* 2009). Understanding what controls fire regimes – the aggregate properties of multiple fires characteristic to an ecosystem – is of growing importance as the size and severity of forest wildfires increase in many regions. Regional to global climatic variability has been a primary driver of fire-regime variability for millennia (Swetnam and Anderson 2008; Whitlock *et al.* 2010), including the 20th century (Littell *et al.* 2009). Recent warming in some regions and ecosystems and at some elevations is at least partly responsible for the increase in the

number and size of wildfires (Westerling *et al.* 2006).

Fire regimes are also driven by relatively fine-scale, local conditions, particularly the spatial and temporal distributions of flammable fuels and ignitions as determined by complex interactions between physical and ecological processes. These controls frame a central challenge in understanding fire regimes: some dynamics are driven primarily by regional climate, others primarily by local ecology and/or humans, and still others – perhaps most commonly – by combinations of these factors. Furthermore, human influences on both fire regimes and climate have expanded from local to regional and even to global scales. Therefore, to understand how fire regimes vary, we need to understand the effects of physical, ecological, and human factors across multiple scales of time and space (Parisien and Moritz 2009; Turner 2010).

Fire is a spatial and temporal process, driven by controls acting across a range of scales. Scale considerations are central in the development of modern ecology (Ricklefs 1987; Turner 2010) and consequently in fire science as well. Although understanding of fire as a landscape process is progressing (McKenzie *et al.* 2011), long time series of linked ecological pattern and process data are rare, especially records spanning a century or longer across landscapes and regions. Fire-history studies are beginning to provide the necessary data for investigation of past and present fire regimes across these broader scales of space and time. One example is the recent proliferation of sedimentary charcoal-based fire histories that are now providing insights into changes in fire regimes and biomass burning at continental and millennial scales (Gavin *et al.* 2007; Marlon *et al.* 2008).

At fine scales, when and where fires start depend largely on the distribution and properties of fuels and ignitions.

In a nutshell:

- Tree-ring fire history networks provide accurate, high-resolution records spanning temporal scales from seasons to centuries and spatial scales from landscapes to continents
- Variations in fire synchrony across scales reflect interactions between local and regional controls of fire regimes, including physical, biological, and human factors
- Understanding past and present fire regimes and their controls allows ecologists and managers to anticipate future fire regimes as forests and climate change

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Panel 1. The fire-scar record

Ecologists have long recognized the potential for fire scars to date past fires. Clements (1910) and Leopold (1924) 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 the southwestern US developed the techniques for reconstructing past fires from fire scars.

Using dendrochronological methods, researchers can date fire scars to their exact calendar year and map their locations precisely (Figure 1). 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 (Gutsell and Johnson 1996); smoldering surface fuels contribute additional heat flux to the tree base and roots after passage of the flaming front. Heat penetrating the bark kills part of the vascular cambium (the layer of actively dividing cells between wood and bark tissues responsible for the annual increase in tree diameter), causing a lesion – a fire scar – where further radial growth cannot occur. In following 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 (Figure 1a). Repeated scarring before the cambium can fully reestablish produces a cavity surrounded by woundwood ribs, termed a “catface” (Figure 1b).

In a carefully sanded cross section, xylem cells are visible under moderate magnification (Figure 1c). To identify the correct calendar year of formation for each ring, dendrochronologists apply a pattern-matching process known as “crossdating”, which identifies and corrects for growth anomalies such as false or 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 1d).

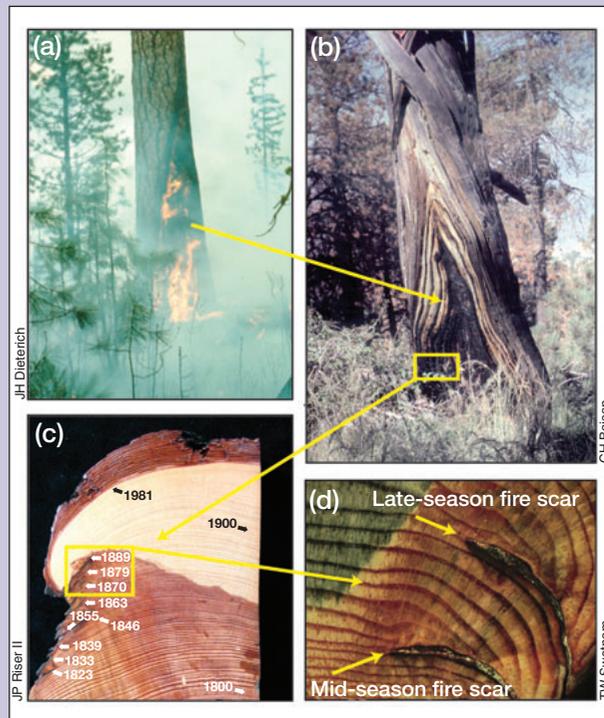


Figure 1. Reconstruction of historical fires begins with processes such as low-severity surface fire that (a) scars a living tree, (b) often several times during its lifetime. (c) When crossdated, scars can provide accurate records of multiple fires with annual resolution. (d) Scars appear as growth lesions occurring in a specific growth-year ring when viewed in cross section.

Once a fire has ignited, its rate and direction of spread are controlled by local fuel conditions, weather, and topography. These fine-scale, *bottom-up* controls modify fire physics and behavior, and consequently effects on vegetation and soils. Thus, most fires create mosaics of fire severity, a signature of bottom-up regulation (see www.mtbs.gov for modern trends in burn severity in the US; Table 1). This heterogeneity affects a wide range of ecosystem components, such as wildlife habitat, soil, and hydrology, and ecological processes, such as forest dynamics, carbon sequestration, and insect outbreaks, as well as influencing subsequent fires (Collins and Stephens 2008; Turner 2010).

Climate variation at interannual to centennial (and longer) time scales tends to have the opposite effect, by synchronizing regional and subcontinental fire occurrence. Climate thus acts as a *top-down* control, the signature of which is synchronous fire occurrence among sites beyond the reach of a single spreading fire, in contrast to the patchy landscape patterns created by bottom-up regulation (Table 1). Understanding the interplay of bottom-up and top-down controls on fire is thus central to understanding fire as an ecosystem process, and to managing fire in the presence of rapid changes in land use and climate (Heyerdahl *et al.* 2001; Falk *et al.* 2007).

Fire history can be reconstructed from a variety of proxies, including forest stand ages and their landscape distribution (Heinselman 1973; Margolis and Balmat 2009). Here, we focus on dendrochronologically crossdated fire-scar networks from low- and mixed-severity fire regimes (Panel 1). The high temporal (to season) and spatial (to tree level) resolution of such records offers unique opportunities for multi-scale ecological analyses. Using examples from recent publications, we demonstrate how these high-resolution temporal data can be linked in a spatially explicit framework to provide new insights into fire regimes. We also discuss questions of interpretation and inference, as well as knowledge gaps, and we examine how these emerging networks are proving useful to land managers.

■ 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 predate this time of great change in some forest types (Panel 2). Most fire scars form on trees in forests that historically sustained

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

	<i>Top-down regulation</i>	<i>Bottom-up regulation</i>
Signature	Persistent annual synchrony of fire- and non-fire years at regional or broader scales	Spatial heterogeneity in fire occurrence, extent, or severity across areas with similar climate
Drivers	Interannual to millennial climate variation	Temporal or spatial variation in fuels (amount, condition, and distribution), ignition sources, topography, weather, and barriers to fire spread
Mechanism	Variations in temperature and moisture associated with regional droughts and pluvials (wet periods) regulate fuel production and flammability; succession and vegetation types govern fire regime	Variation in factors that control ignition and fire behavior leads to variation in fire timing, spread, and effects; post-fire landscape legacies
Typical scale	> 10 ⁴ ha	10 ⁻⁴ –10 ⁴ ha

primarily low-severity fires, although trees also scar along the perimeter of forest patches that burned with high severity (ie where all trees were killed) or in low-severity burn patches within landscape mosaics of varying burn severity (Kipfmüller and Kupfer 2005; Margolis and Balmat 2009).

Networks of fire-scarred trees can be analyzed across a wide range of spatial scales (Figure 2). Local-scale studies may focus on fire seasonality, episodes of tree mortality, and fire as a driver of stand demography. In other studies, trees are sampled to explore variation across environmental gradients, such as elevation, vegetation, and microclimate, leading to inferences about bottom-up drivers of fire regimes (Brown *et al.* 2001; Heyerdahl *et al.* 2001; Fulé *et al.* 2003; Sherriff and Veblen 2007; Margolis and Balmat 2009).

As local fire histories have proliferated across North America, they have been combined into broader-scale networks that are proving especially useful for understanding regional variation in top-down drivers of fire

occurrence over time, including large-scale climate patterns, such as the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO; Swetnam and Betancourt 1998; Kitzeberger *et al.* 2007), and the Pacific North American (PNA) pattern (Trouet and Taylor 2010). These broad-scale fire–climate analyses are novel in that they provide a view of how fire responds to low-frequency climatic variation that cannot be explored with relatively short modern instrumental climate records (Figure 2).

Regional to continental fire-scar networks are expanding as dendrochronologists build chronologies in Europe, Asia, and South America (see Web-only materials). A driving rationale for this work is to understand broad-scale interactions between climate, fire, human activities, and carbon dynamics. The International Multiproxy Paleofire Database (IMPD) was created to facilitate the analysis of such networks through public archiving of fire chronologies, and now holds more than 400 fire-scar

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 but not kill the tree – for example, 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 most paleoecological evidence; for instance, 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 depend on fine-scale variation in bark thickness, heat load at the time of a fire, and subsequent events that may consume scars from earlier fires (Gutsell and Johnson 1996; Stephens *et al.* 2010). Thus, whereas a scar is affirmative evidence of fire, the absence of a scar does not necessarily prove the absence of fire, at least at the scale of an individual tree.

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

Although uncertainties remain, recent work has demonstrated that fire-scar networks accurately record the occurrence, extent, and frequency of historical low- and mixed-severity fire occurrence. Intensive studies have examined a complete site census of fire-scarred material, testing whether differences in sample selection affected the interpretation of fire-regime characteristics (Van Horne and Fulé 2006). Studies combining fire-spread modeling and fire atlases with fire-scar evidence have corroborated the historical and modern records (Fulé *et al.* 2003; Farris *et al.* 2010). Better understanding of the observed variability in scar formation across real landscapes (Stephens *et al.* 2010) is helping to elucidate some of the mechanisms of fire-scar formation.

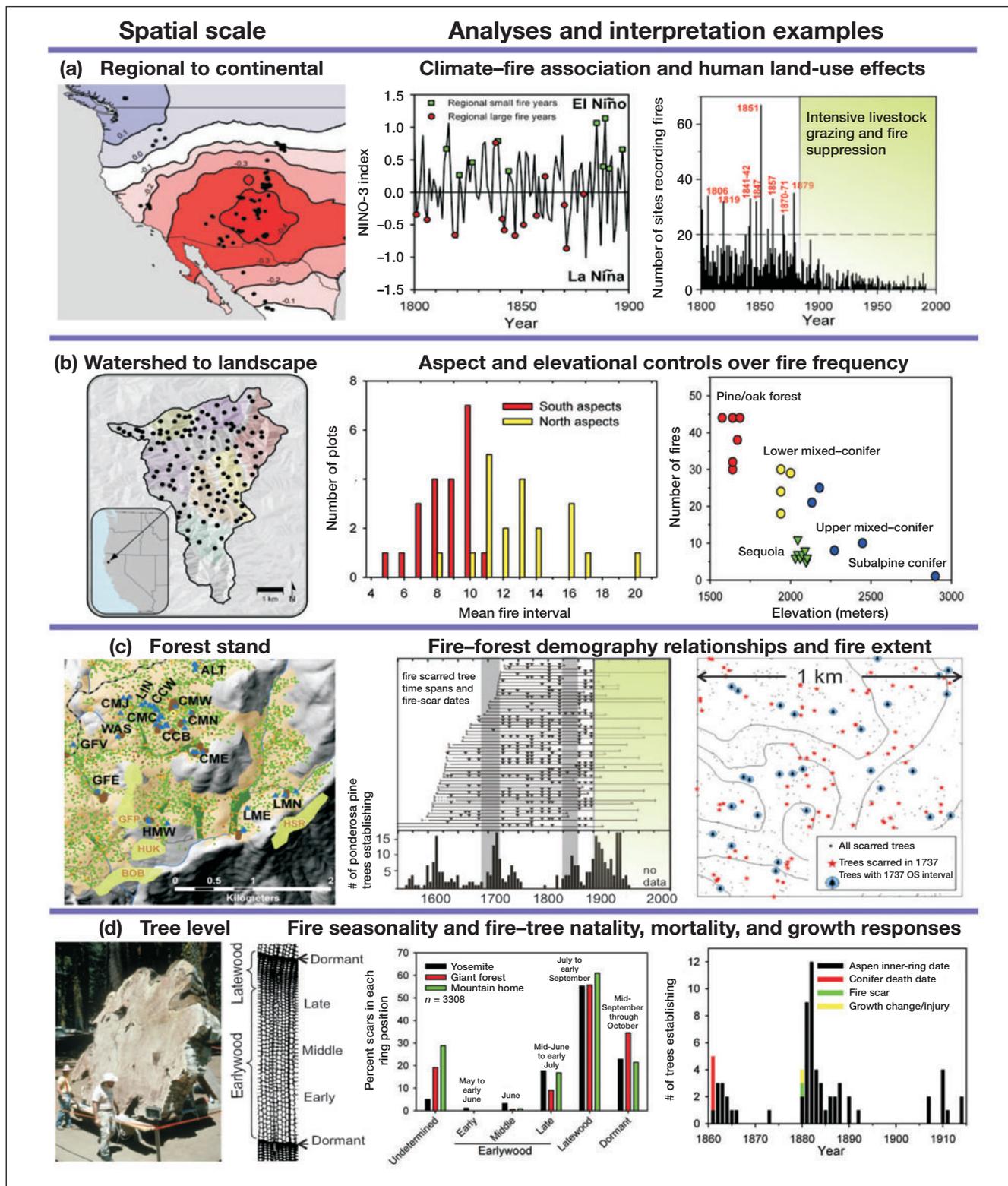


Figure 2. Fire-scar networks can be created and analyzed at a range of spatial scales, from trees and stands to subcontinents, revealing different patterns and processes at different scales. (a) At regional to subcontinental scales, extensive fire-history networks are analyzed in aggregate to identify widespread fire–climate associations and human land-use effects. (b) Watershed and landscape networks can be used to explore topographic controls, such as aspect and elevation, on fire regimes. (c) At forest-stand scales, fire-scarred trees and tree ages can be sampled systematically or randomly to investigate fire–forest demography relations and patterns of synchrony related to fire spread. (d) Studies of individual trees can identify the seasonality of historical low-severity fires, tree-ring growth responses (releases and suppressions), and dates of tree recruitment or death. See WebPanel 3 for more detailed descriptions and references.

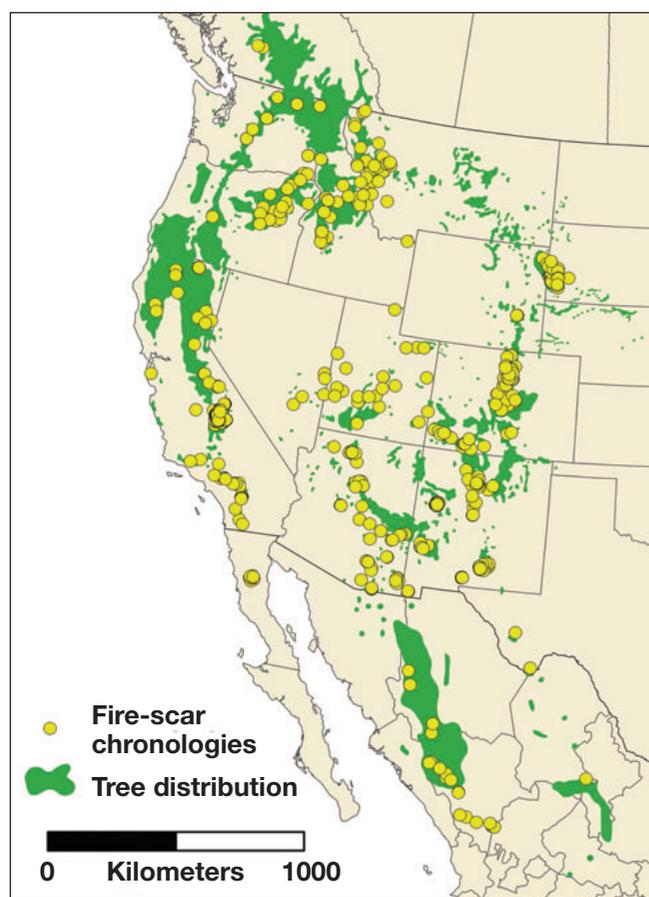


Figure 3. The fire-scar network for western North America includes 415 fire chronologies recorded in the International Multiproxy Paleofire Database and an additional 468 fire chronologies not archived in this database. Tree distribution in the map base layer is the range of giant sequoia (*Sequoiadendron giganteum*), ponderosa, and related pines in Mexico, species that are well represented in the fire-scar record.

records (WebPanel 1). We have compiled more than 460 additional crossdated fire-scar chronologies from western North America that are not yet archived in the IMPD (Figure 3).

Ecological insights from multi-scale fire-scar networks

These new multi-scale fire-history networks provide unprecedented opportunities to examine how climate, vegetation, and topography influence low- and mixed-severity fire regimes over space and time (Kellogg *et al.* 2008). The potential strength of these inferences derives from the increased statistical power that comes from sampling a large number of extensively distributed sites, and from the distribution of samples and plots along biophysical gradients at multiple scales. Below, we focus on three areas of broad interest to ecologists, in which analysis of multi-scale fire-scar networks has enabled substantial scientific progress.

Mapping historical fires

Fire-scar networks can yield basic information about when and where fires occurred (Swetnam *et al.* 2011). Fire perimeters reconstructed from scars correspond well to those mapped from direct observation and from remotely derived data, confirming their reliability as recorders of past fires.

For example, Farris *et al.* (2010) compared fire dates and perimeters reconstructed from systematically sampled fire scars with dozens of historical fires that were mapped independently over a 64-year period by foresters and surveyors in a 2780-ha area of the Rincon Mountains of southern Arizona. Fire scars recorded a complete inventory of all independently mapped fires larger than 100 ha, and even detected some fires that were not mapped (Figure 4). When applied to the patterns of pre-20th-century fire scars, their interpolation method reveals the perimeters of historical fires for which there are no maps. Similarly, Hessl *et al.* (2007) used a network of fire-scarred trees in eastern Washington State to test spatial algorithms for interpolating point data to landscape scales, demonstrating that fire-scar networks can be used to reconstruct perimeters and heterogeneity in burn patterns (Figure 5).

Fire-scar networks can also yield estimates of the extent of large historical fires. In some landscapes, fire-scar networks may not capture every small fire, but they reliably capture large fires, which generally account for most of the area burned. This information could help resolve a current debate about whether contemporary fires are larger and/or more severe than historical fires. Fire-scar networks show that low-severity fires in many dry forests and woodlands burned large areas, often hundreds of square kilometers. The tree-ring record illustrates clearly that in many low- and mid-elevation forests these fires did not cause widespread overstory tree mortality, indicating that they were primarily of 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 in 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

Topographic variation influences the local distribution of plant communities and, together with vegetation, forms the dominant bottom-up control of forest wildland fires (Taylor 2000; Heyerdahl *et al.* 2001; Table 1). For example, aspect and elevation strongly affect solar insolation (exposure to sunlight), which in turn controls dominant vegetation types as well as the amount and moisture content of fuel, and the period during which fuels are dry enough to burn (the fire season). Fuel type and fuel moisture content also vary with elevation, in response to variations in temperature and evaporation rate during the fire season. Dry surface fuels, consisting of long-needled litter and cured

grasses in low-elevation forests of ponderosa (*Pinus ponderosa*) or other pines, tend to facilitate fire spread. By contrast, in mesic high-elevation mixed-conifer (*Pinus*, *Pseudotsuga*, and *Abies* spp) and spruce-fir (*Picea* and *Abies* spp) forests, higher fuel moisture and denser surface fuel beds derived from short-needled species inhibit fire spread except under extreme weather conditions.

Spatial fire-scar networks reveal how historical fire regimes reflected the biophysical template across which they burned (Heyerdahl *et al.* 2001; Taylor and Skinner 2003; Heyerdahl *et al.* 2007; Sherriff and Veblen 2007). Studies in Grand Canyon National Park and the Arizona Sky Islands show that contrasting north and south aspects led to a mixture of fire frequencies and severities in close proximity (Fulé *et al.* 2003; Iniguez *et al.* 2008; Figure 2b). 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 moisture content is higher, regardless of aspect.

Interactions 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 State, Heyerdahl *et al.* (2001) 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 as 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 northern California, Taylor and Skinner (2003) identified persistent similarities in fire chronologies within landscape compartments (ie spatially coherent areas separated by features such as ridges, streams, and aspect changes; Figure 2b). These bottom-up controls served as filters to fire spread, rather than absolute barriers: during years of extreme drought, top-down controls created weather and fuel conditions that overrode bottom-up controls, allowing fires to cross barriers that impeded fire spread under more moderate conditions and spread among landscape compartments.

Recent studies of large landscapes where modern fires burn freely, as well as fire-history studies, reveal fire's self-limiting properties across scales (Collins and Stephens 2008; Scholl and Taylor 2010). Reconstructing fire

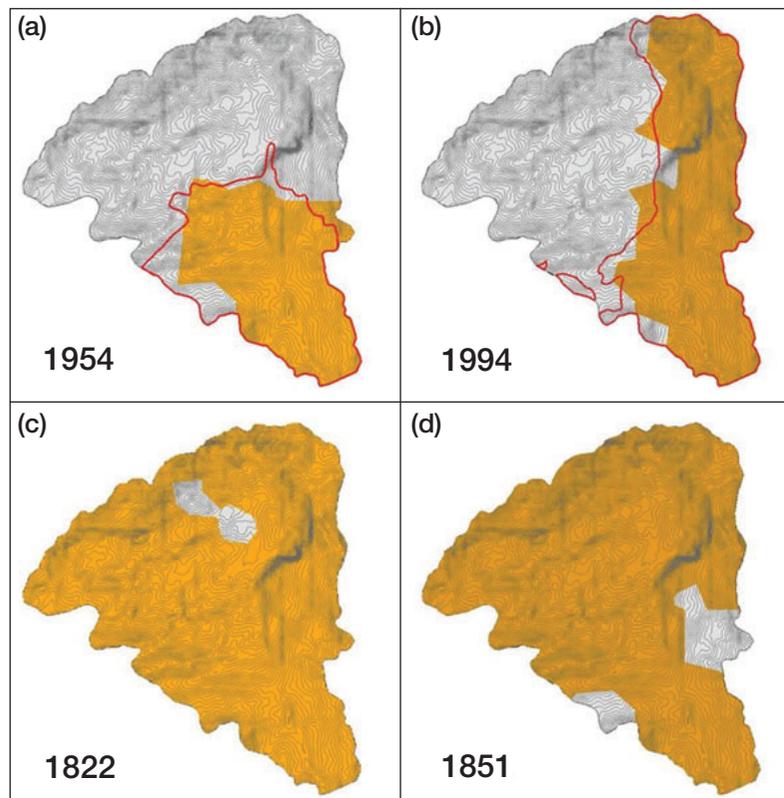


Figure 4. Fire perimeters in the Rincon Mountains, Arizona, reconstructed from a 2780-ha fire-scar network. (a and b): Shaded polygons represent fire areas in 1954 and 1994 reconstructed from fire scars; red outline indicates National Park Service-mapped fire perimeters. (c and d): Shaded polygons represent fire areas for 1822 and 1851, reconstructed from fire scars based on the same interpolation algorithm. Derived from Farris *et al.* (2010).

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 changes in climate. These fuel mosaics influence the behavior of subsequent fires and provide a window into how fire and vegetation interacted before the fuel environment was modified by intensive management.

Applications to ecosystem management

Fire history has long guided ecosystem management in the American West. Weaver (1943) based his recommendations for prescribed burning at the Colville and White Mountain Apache reservations in Washington State and Arizona on insights gained from studies of 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 to be an anomalous and unnatural process.

Spatial fire-scar networks provide managers and scientists with insights into how fire functions in ecosystems lacking the pervasive effects of fire suppression, livestock

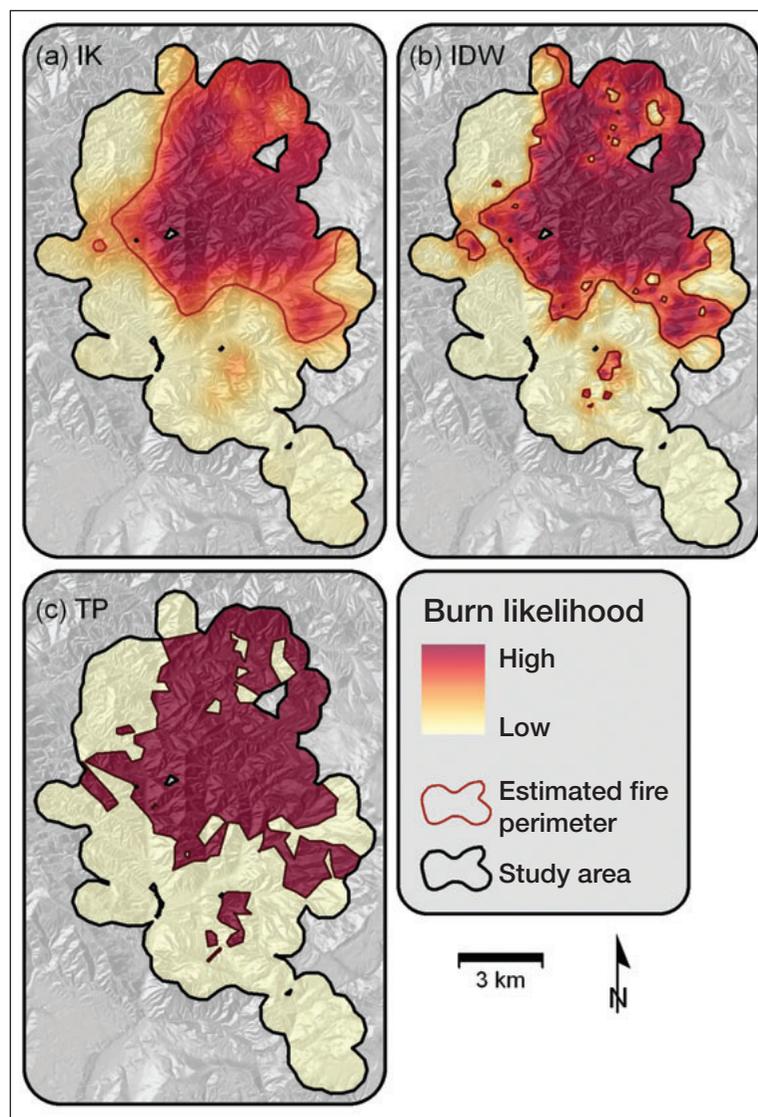


Figure 5. Reconstructed burned likelihood for 1895 in the Swauk Creek watershed, eastern Washington State, through (a) indicator kriging (IK), (b) inverse distance weighting (IDW), and (c) Theissen polygons (TP). Red, orange, and yellow indicate higher likelihood that an area burned (Hessl *et al.* 2007).

grazing, and logging that influence modern fires. For example, in Sequoia and Kings Canyon National Parks, decades of fire-history research “provided a firm justification and basis for the development of the Parks’ prescribed and natural fire management programs” (NPS 2010). This included studies of topographic and climatic controls of fire regimes, departures from historical fire intervals, and landscape patterns of fire severity derived from park-wide fire-scar networks (Caprio 2004).

Fire severity

A key concern in contemporary forest management is the severity and extent of 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 combined fire scars and tree demography to demonstrate differences in past fire regimes as compared with the extensive high-severity fires that currently burn these forests. Other studies, conducted at higher elevations or along elevation gradients, have found a continuum of fire severity, with frequent surface fires at low elevations and infrequent stand-replacing events in higher elevation forests (Sherriff and Veblen 2007; Margolis and Balmat 2009). The Sequoia and Kings Canyon National Parks Fire Management Plan (NPS 2010) used maps of historical 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 ponderosa-pine and mixed-conifer belts, but not in red-fir (*Abies magnifica*) forests at higher elevations, suggesting that fuel type and increasing moisture levels (snow line) along an elevation gradient limited the upslope spread of fire (Taylor 2000). Historical fires were, on average, 20 times the size of contemporary prescribed burns, indicating that the spatial scale of contemporary management burns did not fully represent the historical fire regime. This led to a shift by park managers toward larger burns and use of topographic features such as stream courses, ridge tops, and lava flows to create natural fire compartments (NPS 2005).

The role of climate

Despite more than a century of land-use change, 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 inform scientists and managers about the drivers of modern fires. 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, leading to a broad range of ecological inferences across landscapes and regions. The fire-scar network can be coupled with tree-ring width, sediment charcoal, and other proxies to allow reconstruction of area burned and carbon dynamics over centennial to millennial time scales (Girardin 2007; Whitlock *et al.* 2010). The growth of spatial fire-scar networks around the world (Veblen *et al.* 2003; Yocom *et al.* 2010) promises to reveal new insights about fire as a key-stone ecological process in the Earth system.

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