Chapter 8
Deciphering the Complexity of Historical Fire Regimes: Diversity Among Forests of Western North America

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Abstract Wildfire is a key disturbance agent in forests worldwide, but recent large and costly fires have raised urgent questions about how different current fire regimes are from those of the past. Dendroecological reconstructions of historical fire frequency, severity, spatial variability, and extent, corroborated by other lines of evidence, are essential in addressing these questions. Existing methods can infer the severity of individual fires and stand-level fire regimes. However, novel research designs combining evidence of stand-level fire severity with fire extent are now being used to reconstruct spatial variability in historical fire regimes and to quantify the relative abundance of fire severity classes across landscapes, thereby facilitating comparison with modern fire regimes. Here we review how these new approaches build on traditional analyses of fire scars and forest age structures by presenting four case studies from the western United States and Canada. Collectively they demonstrate the importance of ecosystem-specific research that can guide management aiming to safeguard human, cultural and biological values in fire-prone forests and enhance forest resilience to the cumulative effects of global environmental change. Dendroecological reconstructions, combined with multiple lines of corroborating evidence, are key for achieving this goal.

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8.1 Introduction

Wildfire is a key agent of ecological disturbance in forests worldwide (Bowman et al. 2009). In western North America, fire drives vegetation dynamics, underlies many ecological patterns, and explains ecosystem heterogeneity at a range of spatio-temporal scales (Turner 2010). Subtle changes to fire regimes in western forests can have major impacts on forest composition, structure, biodiversity and productivity (Turner 2010). Changes to fire frequency and severity driven by land use and fire suppression, exacerbated by climate change, have the potential to exceed the historical range of variation of environmental conditions in which species evolved and ecosystems have functioned (Landres et al. 1999; Swetnam et al. 1999). Thus, understanding historical fire regimes and their drivers can help identify vulnerable ecosystems in which active management can enhance forest resilience to the cumulative impacts of environmental change (Stephens et al. 2013). Equally important, ecosystem-specific knowledge can identify forests in which fire regimes have not departed from the historical range of variation, and where management investments are not needed or may compromise ecosystem function or services (Schoennagel and Nelson 2011; Stephens and Fulé 2005; Odion et al. 2014).

Dendroecological research has been instrumental for reconstructing historical fire regimes and quantifying their key attributes. A fire regime is the pattern of the temporal (seasonality, frequency and predictability) and spatial (location, extent and spatial complexity) occurrences of fire, the magnitude (type, intensity and severity) of fire effects, and interactions of fire with other disturbance agents (Agee 1993; Turner 2010). Describing fire regime attributes requires accurate documentation of individual fires. To extend modern fire records back decades or centuries, reconstructions of past fires can be achieved by dendroecological analyses corroborated by multiple lines of evidence (Swetnam et al. 1999). This research framework has facilitated significant advances in our understanding of fire regimes over recent decades, shifting the focus from fire frequency to more nuanced analyses of fire severity, extent and spatial complexity.

In this review, we show how contemporary research focused on mixed-severity fire regimes builds on traditional analyses of fire scars and forest age structures. Novel research designs facilitating analyses across spatial scales and analytical methods for quantifying fire severity and spatial variability allow more nuanced characterization of the spatio-temporal variation in fire regimes. We present four case studies illustrating a variety of research approaches and the complexity of historical fire regimes across forest types in the western United States and Canada. Collectively, they demonstrate the importance of ecosystem-specific research to guide management that aims to safeguard human, cultural and biological values in fire-prone forests and enhance forest resilience to the cumulative effects of global environmental change.

8.2 Fire Regime Reconstructions

Traditionally, fire history research focused on two contrasting fire regime types simplified as high- *versus* low-frequency. The research methods, including dendrochronological evidence, used to reconstruct fire frequency of these contrasting regimes reflect the differences in impacts and physical evidence left by presumably surface *versus* crown fires.

8.2.1 High-frequency, Low-severity Fire Regimes

High-frequency fire regimes are characterized by relatively low-severity surface fires that burn at short intervals, causing low levels of canopy tree mortality (e.g., stand-maintaining fires; Schoennagel et al. 2004). Fire scars on individual live trees, stumps, snags or logs provide point-specific, direct evidence of low-severity fire that damages, but does not kill the tree (Swetnam and Baisan 1996, Swetnam et al. 1999, Yocom Kent 2014; Table 8.1; Fig. 8.1). Scars caused by fire are differentiated from other disturbances (e.g. bark beetles, animals, tree falls or cultural modification by humans) based on their triangular shape at the base of the tree and the presence of charred bark, healing lobes or exposed wood on the face of the scar (McBride 1983; Smith and Sutherland 2001). When properly crossdated, scars provide the exact year of fire occurrence and often season can be determined from the position of the scar within an annual growth ring (Dieterich and Swetnam 1984; Caprio and Swetnam 1995). The presence of resin ducts or micro rings provides secondary dendroecological evidence to corroborate fire scar dates (Brown and Swetnam 1994; Smith et al. 2016). Often large and presumably old trees with multiple scar lobes are targeted to maximize the fire record (Swetnam and Baisan 1996; Swetnam et al. 1999). Fire-scar records from individual trees can include multiple fires over several centuries, depending on the lifespan of the species, rates of wood decomposition, and occurrence of subsequent fires that consume fire-scarred trees (Swetnam and Baisan 1996; Swetnam et al. 1999).

At the site level, sampling multiple fire-scarred trees serves several purposes (Swetnam and Baisan 1996, Swetnam et al. 1999; Fig. 8.1). Replicate samples corroborate fire dates among trees and differentiate spreading fires that scar multiple trees from small isolated fires that scar single trees, although not all burned trees form a scar. Composite fire-scar records from multiple trees are used to calculate site-level fire frequency metrics, such as mean, median, minimum and maximum intervals and time since last fire. Because fire frequency metrics are sensitive to number of samples and the area sampled (Falk et al. 2007), consistency among sites reduces potential bias (Amoroso et al. 2011). Alternately, many fire history studies report fire intervals for the subset of years in which fires scarred at least two trees or at least 10% or 25% of recorder trees (Swetnam and Baisan 1996). Trees are considered recorders after an initial scar exposes the cambium and

Table 8.1 Comparison of fire scars and forest demography (tree age, growth and death data) for reconstructing past fires and interpreting historical fire regimes

Criterion	Fire scars	Forest demography
Advantages	Crossdated samples precise to year (and sometimes season) of fire; most utility for reconstructing low- and mixed-severity fire regimes	Most utility for reconstructing mixed- and high-severity fire regimes; corroborating evidence for low-severity fires or confirming fire as the agent of disturbance
Disadvantages	Time period limited by oldest wood; older scars lost in subsequent fires; limited to forest types where trees form scars; not all fires scar trees; research and sampling designs can introduce bias; mean intervals vary with sample size and area sampled	Reconstructions are strongest for the period following the last mixed- or high-severity fire; older evidence lost in subsequent fires; fire dates not precise due to post-fire regeneration lags; fine-scale fires difficult to reconstruct
Amount of uncertainty	None at the point of a scarred tree; uncertainty about fire extent between scarred trees	Causal agent and fire dates uncertain unless accompanied by fire scar
Direct/indirect evidence	Direct at point of a scarred tree; indirect when inferring spread between scarred trees	Direct for year of death of fire-killed trees; indirect when inferring fire from even-aged cohort or growth releases
Assumptions	Multiple fire-scarred trees in a study site in the same year are the result of a spreading surface fire, not individual fires at each tree	Even-aged cohorts, tree releases or deaths caused by fire and not another disturbance agent
Length of reconstruction	Decades to centuries depending on species and forest types; limited by loss in subsequent fires or decay	Decades to centuries depending on species and forest types; limited by loss in subsequent fires or decay
Spatial resolution	Individual tree to stand or landscape depending on research design	Stand to landscape depending on research design; small fires difficult to detect
Temporal resolution	Precise to year of fire, sometimes to season	Precise for year of death of fire-killed trees; not precise for tree ages or post-fire cohorts unless corroborated by a fire scar
Reconstruction of fire regime attributes	Direct evidence of fire type, severity, seasonality and frequency; indirect evidence of fire size	Direct or indirect evidence of fire type and severity; indirect evidence of frequency and size; no evidence of seasonality

Adapted from Yocom Kent 2014

increases susceptibility to subsequent fires (Romme 1980). The resulting “filtered” fire interval statistics are relatively immune to changes in sample size or area in some ecosystems (Van Horne and Fulé 2006; Farris et al. 2013), allowing comparison among sites or studies with differing sampling designs (Kitzberger et al. 2007; Falk et al. 2011), but not necessarily for all ecosystems or fire regime types (Stretch et al. 2016).

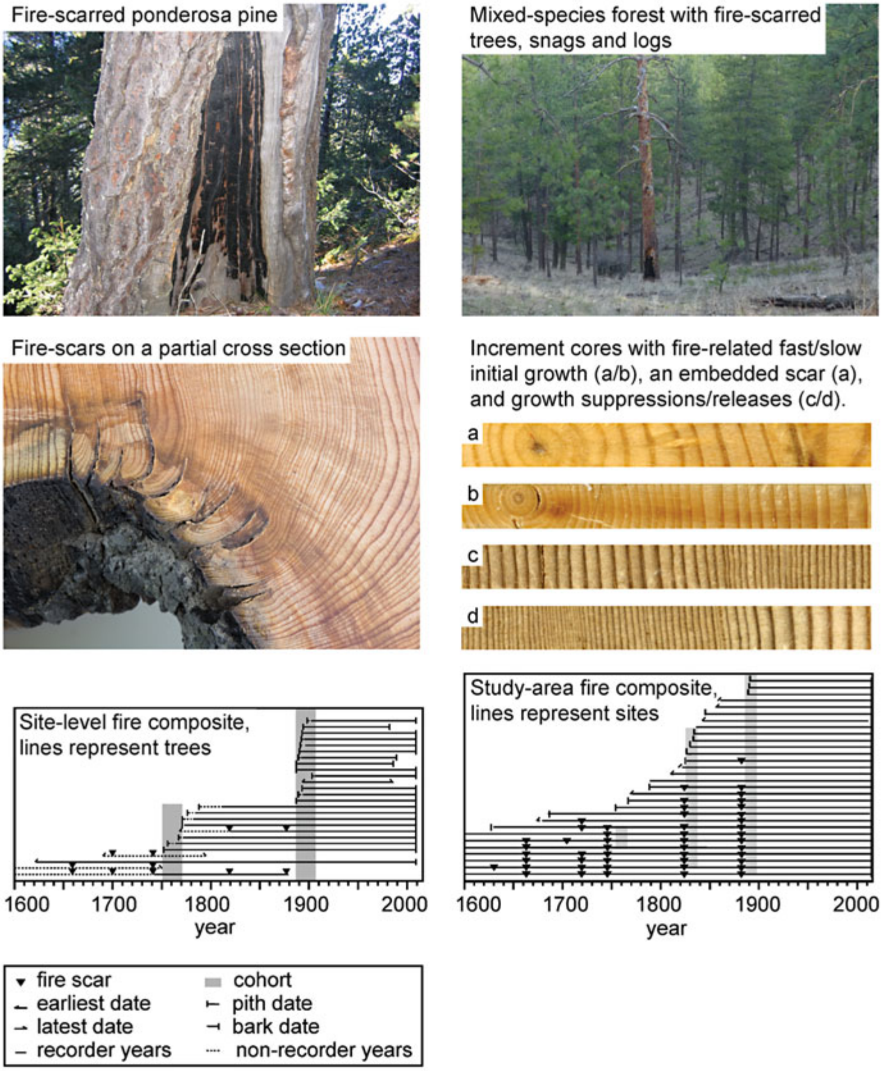

Fig. 8.1 Examples of fire scar, tree growth and forest demography evidence used to reconstruct fire history at tree, site and study area scales (Graphics by R.D. Chavardès)

8.2.2 Low-frequency, High-severity Fire Regimes

In contrast, low-frequency fire regimes are characterized by high-intensity crown fires burning at long intervals causing high levels of tree mortality (e.g., high-severity or stand-replacing fires; Schoennagel et al. 2004). These fires result in forest patches with relatively distinct boundaries that are distinguishable on air photographs and in the field. Forest polygons are mapped and sampled for forest age, with the assumption that even-aged patches of forest were initiated by high-severity fire. Age sampling is often combined with analysis of fire scars formed at polygon boundaries to refine these estimates to an annual level (Johnson and Gutsell 1994; Sibold et al. 2006). Landscape-scale fire history is represented by a stand-origin map (e.g., time since the last stand-replacing fire; Heinselman 1973) or a time-since-fire map (e.g., time since last fire of any severity; Johnson and Van Wagner 1985). Patch sizes and ages are summarized as cumulative time-since-fire (survival) distributions from which the fire cycle, the number of years required to burn an area equal to the study area, is calculated by fitting negative exponential or Weibull models (Van Wagner 1978).

Even-aged cohorts that include the oldest trees in the stand indicate past high-severity disturbances that created openings large enough for many trees to establish simultaneously (Heinselman 1973). Cohorts are indirect evidence of fire because the ages assigned to trees in a cohort are less precise than crossdated fire scars due to lags in tree establishment following disturbance, errors inherent to tree age estimates, and the facilitation of tree establishment by disturbances other than fire or during periods of suitable climate (Yocom Kent 2014; Table 8.1). The importance of these considerations also varies by species composition and environment. Therefore, tree age estimates need to be as accurate as possible (Table 8.2), sample sizes must

Table 8.2 Critical assessment of the accuracy of tree age estimates from increment cores

Attribute	Source of error and *dendroecological method to increase accuracy*
Outer-ring date of living trees	Outer ring dates of living trees may not equal the year of sampling due to competition, disturbance or environmental stress. *Crossdating cores from living trees verifies the calendar year of the outer ring (Cherubini et al.* 2002*; Amoroso and Daniels* 2010*; Jones and Daniels* 2012*)*
Outer-ring date of dead trees	Outer ring dates of dead trees are unknown. *Crossdating estimates the outer ring date and year of death (Daniels et al.* 1997*); but, inaccuracies may result from wood decay and erosion (Jones and Daniels* 2012*)*
Inner-ring date	False or missing rings cause inaccurate calendar years to be assigned to rings causing errors in estimated year of establishment and tree age (outer-ring date—inner-ring date +1). *Crossdating ensures an accurate date is assigned to the inner ring when determining tree age (Fritts and Swetnam* 1989*)*
Pith date	Cores may not intercept the pith, even after multiple cores are extracted from a tree. *The number of missing rings can be estimated from visual assessments (Applequist* 1958*) or geometric measurements of curved inner rings (Duncan* 1989*) or from the length of the core relative to the average tree radius inside the bark at coring height (Norton et al.* 1987*)*
Establishment date	Cores extracted above the root-shoot interface overestimate the establishment date and underestimate age. *Species-specific regressions of age-on-height correct for the number of years to coring height (Villalba and Veblen* 1997*; Wong and Lertzman* 2001*). Height growth rates may vary with resource availability at the time of establishment, requiring different corrections for trees with fast (wide rings) and slow (narrow rings) initial growth*

be sufficient to detect cohorts, and corroborating evidence should support inferences of past high-severity fires. Optimal sample sizes vary among forest types and age. For example, sampling ≥10 of the largest trees in even-aged post-fire lodgepole pine forests is likely to detect the oldest tree to estimate the fire year, but samples sizes of ≥15 large trees are needed in uneven-aged mixed-conifer forests (Kipfmueller and Baker 1998). Multiple lines of evidence differentiate post-fire cohorts from those initiated by insects, pathogens, wind or periods of suitable climate (Ehle and Baker 2003; Brown and Wu 2005; Sherriff and Veblen 2006). Dendroecological evidence corroborating high-severity fire includes (Sibold et al. 2006; Margolis et al. 2007, 2011): (a) a cohort comprised of fire- and shade-intolerant, fast-growing trees indicating establishment in open conditions, (b) fire scars on the boundary of even-aged stands concurrent with cohort initiation, (c) year of death of fire-killed trees (e.g. small or thin-barked trees, trees with charred bark) immediately preceding the cohort, although such evidence decays rapidly in many mesic forests, and (d) few or no remnant trees older than the cohort.

8.2.3 Mixed-Severity Fire Regimes

It is now widely recognized that classifying fire regimes as either high- or low-frequency oversimplifies the inherent variability in fires across a diversity of forests (Perry et al. 2011). The term "mixed-severity fire regime" describes the complex patterns and effects of heterogeneous fires across a range of spatial and temporal scales (Agee 1998; Lertzman et al. 1998; Schoennagel et al. 2004). Variable intensity within individual fires results in patches with low, moderate and high levels of tree mortality (Agee 1993). Within a fire, thin-barked species, small regenerating trees, and even large trees with thick bark are killed if exposed to torching, crowning or surface fire for sufficient duration to damage the cambium. Post-fire cohorts may colonize the resulting gaps, so forests are uneven-aged with multiple cohorts and remnant trees that survive fire, some of which form single to multiple fire scars. Successive fires at one location may burn with a range of severities resulting in compositionally and structurally diverse stands with complex dynamics (e.g., Heyerdahl et al. 2012; Marcoux et al. 2015). At the landscape scale, fires burn with a range of severities simultaneously and through time yielding heterogeneous patch sizes, shapes and spatial patterns (Hessburg et al. 2007; Halofsky et al. 2011; Perry et al. 2011).

Given the complexities of mixed-severity fire regimes, they are particularly challenging to characterize and reconstruct. Unlike high- and low-severity regimes, there is no *a priori* assumption about the impacts of individual fires. Instead, physical evidence is required to infer the severity, as well as the timing, of each fire. Scaling up from individual fires, the severity of successive fires at a site indicates fire history through time and comparing multiple sites across a landscape characterizes the historical fire regime. To simultaneously characterize the timing and severity of individual fires and spatio-temporal variations among sites requires multiple types

Table 8.3 Example criteria for classifying fire severity across spatio-temporal scales

Spatial scale	Temporal scale (source)	Criteria for severity classes		
		Low	Moderate	High
Individual fires	Contemporary (Agee 1993)	≤20% basal area of live trees killed	21–70% basal area of live trees killed	>70% basal area of live trees killed
	Reconstructed (Sherriff and Veblen 2006)	≥80% of living trees are remnants and <20% established post-fire; fire scar(s) present	<80% of living trees are remnants and 21–80% established post-fire	≤20% of living trees are remnants and >80% established post-fire
		Low	Mixed	High
Individual sites	Reconstructed through time (Sherriff and Veblen 2006)	MFI ≤ 30 years; trees with multiple fire scars; low-severity fires only	MFI > 30 years; low-, moderate- or high-severity fires through time	MFI >30 years; moderate- or high- severity fires through time
	Reconstructed through time (Heyerdahl et al. 2012)	≥1 fire scar year(s); no cohorts	≥1 fire scar year(s) and ≥1 cohort OR post-fire cohort with remnant trees	no fire scars; 1 post-fire cohort; no remnants
Study area	Reconstructed through time at individual sites (Marcoux et al. 2015)	≥81% low-severity and <20% mixed- or high-severity	<80% low severity and 21–80% mixed- or high-severity	≤20% low-severity and ≥81% mixed-or high-severity

of dendroecological evidence. The methods typically used to reconstruct high- or low-severity fires are best used in combination. In concert with fire scars, living and dead trees are sampled to represent tree population age structures and to identify cohorts, remnant survivors of past fires, and fire-killed trees (Ehle and Baker 2003; Baker et al. 2007). Independent, corroborating evidence is also sought (Swetnam et al. 1999; Baker et al. 2007).

Classifying the severity of historical fires has proven to be difficult in all but the most homogeneous systems. The severity of contemporary fires is often measured as the mortality rates of overstory trees (e.g. Agee 1993; Table 8.3). When reconstructing fire history, pre-fire forest densities are unknown (Schoennagel et al. 2011); therefore, severity is inferred from fire scars, forest demography and other corroborating evidence. Sherriff and Veblen (2006) introduced a method to classify the severity of individual fires as low, moderate or high based on the proportion of remnant trees (e.g. trees that established before fire) and those establishing in the 40 years after fire (Table 8.3; Case Study 1). Of these two metrics, remnant trees provide a more direct measure of fire severity than post-fire establishment, as tree colonization rates vary (e.g. <20 to >40 years; Amoroso et al. 2011, Chavardès and Daniels 2016) due to the availability of local seed sources and dispersion rates, availability of suitable microsites and variation in climate facilitating germination and survival (Sherriff and Veblen 2006). Both pre-fire remnant trees and post-fire tree establishment have uncertainties for evaluating fire severity and are not a perfect complement, but when used in conjunction with fire-scar dates, they represent a robust way to reconstruct historical fire severity in montane forests. Other corroborating evidence includes the presence and spatial distribution of fire scars, tree mortality synchronous with a fire date, and presence of resin ducts, micro-rings and radial-growth suppressions or releases in remnant trees (Brown and Swetnam 1994; Sherriff and Veblen 2006; Smith et al. 2016). The classification of historical fire severity works best for recent fires (Yocom Kent et al. 2015; Chavardès and Daniels 2016). Estimating the effect of fires that burned prior to a moderate- or high-severity fire is less reliable because of loss of evidence during subsequent fires, mortality and decay of older trees with time (Sherriff and Veblen 2006). To overcome this limitation, Tepley and Veblen (2015) recently introduced a metric to quantify variation in fire severity through time. In their models, tree density through time is a function of the cumulative number of fires that have burned at a site. The severity of an individual fire is a relative measure of the change in tree density before and after the n^{th} fire at the site compared to landscape-level mean tree densities associated with the n^{th} fire at that site.

There is no standard definition for low-, mixed- or high-severity fire regimes and different authors have classified them using different criteria. For example, at the site level, Sherriff and Veblen (2006) classified the predominant fire regime based on fire frequency, the severity class of individual fires and their cumulative effects over time (Table 8.3; Case Study 1). Similarly, Heyerdahl et al. (2012) classified site-level fire severity through time, but they did not attempt to classify individual fires within the sites (Table 8.3; Case Studies 2 and 3). In their approach, all site-level evidence was assessed simultaneously. Fire scars and remnant trees indicated past low- and moderate-severity fires. Post-fire cohorts indicated past moderate- and high-severity fires. Cohorts were identified based on the proportion of sampled trees within a defined establishment period (e.g., $\geq$25% of sampled trees established in a 30-year period) and were considered a post-fire cohort if trees were absent from the age classes immediately preceding a cohort (e.g., a moderate- or high-severity fire had killed young, small trees). Combinations of scars, remnant trees and cohorts were used to classify sites as having a low-, mixed- or high-severity fire history through time.

The relative abundance and distribution of forests with low-, mixed- or high-severity fire histories has emerged as a critical factor in determining if fire regimes have been altered during the twentieth century. Networks of research sites are used to reconstruct and classify fire regimes at landscape to regional scales (Falk et al. 2011; Table 8.3; Case Studies 1 and 2). Stratifying study areas according to biophysical attributes, then comparing fire regime attributes across strata is one way to quantify spatial variability and test for drivers of that variation (Heyerdahl et al.

2001; Taylor and Skinner 2003; Sherriff and Veblen 2007). Representative sampling allows inferences to be extrapolated from the site-level data to the study area (Sherriff et al. 2014; Marcoux et al. 2013, 2015). Current classification systems for fire regimes lack quantitative criteria to differentiate low-, mixed- and high-severity regimes (Brown et al. 2008; Perry et al. 2011); however, universal criteria may not be ecologically meaningful or relevant for management on all landscapes. Since fire regimes vary along a continuum rather than forming discrete classes, research on the relative importance of fires of different severities may more effectively guide spatial and temporal strategies to achieve management and conservation goals.

Most research on historical low- and mixed-severity fire regimes has focused on magnitude and temporal attributes, rather than spatial attributes. Combining dendroecological evidence with spatial analysis has yielded new ways to reconstruct severity within a fire and quantify the spatial extent of past fires. Research designs that include sample plots distributed on a systematic grid are conducive to such spatial analyses (Heyerdahl et al. 2001). Simulation modeling can also be used to infer spatial attributes of fire (e.g., Brown et al. 2008, Case Study 3). Such models can be corroborated by dendroecological evidence, lending confidence to their use in extrapolating fire behavior across landscapes and into the future to infer changes in fire regimes through time and to test the relative importance of fuels and weather as drivers of fire severity (Heyerdahl et al. 2014). Another quantitative approach for estimating spatial fire regime attributes is the spatial mean fire interval method (Hessl et al. 2007; Kernan and Hessl 2010). This method uses the fire evidence (e.g., fire-scar dates or tree ages representing stand-replacing fires; Yocom Kent et al. 2015, Greene and Daniels 2017; Case Study 4) at individual sample plots in a geographic information system (GIS) and inverse distance weighting to interpolate between plots and estimate the boundaries and size of individual fires (Hessl et al. 2007; Kernan and Hessl 2010; Swetnam et al. 2011). Similarities between reconstructions of fire extent and corresponding documentary fire records demonstrates the efficacy of this approach (Farris et al. 2010). The spatial extent of multiple fires through time is composited in a spatial mean fire interval map, to estimate point-specific fire frequencies and landscape-level fire rotation (Kernan and Hessl 2010). These maps enable qualitative and quantitative analysis of relationships between fire and topography (Kernan and Hessl 2010; O'Connor et al. 2014).

8.3 Mixed-Severity Fire Regimes Reconstructed Using Dendroecology

Below, we present four case studies from across the western United States and Canada to illustrate how dendroecological evidence is used to decipher the complexity of historical fire regimes (Fig. 8.2). We focus on mixed-severity fire in these case studies because it requires the use of various methods and multiple lines of evidence to reconstruct fire regimes. The first two case studies show how detailed reconstructions of past fire frequency and severity at representative sites can be used

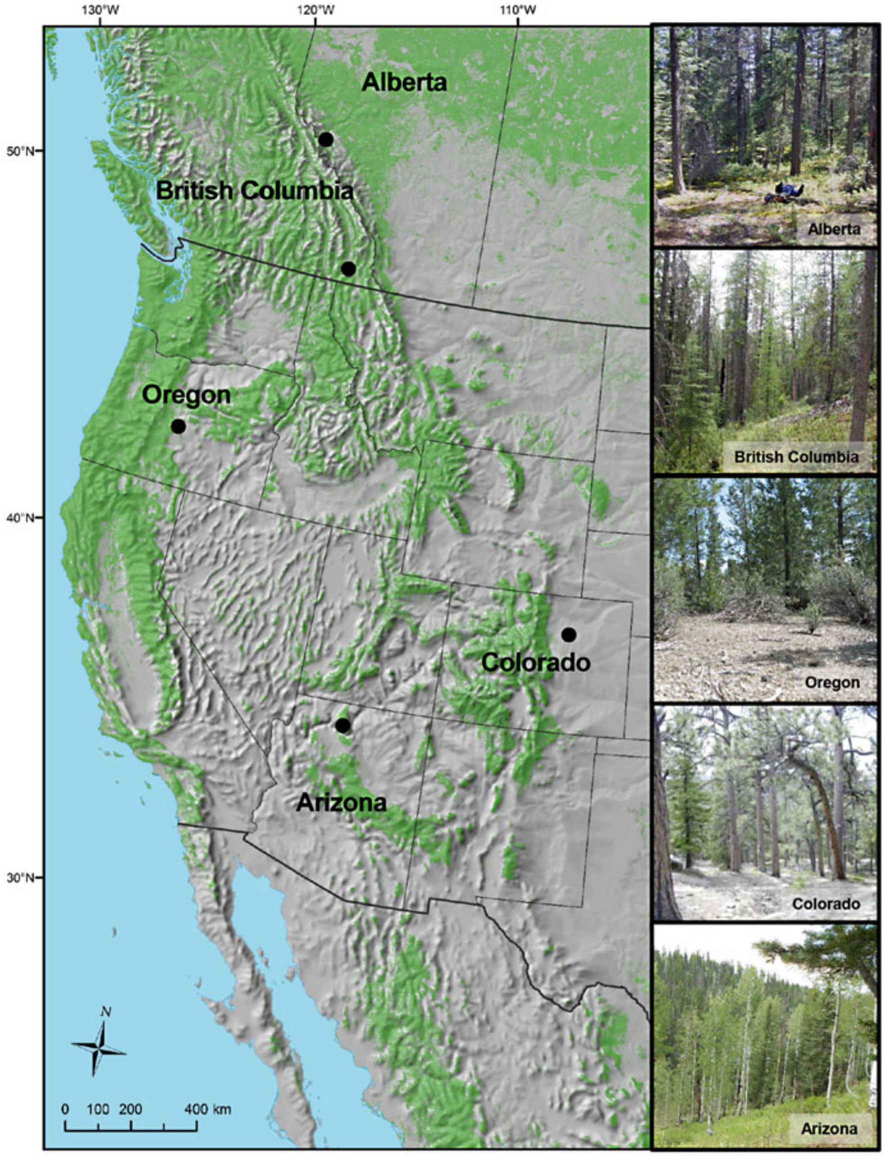

Fig. 8.2 Four case studies on mixed-severity fire regimes represent research in the Canadian Cordillera, central Oregon, Colorado Front Range and Grand Canyon in Arizona (Graphics by D. Snow and R.D. Chavardès)

to illustrate landscape-scale variation in fire regimes. The latter two case studies demonstrate a suite of methods to quantify spatio-temporal variation in fire severity within a landscape.

8.3.1 Montane Forests of the Colorado Front Range

In ponderosa pine and mixed-conifer forests of the Colorado Front Range of the Rocky Mountains, fire-scar records and tree age structures from unlogged forests were used to evaluate the historical fire regime (e.g., before 1920) and determine the parts of the landscape characterized by predominantly low-severity or mixed-severity (including moderate- or high-severity) fires (Figs. 8.2 and 8.3a). The 232 sites compiled from multiple studies (Veblen et al. 2000; Sherriff and Veblen 2006, 2007; Schoennagel et al. 2011; Gartner et al. 2012; Sherriff et al. 2014) were representative of the relative proportion of the dominant forest types in the study area, allowing inferences from site-level data to 564,413 ha of montane forest (Sherriff et al. 2014; an example of fire-scar dates and the last fire-cohort date at each site are compiled for 92 sites in Fig. 8.3a). In the study region, the lower montane zone (*c*. 1800–2200 m) comprises primarily pure ponderosa pine *(Pinus ponderosa* Lawson & C. Lawson) on south-facing slopes and a mixture of ponderosa pine and Douglas-fir (*Pseudotsuga menziesii var. glauca* (Beissn.) Franco) on north-facing slopes. The upper montane zone (*c*. 2200–3000 m) is comprised of ponderosa pine stands on south-facing slopes and denser stands of ponderosa pine and Douglas-fir on north-facing slopes along with lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm. ex S. Watson), aspen (*Populus tremuloides* Michx) and dispersed limber pine (*Pinus flexilis* James) trees at higher elevations.

At each site, fire scars (number of fire-scarred trees and fire scars per tree, and fire dates), forest structure, and tree age structure were systematically sampled to identify the fire-severity regime. In total, 7680 tree cores and 1262 fire-scar samples were used to delineate fire dates and severity across all sites. There was evidence of 322 spreading fires that scarred ≥2 trees between 1597 and 1995. Only 22% of spreading fires were unique to one site; all other fires were recorded at ≥2 sites. The severity of spreading fires at each site was classified based on their influence on forest structure. Along with the dates of spreading fires, the percentage of remnant *versus* post-fire tree establishment was used to classify individual fires as low, moderate or high severity (Table 8.3). Based on the fire-severity classifications, a predominant fire regime at each site was assigned based on the cumulative fire effects over time (Table 8.3).

In the lower montane forests in the Colorado Front Range, a decline in fire frequency over the past 100 years led to substantial increases in stand density. These forests were characterized mainly by frequent low-severity fires that burned at average intervals <30 years and maintained open forests by killing mostly juvenile trees, resulting in low densities of mature trees. The cessation of these fires coincides with increased stand densities. This pattern also occurred at some higher elevations on less steep sites where montane grasslands most likely occurred. Overall this change to the fire regime and forest structure represents a relatively small proportion of the montane forest of the Colorado Front Range as only 27.8% of the study area is mapped with the historical low-severity fire regime (Sherriff et al. 2014).

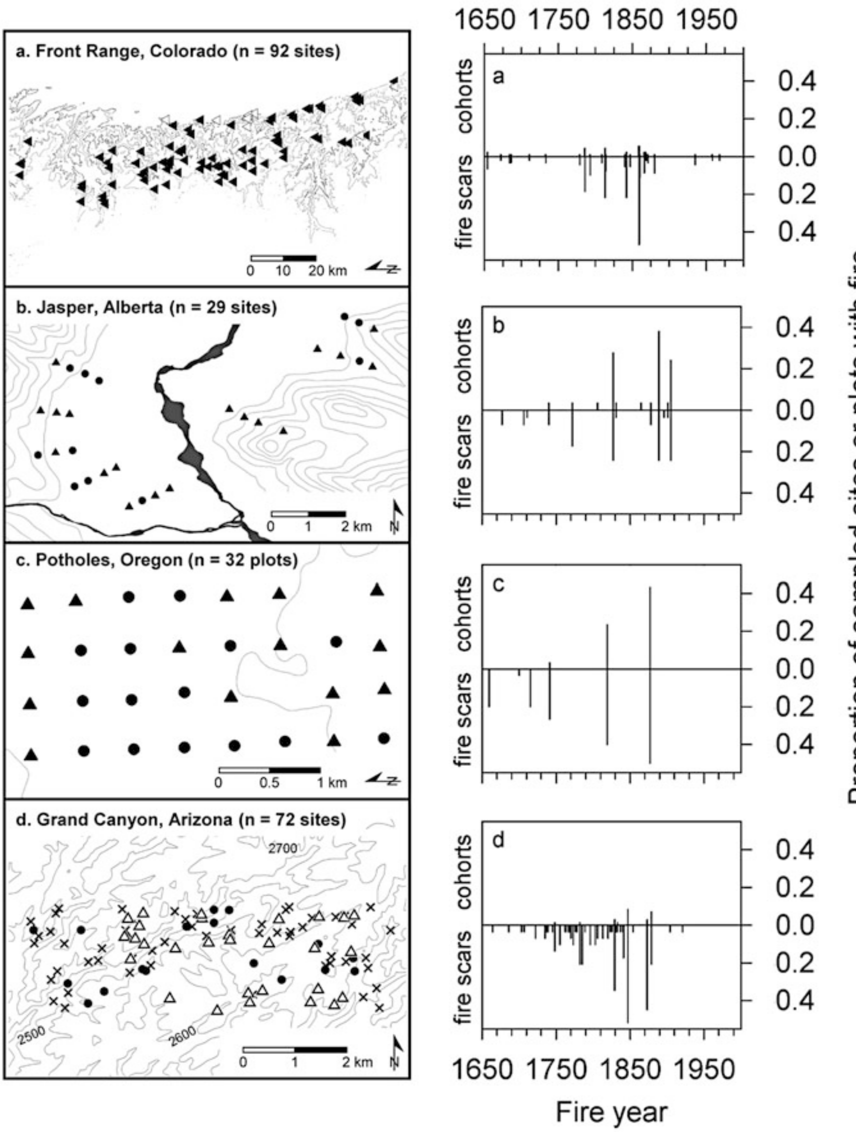

Fig. 8.3 Research designs and fire records for the four case studies on mixed-severity fire regimes in (**a**) Colorado (564,413 ha), (**b**) Alberta (2400 ha), (**c**) Oregon (783 ha), and (**d**) Arizona (1400 ha). In the maps, *solid circles* are sites/plots with cohorts only, *solid triangles* have cohorts and fire scars, *open triangles* have fire scars only, and x indicates no scars or cohorts

The majority (72.2%) of the 564,413 ha study area historically was dominated by a mixed-severity fire regime, with the average interval between fires typically >30 years. In the upper montane forests, stand structures were shaped primarily by moderate-severity (46.5% of sites) and high-severity (45.7% of sites) fires; only 7.8% of sites recorded predominantly low-severity fires. Evidence of mixed-severity fires occurred in all dominant forest types, including stands in which ≥80% of the canopy trees were ponderosa pine or lodgepole pine, as well as mixed-conifer stands. Fire effects varied from non-stand-replacing to canopy-replacing fires within sites and across broad landscapes, with severity often related to topographic variability. Although the ability to interpret the spatial extent of historical fires is limited by the sampling unit size (up to 232 ha), subsequent fire events, and sample depth, the evidence indicates mixed-severity fires occurred in patches up to 200 ha or more, with *c.* 50 ha of high-severity fires at some sites. Fire years of 1654, 1786, and 1859–1860 were particularly extensive with 36%, 43%, and 48% of the available recorder sites (with ≥2 fire-scarred trees) recording each fire year, respectively. These fires were recorded at multiple sites that extended over 9 km (1654), 7.5 km (1786), and up to 30 km (1859–1860) away from one another.

Consistent site- to landscape-scale evidence indicates historical mixed-severity fire regimes varied with elevation in the Colorado Front Range. Although frequent, low-severity fires dominated in lower montane forests, the majority of the study area was in the upper montane zone where moderate- and high-severity fires shaped current forest age structures. Reconstructions of stand structures and fire history are most effective when supported by diverse evidence, gathered independently, that converges to the same overall interpretations. In the Colorado Front Range, tree-ring evidence, historical landscape photographs, Forest Reserve Reports, and General Land Office surveys converge to the same conclusions demonstrating that the historical fire regime of ponderosa pine and mixed-conifer forests included low-severity fires as well as high-severity fires (e.g., Veblen and Lorenz 1986, 1991; Mast et al. 1998; Baker et al. 2007; Schoennagel et al. 2011; Williams and Baker 2012; Sherriff et al. 2014). Combined evidence indicates an historical fire regime of more frequent, low-severity fires at low elevation (<2260 m) that supports a convergence of management goals of ecological restoration and fire hazard mitigation in those habitats. In contrast, at higher elevations mixed-severity fires were predominant historically and continue to be so today.

8.3.2 Montane Forests of the Canadian Cordillera

Dendroecological evidence shows that fires of a range of severities historically burned in the Canadian Cordillera, despite the northerly latitude and continental climate (Fig. 8.2). Landscape studies conducted west of the Rockies in southeastern British Columbia (Marcoux et al. 2013, 2015; Greene and Daniels 2017) and east of the Rockies in Jasper National Park, Alberta (Chavardès and Daniels 2016) form a 500 km south-north gradient. Collectively, 102 sites in mesic mixed-conifer montane and lower subalpine forests were selected using a stratified-random research design to represent the environmental gradients in each landscape. Fire-scarred trees sampled in 1-ha plots provided evidence of low-to-moderate-severity fires. Forest composition, size- and age-structure were sampled at the center of fire-scar plots using an n-tree design. The resulting evidence indicated historical fires (1439–1966) burned at a wide range of frequencies and severities at site and landscape scales. Even-aged cohorts determined from stand age-structure analyses and an absence of fire scars or remnant trees provided evidence of high-severity fires at 43 of 102 sites. Crossdated, annually-resolved fire records were used to quantify return intervals of low-to-moderate severity fires at the other 59 sites. In southeastern British Columbia (n = 73 sites), fire-scars were most common on thick-barked western larch (*Larix occidentalis* Nutt.), Douglas-fir and ponderosa pine; in Jasper (n = 29) fire scars were most common on lodgepole pine and Douglas-fir.

Crossdated fire scars combined with age structure analyses allowed detailed site-level reconstructions of fire history and forest dynamics through time (Table 8.3). In southeast British Columbia, 37 fire years between 1600 and 2009 were identified based on fire scars (n = 31) or cohorts only (n = 6; Marcoux et al. 2013, 2015). Eleven of 20 sites included fire scars and cohorts indicating mixed-severity fire histories. These sites last burned between 1910 and 1953, yielding times since fire of 56–99 years (at time of sampling) which exceeded the maximum recorded fire return intervals at five sites and the mean interval at all sites. The remaining sites had cohorts only, indicating high-severity fires burned <150 years ago at four sites or >270 years ago at five sites. In this landscape, tree species composition varied with disturbance history. Mixed-severity sites were dominated by Douglas-fir and western larch that regenerated after frequent low- or moderate-severity fires indicated by scars. Periodic moderate-severity fires generated even-aged cohorts with surviving remnant trees. At higher-elevations, severe fires <150 years ago generated cohorts dominated by lodgepole pine and high-severity sites that last burned >270 years ago were dominated by subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). Tree size attributes did not distinguish mixed- from high-severity sites. Across fire history classes, canopy tree densities were 70–500 ha^{-1}. Subcanopy trees were up to 5600 ha^{-1} having established then persisted following the last fire at most sites. In this landscape, selective harvesting and fire suppression during the twentieth century have reduced fire frequency in montane forests and homogenized contemporary forest structures across elevations.

In Jasper, 13 fire years between 1646 and 1905 were identified based on fire scars (Chavardès and Daniels 2016; Fig. 8.3b). All 29 sites had at least one post-fire cohort (Fig. 8.3b). At 18 of 29 sites fire-scars and remnant trees combined with post-fire cohorts were legacies of past fires of mixed severity through time. Single even-aged cohorts provided evidence of high-severity fires at 11 sites. The most recent fires initiated post-fire cohorts at 24 sites, providing evidence of moderate-to-high severity fires between 1889 and 1905. No fire scars were detected after 1905, although young thin-barked trees could have recorded fire at all sites. The simultaneous, long fire-free intervals during the twentieth century are unprecedented in the 250-year fire-scar record. The dendroecological evidence showed that lodgepole pine, hybrid spruce and Douglas-fir establish simultaneously after low-, moderate- and high-severity fires. Thus, forest canopies were mixed in composition regardless of fire history and subtle differences such as the presence of remnant trees and discontinuous age structures distinguished sites with mixed-severity fire histories. In general, subcanopies were strongly dominated by shade-tolerant spruce, which are similar in age to the canopy trees despite their small size. Subcanopy spruce do not represent recent recruitment and stand infilling; rather, species-specific growth rates and adaptations to shade resulted in size stratification among species and canopy layers. These subcanopy trees have survived in the absence of surface fires during the twentieth century so that forests with mixed- and high-severity fire histories have developed similarly, homogenizing the landscape. Current dense subcanopies (up to 3100 ha^{-1}) provide ladder fuels, increase fire hazard and decrease forest resistance to high-severity fire, especially during droughts.

Dendroecological evidence indicates mixed-severity fire regimes dominate in many forests of the Canadian Cordillera. This interpretation contrasts with the traditional view that high-severity fire regimes dominated, a perception that strongly influences forest and fire management. Instead, low-to-moderate severity fires were common historically but have been effectively eliminated during the twentieth century. Altering these fire regimes can homogenize forests, reducing stand- and landscape-level diversity and resilience to environmental change.

8.3.3 Lodgepole Pine Forests of Central Oregon

Lodgepole pine forests are widely distributed in western North America and historically sustained a range of fire regimes (Schoennagel et al. 2008; Amoroso et al. 2011). While these fire regimes have been well documented at the high-severity end of this range (e.g., in portions of the Greater Yellowstone Area and parts of the U.S. northern Rocky Mountains), they are not as well documented in mixed-severity systems, such as central Oregon's Pumice Plateau Ecoregion (Heyerdahl et al. 2014; Fig. 8.2). This region covers over a million hectares and is characterized by thick deposits of pumice and ash that combine with generally flat topography to favor lodgepole pine, but restrict the establishment of other overstory and understory species (Geist and Cochran 1991; Simpson 2007). On parts of the Plateau, coarse-textured pumice substrates limit forest composition to low-density lodgepole pine with scattered ponderosa pine and a shrub understory dominated by antelope bitterbrush (*Purshia tridentata* (Pursh) DC.; hereafter bitterbrush). This woody shrub is intolerant of shade and highly flammable. It acts as a ladder fuel and facilitates passive crown fire (e.g., torching of individual trees or small patches of trees; Busse and Riegel 2009). It is the primary understory fuel in these forests because the coarse-textured, nutrient-poor pumice substrate limits the growth of grass and herbaceous fuels (Geist and Cochran 1991). Although fire initially reduces the abundance and biomass of bitterbrush, it also stimulates regeneration and populations can recover to pre-fire levels, especially where fire creates canopy gaps (Ruha et al. 1996; Busse and Riegel 2009).

The historical fire regime and its spatial complexity were reconstructed at 30 2-ha plots distributed over 783 ha of forest dominated by lodgepole pine with scattered ponderosa pine at an elevation of 1485 m (Heyerdahl et al. 2014; Fig. 8.3c). The occurrence of low-severity fires was reconstructed from 56 fire-scarred trees (37 ponderosa and 19 lodgepole pine). The occurrence of high- and moderate-severity fires was reconstructed from the establishment dates of 752 live or dead trees. From these establishment dates, a cohort was assumed to have initiated when ≥5 trees recruited within 20 years at a plot, preceded by at least 30 years without recruitment. Death cohorts were identified when ≥5 trees died in the same year.

During the analysis period (1650–1900), 6 fires were reconstructed from 129 fire scars and 19 of the cohort initiation dates (Fig. 8.3c). All but two of the cohorts satisfied the criteria for assignment to fire-scar dates in 1750, 1819, or 1877. From these 6 fires, 34 plot-composite fire intervals of variable length (26–82 years) were computed. Fire scars from five of these same six fires (all but 1700) were crossdated on trees sampled between plots. Twenty-one cohort initiation dates were identified. Although trees established between 1624 and 1962, all but one cohort initiated between 1822 and 1888. The remaining cohort initiated in 1752. Cohorts occurred in two-thirds of the plots, most of which had a single cohort except for one plot with two. Two death cohorts were identified in 1988, during a widespread outbreak of mountain pine beetles in central Oregon (Preisler et al. 2012).

For centuries (1650–1900), extensive mixed-severity fires occurred every 26–82 years, creating a multi-aged forest and shrub mosaic. Although widespread synchrony in fire-scar dates during several years suggests extensive low-severity fires, these scars were also synchronous with cohorts of tree recruitment, suggesting that individual fires included patches of both high- and low-severity fire. The inference of historical mixed-severity fire is also consistent with the general lack of serotinous lodgepole cones in central Oregon (Mowat 1960) because extensive high-severity fires select for cone serotiny in pines (Keeley and Zedler 1998). Fire intervals of 26–82 years are long enough for bitterbrush to regain sufficient cover and height to facilitate fire spread across the site and into the canopy in a mosaic pattern. In turn, this mosaic pattern would have allowed for post-fire regeneration of bitterbrush by creating canopy gaps while maintaining some unburned plants as seed sources and stimulating vigorous sprouting from undamaged portions of surviving plants (Ruha et al. 1996; Busse and Riegel 2009). This work supports findings about the drivers of mixed-severity fire regimes elsewhere in the region (Halofsky et al. 2011).

The effect of fire exclusion on the fire regime at this site is unusual among mixed-conifer forests in the interior Pacific Northwest (Hagmann et al. 2013). While forest composition is topoedaphically limited primarily to lodgepole, contemporary, low shrub fuel loads at the site are likely insufficient to spread fire to the canopy. In contrast, the tree-ring reconstructed fire history indicates that patches of high-severity fire occurred periodically, generating multi-aged stands that may have been more resilient to beetle attacks. Because topographic relief at the site is low, spreading fires were likely wind driven, and would have required sufficient surface fuel loads for horizontal and vertical spread. However, fuel loads, in particular the abundance and cover of bitterbrush, the primary understory species, has likely decreased since the exclusion of fire 130 years ago, reducing the ability of the site to support a mixed-severity fire regime. Because bitterbrush is both sensitive to and stimulated by fire, continued lack of fire within the ecosystem is likely to promote a negative feedback cycle. Without fire, canopy gaps are not created and bitterbrush sprouting is not stimulated, thereby restricting shrub growth. In turn, limited shrub abundance and cover restricts horizontal and vertical spread of fire, thus eliminating some opportunities for creation of canopy gaps and perpetuating conditions that limit fire.

It is challenging to extrapolate future fire regimes from tree-ring reconstructions of past fire alone because more than a century of fire exclusion has likely changed forest structure, hence fire behavior, and climate is projected to continue changing in the future. However, if simulation models corroborate past fire behavior reconstructed from tree rings, such models can be used to simulate potential future fire behavior. At Potholes, past, present, and future fire behavior was simulated with a landscape-scale program (FlamMap; Finney 2006) to infer whether modern fire behavior has changed since fire exclusion and to assess the relative importance of fuels and weather as drivers of fire severity. Simulations of past fire behavior were consistent with tree-ring reconstructions of patchy mixed-severity fire and suggested that fuel loadings and wind speed were the primary drivers of fire behavior at Potholes. In contrast, simulations of modern fire behavior suggested that a century of fire exclusion has reduced the potential for the high-severity patches of fire that were common historically. This occurred because the loadings of modern understory fuels (i.e., bitterbrush cover, the primary ladder fuel) have declined and are now insufficient to spread the mix of surface and torching fire that occurred at Potholes in the past. Simulations with historical fuels included torching, especially under extreme wind speeds, but simulations with modern fuels were dominated by surface fire except under extreme wind speeds. Active crown fire was very rare regardless of the scenario. In the absence of the abundant shrub fuels of the past, flame lengths of sufficient height to carry fire into the canopy occurred only with extreme winds. Coupling simulation modeling with tree-ring reconstructions of fire at Potholes provided a more complete picture of the consequences of changes in the forest due to fire exclusion.

8.3.4 The North Rim of Grand Canyon National Park, Arizona

Grand Canyon National Park in northern Arizona has a progressive and active fire management program, making frequent use of prescribed fire and managed wildfire. Park managers have a goal of restoring fire as a natural process throughout the park, including the mixed-conifer zone. The fire scar record provides strong evidence of historical low-severity fires (Fulé et al. 2003; Fig. 8.2). In this study, three complementary analyses using dendroecological evidence were applied to estimate the size of historical high-severity patches in the mixed-conifer forests (Yocom Kent et al. 2015).

The 1400-ha study area, at *c.* 2600 m in elevation, is located on the Kaibab Plateau in the North Rim area of the Park. The forest in the study area is highly stratified by aspect. The vegetation was mapped and polygons were classified the into four major forest types by dominant overstory tree species: white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), blue spruce (*Picea pungens* Engelm.), subalpine fir and aspen. Other common tree species are ponderosa pine, Douglas-fir and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). Using a stratified-random research design, plots were randomly placed in 72 mapped vegetation polygons, 18 in each forest type (Fig. 8.3d). At each plot, the *n*-tree method (Jonsson et al. 1992) was used to identify and core the ten large overstory trees closest to plot center. To quantify fire-related tree establishment, species-specific minimum diameters were used to target "large" trees that most likely established before 1879, the last widespread fire in the study area (Fulé et al. 2003). The cores from 647 trees were crossdated using a local chronology (Fulé et al. 2003) and inner-ring dates were determined. Fire dates were obtained from crossdated fire-scarred trees sampled in the area previously (Fulé et al. 2003; Fig. 8.3d).

High-severity fire patches were reconstructed using three different methods, each using dendroecological data. First, similar to the other case studies, even-aged cohorts establishing after high severity were identified based on the following conditions: (a) trees formed one even-aged cohort with an initiation date that corresponded to a nearby fire scar or a widespread fire date, (b) $\geq$2 cohorts were present, but the oldest cohort was even-aged with an initiation date that corresponded to a nearby fire scar or a widespread fire date, or (c) fire-sensitive species (aspen, white fir, subalpine fir, or spruce) were even-aged but there were some older remnant ponderosa pines or Douglas-firs. Plots met these criteria if $\geq$2 aspen pith dates followed fire by $\leq$5 years or if $\geq$4 conifer pith dates followed fire by $\leq$20 years. The size of each patch represented by a fire-initiated plot was determined using GIS.

The second method for reconstructing high-severity patches was a dichotomous classification based on the regeneration dynamics of aspen. Aspen regenerates quickly after high-severity fire by suckering from clonal root stock (Margolis et al. 2007). Thus, mapped patches dominated by aspen were classified as initiated by high-severity fire; all other patches were classified as not initiated by high-severity fire.

The third method used GIS and the inverse distance weighting method to interpolate high-severity fire patch boundaries and sizes (Hessl et al. 2007). The pith date of the oldest fire-sensitive tree (aspen, white fir, subalpine fir or spruce), refined by fire-scar dates, estimated the minimum time since the last high-severity fire. Fire boundaries and sizes for the seven high-severity fires (1785, 1813, 1829, 1841, 1847, 1873, and 1879) were estimated using 3 different thresholds of interpolated values to define high-severity *versus* low-severity or unburned forests.

Of these three methods, the aspen method yielded the smallest estimates of high-severity fire patches, while the interpolation method resulted in the largest estimates that varied depending on the threshold value for fire boundaries (Table 8.4). The aspen method and the fire-initiated polygon method may be more valuable

Table 8.4 Comparison of estimated metrics of high-severity fire patches reconstructed using three different methods (Yocom Kent et al. 2015)

Metrics of high-severity patches	Aspen method (N = 49)	Fire-initiated patch method (N = 18)	Interpolation method (N = 7) minimum threshold		
			0.5	0.4	0.3
Minimum size (ha)	0.1	0.5	1.9	3.9	9.0
Maximum size (ha)	10.8	35.6	200.2	309.1	555.9
Average size (ha)	1.1	4.2	30.2	53.3	102.4
Average area burned (ha) per fire year			129.3	182.8	263.2
Average number per fire year			4.3	3.4	2.6

for understanding estimates of minimum high-severity patch size, whereas the interpolation method may be more valuable for understanding estimates of the total area burned in high-severity fire in a given year.

Consensus among the three different methods indicates high-severity fire was a regular component of the historical fire regime along with low-severity fire, throughout the nineteenth century. In some fire years, such as 1847, high-severity fire was widespread. Patch size of high-severity fire during the 1800s likely ranged from small patches (0.1 ha) that allowed a few trees to establish to large patches (100 ha) that initiated multiple stands across the landscape. However, the forest in the study area was quite young, with the majority of trees having pith dates in the 1800s or later. A large stand-replacing fire during or prior to the mid-1700s cannot be ruled out.

The mixed-conifer forests on the North Rim of Grand Canyon National Park are highly stratified by aspect, and likely experienced a very complex historical fire regime with mixed low- and high-severity effects in individual fires and over time. Although fire was a regular and important driver of forest dynamics throughout the 1800s, the last widespread fire was in 1879. Without periodic fires, the forest has increased in density and changed in species composition over the past century (Fulé et al. 2003; Vankat 2011). Allowing fires to behave differently on south-facing and north-facing slopes could help promote diversity of tree species and keep the high level of heterogeneity present in these forests.

8.4 Discussion

In each case study, dendroecological analyses were central for understanding past fire frequency, severity and spatial attributes. Although they each feature a mixed-severity fire regime, variations among them demonstrate the importance of ecosystem-specific understanding of historical fires to guide science-based management that aims to maintain forest resilience.

The juxtaposition of traditional management paradigms in the montane forests of the Colorado Rockies and Canadian Cordillera exemplifies this point. In the Colorado Front Range, ponderosa pine is common. Although high-frequency, low-severity fire regimes are often associated with this species and dominate the lower montane forests, mixed- and high-severity fires historically dominated the upper montane forests. For the majority of this landscape, managing for a low-severity fire regime is not consistent with the historical range of variation; moderate- and high-severity fires must be taken into account. In contrast, timber and fire management largely reflect the presumed high-severity fire regime in the Canadian Cordillera. Reconstructions provide strong evidence of historical mixed-severity fire regimes but reduced surface fires during the twentieth century. Despite the high latitude, surface fires were an important component of historical fire regimes and need to be reflected in contemporary management.

Land-cover change and fire exclusion can simplify mixed-severity fire regimes, altering forest composition and structure. For example, the mixed-conifer forests of the North Rim of the Grand Canyon are rich with fire scars indicating surface fires, but high-severity patches burned during periodic widespread fires. In the absence of mixed-severity fires for more than a century, forest density increased and composition shifted toward fire-susceptible species, conditions conducive to high-severity fire. Fire exclusion has had the opposite effect in the lodgepole pine–antelope bitterbrush forests of central Oregon's Pumice Plateau. Historically, its mixed-severity fire regime also included high-severity patches embedded in extensive low-severity fires. The resulting gaps facilitated bitterbrush regeneration, which enabled fire spread, perpetuating a positive feedback. Fire exclusion has disrupted this feedback, driving the decline of bitterbrush and limiting torching fire across this landscape. Although fire exclusion has had contrasting impacts, a mixed-severity fire regime is needed to maintain forest diversity and resilience in both landscapes.

8.5 Future Directions and Research Priorities

Recent large and costly fires in western North America and globally have raised urgent questions about altered fire regimes, including fire causes, effects and feedbacks, as well as post-fire vegetation recovery (Bowman et al. 2009; Stephens et al. 2013). Are contemporary fires more severe or larger than the historical range of variation? To what degree are current high-severity fires driven by climatic conditions *versus* forest structures and fuel availability? Are contemporary forests resilient to fire? Reconstructions of historical fire frequency, severity, spatial variability and extent are essential to gauge changes in contemporary fire regimes. Existing classification methods have proven effective for inferring the severity of individual fires and stand-level fire regimes in a range of forest types. Combining evidence of fire severity with reconstructions of past fire extent provides a powerful framework for quantifying the spatial variability within and among historical fires.

This type of integrated approach could be used to develop empirically-based, quantitative estimates of the relative abundance of different fire severity classes at stand to landscape levels. Such criteria are an important next step toward determining if fire severity is increasing relative to historical conditions.

Knowledge of historical fire regime attributes provides an empirical framework for management strategies to improve forest resilience to the cumulative effects of environmental change (Stephens et al. 2013). Climate change projections for western North America include increased temperatures, earlier snowmelt, longer fire seasons with enhanced drought, potentially driving more frequent, large and severe forest fires (McKenzie et al. 2004; Flannigan et al. 2009). These climatic effects may be exacerbated by land-use change, fire exclusion, and urban expansion (Moritz et al. 2014). In forests where low-severity fires have been reduced, proactive management may include restoration of forest composition, structure and spatial patterns or mitigation of fuels (Stephens et al. 2013). In forests historically dominated by high-severity fires, understanding variation in fire attributes and vegetation patterns across climatic regions helps anticipate changes in forest types and age structures at landscape to regional scales (Stephens et al. 2013). As dendroecological research has shown, forests with mixed-severity fire regimes form a continuum between these extremes. Therefore, ecosystem-specific knowledge of the relative importance of low- *versus* high-severity fires is essential to ensure management enhances rather than compromises forest resilience. Dendroecological reconstructions, combined with multiple lines of corroborating evidence, are key for achieving this goal.

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