Mixed-severity fire regimes in dry forests of southern interior British Columbia, Canada

Emily K. Heyerdahl, Ken Lertzman, and Carmen M. Wong

Abstract: Historical fire severity is poorly characterized for dry forests in the interior west of North America. We inferred a multicentury history of fire severity from tree rings in Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) – ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) forests in the southern interior of British Columbia, Canada. In 2 ha plots distributed systematically over 1105 ha, we determined the dates of fire scars, indicators of low-severity fire, from 125 trees and inferred dates of even-aged cohorts, potential indicators of high-severity fire, from establishment dates of 1270 trees. Most (76%) of the 41 plots contained fire-scarred trees with a mean plot-composite fire scar interval of 21 years (1700–1900). Most (76%) also contained one or two cohorts. At the plot scale, we inferred that the fire regime at most plots was of mixed severity through time (66%) and at the remaining plots of low (20%), high (10%), or unknown (4%) severity through time. We suggest that across our study area, the fire regime was mixed severity over the past several centuries, with low-severity fires most common and often extensive but small, high-severity disturbances also occasionally occurred. Our results present strong evidence for the importance of mixed-severity fire regimes in which low-severity fires dominate in interior Douglas-fir – ponderosa pine forests in western Canada.

Résumé : La sévérité des feux de forêt passés est mal caractérisée dans le cas des forêts sèches continentales de l'ouest de l'Amérique du Nord. Nous avons déduit plusieurs siècles d'histoire de la sévérité des feux à partir des cernes annuels des arbres dans des forêts composées de douglas vert (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) et de pin ponderosa (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) et situées à l'intérieure des terres dans le sud de la Colombie-Britannique, au Canada. Dans des parcelles de 2 ha systématiquement distribuées sur une superficie de 1 105 ha, nous avons daté les cicatrices de feu, un indicateur de feux de faible sévérité, sur 125 arbres et déduit l'âge des cohortes équiennes, un indicateur potentiel de feux de sévérité élevée, depuis la date d'établissement de 1 270 arbres. La plupart (76 %) des 41 parcelles contenaient des arbres qui portaient des cicatrices de feu et l'intervalle moyen entre les feux, basé sur les cicatrices de feu dans l'ensemble des parcelles, était de 21 ans (1700–1900). La plupart (76 %) contenaient également une ou deux cohortes. À l'échelle de la parcelle, nous avons déduit que le régime des feux dans la plupart des parcelles (66 %) était caractérisé par une sévérité mixte au fil du temps et dans le reste des parcelles, par une sévérité faible (20 %), élevée (10 %) et inconnue (4 %). Nous croyons que, dans notre aire d'étude, la sévérité du régime des feux a été mixte au cours de plusieurs siècles passés; les feux de faible sévérité ont été les plus communs et ont souvent brûlé de grandes superficies, mais de petites perturbations très sévères sont survenues occasionnellement. Nos résultats constituent une preuve solide de l'importance des régimes des feux de sévérité mixte où les feux de faible sévérité dominent dans les forêts continentales de douglas vert et de pin ponderosa au Canada.

[Traduit par la Rédaction]

Introduction

Fires are a primary disturbance to forests in much of western Canada, including the mixed conifer forests of southern interior British Columbia (Stocks et al. 2003). Understanding the drivers of fire severity is important for many reasons, including accounting for the relative contribution of forests to carbon emissions over time (Hurteau et al. 2008; van Bellen et al. 2010), placing modern forest structure in the context of its historical ranges of variability (Morgan et al. 1994), and tracing the complex developmental trajectories of forests subject to multiple disturbances (Turner 2010; Halofsky et al. 2011). However, fire severity changes dynamically in response to management actions and climate and is thought to have changed over the past century in some dry mixed conifer forests of western North America due to fire exclusion (Perry et al. 2011). To understand the nature and magnitude of such changes, we need information on the severity of fire regimes in the past. While the severity of modern fires can be measured as the direct effects of combustion on plants, in-

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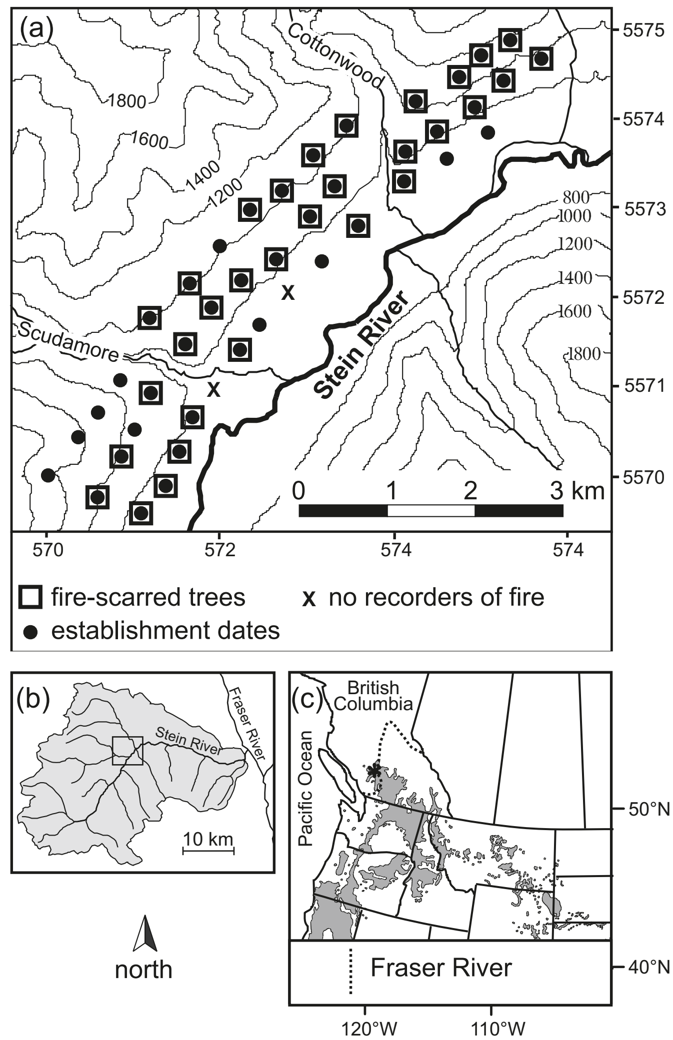
cluding fine-scale variation in tree mortality and the loss of living and dead biomass, to examine the severity of past fires, we need to seek their signatures in the dendrochronology and demographic patterns retained in forest structure.

The effects of fire are inherently complex across landscapes, both within individual fires and among multiple fires over time (Lentile et al. 2005; Turner 2010; Halofsky et al. 2011). These effects are driven by heterogeneity in vegetation, the underlying landscape, and fire weather (Pyne et al. 1996). Spatially structured drivers of disturbance severity create a complex pattern of forest history, forest structure, and forest dynamics across landscapes. These patterns are both difficult to understand and pose challenges for managers. This spatial and temporal variation in severity is often ecologically important and leaves legacies that can persist for decades to centuries. While the physical effects of fire severity vary continuously, those effects are often dichotomized into low versus high severity; fire regimes or individual fires bearing a signature of a mix of the two are referred to as "mixed severity". Mixed-severity fire regimes are more than a trivial combination of low- and high-severity characteristics but present a distinct type of ecological mosaic in terms of habitat, fuels- versus weather-driven fire behavior, and patterns of postfire recovery (Halofsky et al. 2011).

Dry forests in the southern interior of British Columbia cover 4.5 million ha, about 5% of the province. They include the Ponderosa Pine and Interior Douglas-fir biogeoclimatic zones (Meidinger and Pojar 1991) and lie at the northern range limit of ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson). Elsewhere near this northern limit, dry forests historically sustained frequent low-severity fire regimes (e.g., Heyerdahl et al. 2001, 2007; Hessl et al. 2004; Wright and Agee 2004) but the historical importance of a low-severity fire regime in dry forests in British Columbia has recently been challenged (Klenner et al. 2008). The significance of understanding historical fire severity has been highlighted by the modern occurrence of severe, stand-replacing fires in some dry forests in the province (e.g., Filmon 2003). To the south in the United States, some ponderosa pine and mixed conifer forests historically sustained mixed-severity fire regimes (e.g., Brown et al. 1999, 2008; Veblen et al. 2000; Fulé et al. 2003; Sherriff and Veblen 2006) or were juxtaposed with more mesic forests that historically sustained mixed- or high-severity fire regimes (Heyerdahl et al. 2001; Stephens 2001; Fulé et al. 2003). Resolving the spatial and temporal nature of the mix in mixed-severity fire regimes is becoming an increasingly critical problem for a broad range of decisions about forest management and conservation in the dry forests of western North America (Klenner et al. 2008; Halofsky et al. 2011).

We used tree rings to reconstruct a multicentury, spatially distributed history of fire in a portion of the Stein River Valley in the Coast Range of British Columbia (Fig. 1). The Stein River is a west-to-east tributary of the Fraser River in the southwest interior of the province and its watershed is about 107 000 ha in size. Forest composition varies dramatically along the length of the valley, ranging from cool, moist, coastally influenced ecosystems at the head of the valley to dry forests of ponderosa pine and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) at the mouth. There is a corresponding gradient in the severity

Fig. 1. (*a*) Our study area on the north side of the Stein River showing the locations of the sampling plots (graticule is Universal Transverse Mercator units × 1000 in North American Datum 27, zone 10). (*b*) Location of our study area about 20 km upstream of the confluence of the Stein and Fraser rivers. (*c*) Location of the study area in the southern interior of British Columbia west of the Fraser River (graticule is latitude and longitude). The shaded area is the range of ponderosa pine (*Pinus ponderosa*), the primary fire-scarred species sampled for this study (US Geological Survey 1999).



of historical fire regimes from primarily high severity in the west end to primarily low and mixed severity in the east (Riccius 1998; Wong 1999; Dorner et al. 2002; Heyerdahl et al. 2007). We located our study area in the middle of this gradient in dry forests containing a mix of ponderosa pine and Rocky Mountain Douglas-fir.

Our first objective was to determine the relative importance of high- and low-severity fires over time at the plot scale (2 ha) in dry forests of the middle Stein Valley using fire scars and the establishment dates of trees. Our second objective was to determine whether the mix of severities varied across our study area. This work was conducted as part of a broader study of the way natural disturbances shape long-term dynamics of forests across spatial scales from stands (<10 ha) to landscapes (10^5 ha) in and around the

Stein Valley (Riccius 1998; Wong 1999; Dorner et al. 2002; Heyerdahl et al. 2007; Jordan et al. 2008).

Methods

Study area

The forests of the Stein River Valley vary from the cool, moist types of the Coastal Western Hemlock and Engelmann Spruce – Subalpine fir biogeoclimatic zones (CWHms1, ESSFmwp, ESSFmww, and ESSFmw2 variants) at the head of the valley to the west to the hot, dry types of the Ponderosa Pine and Interior Douglas-fir zones (PPxh2, IDFxc, and IDFdc) at the mouth of the valley to the east (Meidinger and Pojar 1991). The Stein Valley Nlaka'pamux Heritage Park encompasses the entire valley. Annual precipitation at Lytton, near the confluence of the Stein and Fraser rivers, is 423 mm (1970–1990) (Environment Canada 1993) (Fig. 1*b*). Winters are cold and summers hot with a daily January minimum of –6 °C and daily July maximum of 28 °C. Most precipitation falls as snow between November and March (77%). Modern lightning and lightning-ignited fires occur primarily in July and August (1950–1994) (British Columbia Forest Service 1995*a*, 1995*b*).

The Stein Valley is in the traditional territory of the Nlaka'pamux and St'át'imc First Nations bands. No physical evidence of permanent village sites has been found near our middle valley study site, but the valley has abundant archaeological evidence of past use for sustenance, cultural, and ceremonial activities and the valley continues to be important to First Nations people today (M'Gonigle and Wickwire 1988). Although some European influence had penetrated to the interior from the coast by 1808, the time of Simon Fraser's journey down the Fraser River, major changes in First Nations culture and land use were associated with the large influx of nonaboriginal people following the gold rush along the Fraser River in 1858 (Harris 1997; Laforet and York 1998). Beginning in the early 1860s, the Fraser Canyon, perhaps including the mouth of the Stein River, was grazed by domestic livestock (Weir 1964), but there is no record of grazing in our study area, likely because the steep walls of the valley would be difficult for domestic livestock to traverse. The valley has not been commercially logged. Historical trapping is the only commercial activity that we know of in our study area.

Our study area is in the lower midvalley, about 20 km west of the confluence of the Stein and Fraser rivers (Fig. 1). At low elevations, it is in the Very Dry Cold variant of the Interior Douglas-fir biogeoclimatic zone (IDFxc), and at the upper and western parts, it is transitional to the Very Dry Cold and Wet Warm variants of the Interior Douglas-fir biogeoclimatic zone (IDFdc and IDFww1). Over 1105 ha on the north side of the Stein River, we placed 43 plots on a roughly regular grid across an area of similar topography. The plots were 384 m apart on average (range 258–610 m) (Fig. 1). We did not sample two of them because they lacked conifers large enough to meet our sampling criterion (i.e., 10 or more centimetres in diameter at breast height (DBH), 1.4 m). The remaining 41 plots span 585 m of elevation (665–1250 m above sea level). The majority of the plots are on southeasterly slopes with a few (four) on flat terraces adjacent to the river. Slope at the plots averaged 39% (range 0%–90%).

Forest composition

Small trees were generally much more abundant than large ones, so to avoid oversampling the small trees, we sampled them over an area smaller than that over which we sampled the large trees. Specifically, we sampled all of the live trees in three diameter classes (small: 10–30 cm DBH, medium: 30–50 cm DBH, and large: >50 cm DBH) that occurred in three nested, circular plots, 0.03, 0.13, and 0.79 ha, respectively. However, where the small plot had fewer than five small trees (10 plots), we sampled small trees in an additional small plot located 25 m along a random azimuth from the plot center. Where the large plots had dense large trees (five plots), we sampled them only in two randomly chosen quadrants. We computed tree density at plots by scaling and combining information from the trees that we sampled in all three of the nested plots. From the center of each plot, we visually estimated the live basal area of each tree species using a 10-factor English basal area prism.

Even-aged cohorts of trees

We estimated establishment dates from increment cores that we removed from the trees in our nested plots and tallied live trees with pockets of decay that we could not core. We cored close to the ground (average height 27 cm). We sanded all cores until the cell structure was visible with a binocular microscope and assigned calendar years to tree rings using visual crossdating of ring widths against existing ring width chronologies from the Stein Valley (Riccius 1998; Wong and Lertzman 2001) and those that we developed from the trees that we sampled. To estimate establishment dates from the date of the innermost ring sampled, we applied one, and sometimes two, corrections. First, to account for the number of years for a tree to reach coring height, we assumed that Douglas-fir increased in height 20 cm·year^{-1}, while ponderosa and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex S. Watson) increased 16 cm·year^{-1}, based on a previous analysis of early height growth in the Stein Valley (average correction 4 years, range 0–11 years; Wong and Lertzman 2001). Second, for cores that did not intersect the pith (78%), we estimated the number of rings to the pith based on the curvature of the innermost rings sampled (average correction 6 years, range 1 to 25 years; Applequist 1958).

Disturbances that kill some or all of the overstory trees in a plot can be followed by the establishment of an even-aged cohort of trees. In our study area, such disturbances include fire, insect outbreaks, and windthrow. For this analysis, we assumed that all cohorts resulted from fire because there is abundant evidence of fire in our study area in the form of fire scars but we lack evidence for insect outbreaks and windthrow as significant components of the historical disturbance regime there. We discuss possible implications of this assumption below. We identified a cohort of trees at a plot when five or more trees established in that plot within a 20 year period, proceeded by at least 30 years during which no trees established. More than one cohort can coexist in a plot if a disturbance does not kill all of the overstory trees but leaves some residual trees (Turner 2010). For example, if a cohort established in 1619 in response to a fire that killed all of the trees in a plot, a second cohort could established in 1899 in response to a fire that killed some, but not all, of the trees in the 1619 cohort.

Cohorts in open-canopy ponderosa pine forests of the southwestern United States can establish during periods when cool and (or) wet climate inhibits frequent surface fire but encourages tree establishment (Brown and Wu 2005). This effect is scale dependent such that climatically forced cohorts establish synchronously across climatically homogeneous sites or regions whereas fire-caused cohorts will be local in scale when severe fires are small or synchronous across large areas when severe fires are extensive. We assessed whether cohorts in our study area may have been climatically forced by assessing whether cohorts established synchronously across the site during periods of relatively cool, wet climate by visually comparing their establishment dates with a tree-ring reconstruction of the summer Palmer Drought Severity Index (PDSI) (June–August; grid point 31; Cook et al. 2004).

Fire scars

At each plot, we searched for fire-scarred trees over about 2 ha, an area 2.5 times the size of our establishment date plots, because the majority of trees in our study area do not have fire scars. At plots where we found fire-scarred trees, we used a chainsaw to remove partial cross sections from an average of four live or dead trees with the greatest number of well-preserved visible scars (range one to five trees; Arno and Sneck 1977). We crossdated the sections as described above for increment cores and excluded samples that could not be crossdated (5% of trees). The dating for some samples (35%) was verified using cross-correlation of measured ring width series (Grissino-Mayer 2001). We generally assigned ring boundary scars to the preceding calendar year because modern fires generally occur in mid- to late summer in this area (British Columbia Forest Service 1995*a*, 1995*b*). However, when ring boundary scars in a given year were accompanied by many early-season scars the following year, we assumed that all of the scars were created by a fire that burned before some of the trees began radial growth and therefore assigned the ring boundary scars for these fires to the following year (4% of scar dates changed). We excluded fire dates that were only recorded on a single tree in the study area (40 fire scar dates). We composited the fire dates from all trees in a plot into a single record of low-severity fire for that plot and computed plot-composite fire intervals.

The tree establishment dates, fire scar dates, and associated metadata are available from the International Multiproxy Paleofire Database, a permanent public archive maintained by the Paleoclimatology Program of the National Oceanic and Atmospheric Administration in Boulder, Colorado (http://www.ncdc.noaa.gov/paleo/impd/paleofire.html).

Inferring fire severity

We assigned each plot to one of four fire severity categories (high, mixed, low, or unknown) that reflected the mix of evidence for different fire severities at that plot over time. We assigned high-severity regimes to those plots with no fire scars, a single cohort, and no residual trees that established before the cohort. We assigned mixed-severity regimes to those plots with (*i*) fire scars and one or more cohorts or (*ii*) a distinct cohort plus older, residual trees that survived the fire that resulted in the cohort. We assigned low-severity regimes to those plots with fire scars but no distinct cohorts. Plots that lacked both fire scars and cohorts were not assigned to a severity category.

To evaluate the sensitivity of our classification of fire severity to the criteria that we used to identify cohorts, we repeated our analyses with cohorts that we identified using two alternative criteria. For alternative A, we required that five or more trees establish within 10 years of each other, preceded by at least 20 years during which no trees established. For alternative B, we required that five or more trees establish within a 30 year period, preceded by at least 40 years during which no trees established.

We computed an index of fire severity as the percentage of cohorts in each plot (the number of cohorts in the plot divided by the number of cohorts plus fire scar dates over the entire period of record). Plots with only low-severity fires have an index value of 0 (only fire scars) whereas plots with only high-severity fires have an index value of 100 (only one cohort). Plots with mixed-severity fires have index values ranging from >0 (fire scars and cohorts) to 100 (two or more cohorts but no fire scars).

Spatial variation in fire regimes

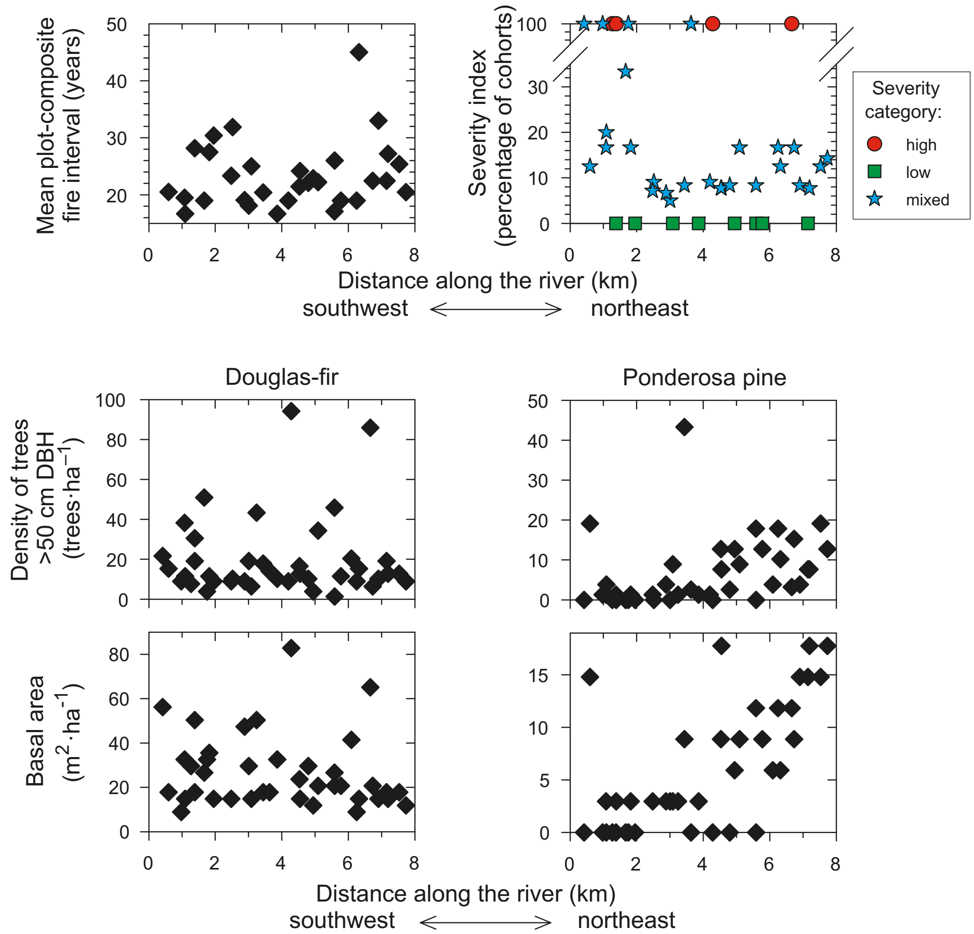
To assess whether fire frequency or severity varied systematically across the study area, we correlated each plot's distance along the river from the western end of the study area with its mean plot-composite fire interval and with our index of fire severity using nonparametric Spearman rank correlation (SAS Proc Corr: SAS Institute Inc. 2003). Before testing for correlation, we determined that neither fire intervals nor our fire severity index was spatially autocorrelated (α = 0.05) by computing an omnidirectional Moran's I for 10 distance classes of 400 m each under a randomization null hypothesis. We tested the overall significance of the correlogram of Moran's I using a Bonferroni correction that accounts for multiple tests by reducing the significance level by dividing it by the number of distance classes (Oden 1984; Sawada 1999).

Results

Forest composition

Ponderosa pine trees occurred in most plots (34 of 41 plots or 83%) and Douglas-fir trees occurred in all plots. The density of large ponderosa pine trees (those >50 cm DBH) averaged 7 trees·ha^{-1}, while the density of large Douglas-fir averaged 20 trees·ha^{-1} (Fig. 2). One plot in the southwest corner of the study area was dominated by lodgepole pine (510 trees·ha^{-1}) with some Douglas-fir (49 trees·ha^{-1}) and ponderosa pine (1 tree·ha^{-1}). The basal area of ponderosa pine averaged 6 trees·ha^{-1} and that of Douglas-fir averaged 27 trees·ha^{-1} (Fig. 2). A few trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), black cottonwood (*Populus balsamifera* subsp. *trichocarpa* (Torr. & Gray ex Hook.) Brayshaw), Pacific yew (*Taxus brevifolia* Nutt.), and western redcedar (*Thuja plicata* Donn ex D. Don) occurred in some plots with basal areas ranging from 3 to 9 trees·ha^{-1}.

Fig. 2. Spatial variation in fire regimes and forest structure and composition at plots across the study area.



Even-aged cohorts of trees

In our plots, we found 1601 live trees that were >10 cm DBH, mostly Douglas-fir (81%) or ponderosa pine (17%) but including a few lodgepole pine (17 trees) and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) (one tree). We were unable to remove an increment core from 235 of these trees (15%) because of decay and were unable to crossdate cores from an additional 96 trees (6%) for an average of eight undated trees per plot (range 0–22 trees). The undated trees were mostly Douglas-fir (55% large trees, 11% medium trees, and 10% small trees) and large ponderosa pine (19%). The remaining 5% were medium and small ponderosa pine or small lodgepole pine trees. We crossdated 1270 trees (average 31 trees and range 8–59 trees per plot) and they established between 1479 and 1953 (Fig. 3). Seven of these trees were from two of the four high-severity plots; one of these plots had five out of 37 large trees undatable and the other had two out of 28 large trees undatable. We think that it is not likely that dating these trees would have identified another, older cohort.

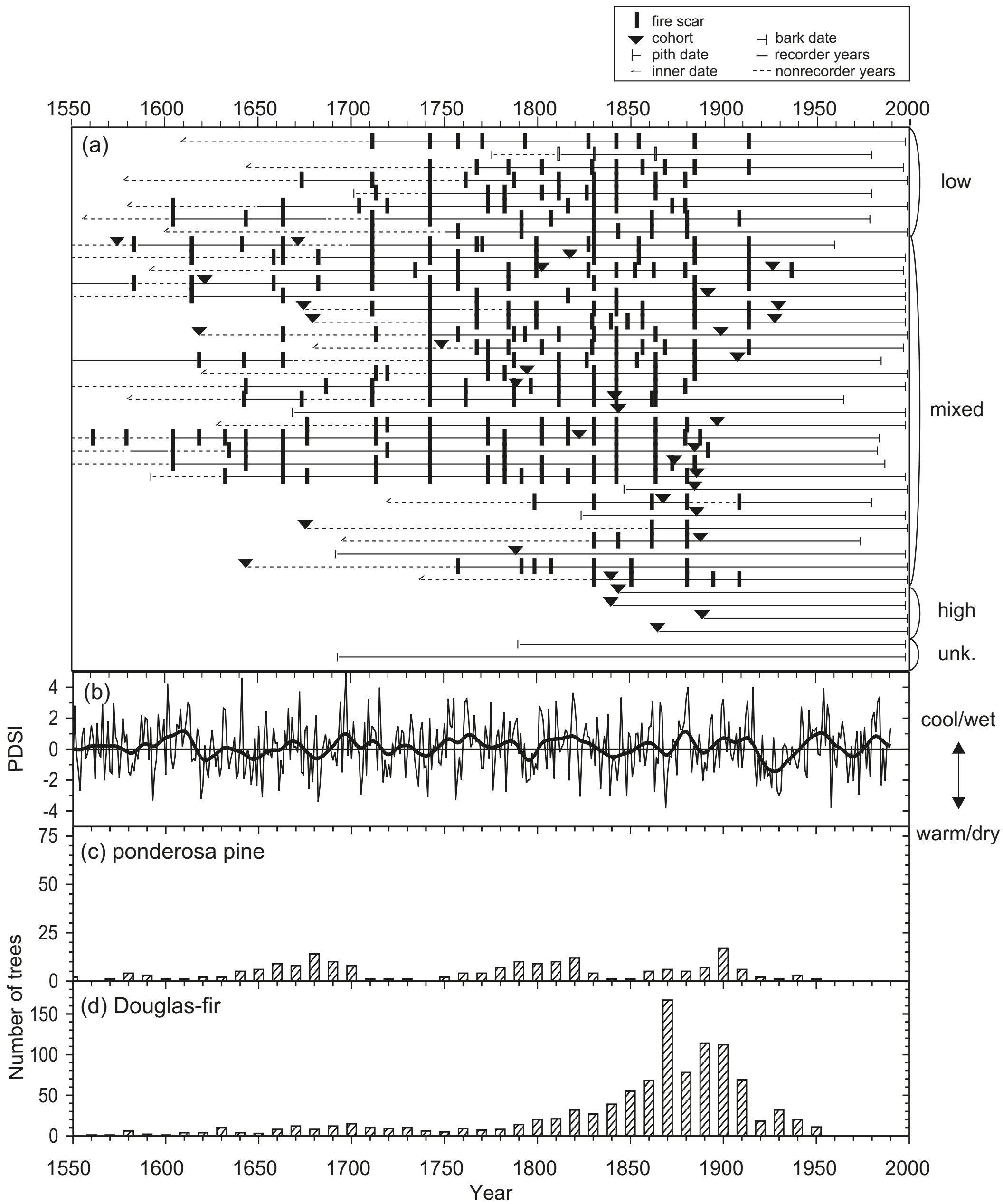
We identified cohorts of trees at most of our plots (31 of 41 plots or 76%). The majority of plots with cohorts had only a single cohort (26 of 31 plots or 84%) and the remaining five plots had two cohorts for a total of 36 cohort dates (Fig. 3). Cohort dates (establishment date of the oldest tree in the cohort) ranged from 1575 to 1930, but more than half (56%) established in the 1800s. The cohorts contained an average of 12 trees (range 5–37) and varied in composition. Every cohort contained at least one Douglas-fir tree (range 1–35 trees) and just over half of the cohorts contained ponderosa pine (21 of 36 cohorts or 58%), with an average of three trees of this species contributing to the cohort (range one to nine trees). One cohort was dominated by lodgepole pine (13 of 19 trees).

We found no evidence that the cohorts in our study area were climatically forced. They did not establish synchronously across the study area during periods of cool, wet Palmer Drought Severity Index (Fig. 3).

Fire scars

Most plots contained fire-scarred trees (31 of 41 plots or 76%). We removed one to three partial cross sections from each of 132 fire-scarred trees and crossdated samples from 125 of them. Of the crossdated trees, most were ponderosa pine (96%) with the rest Douglas-fir, and more than half were dead when sampled (69%). We dated 999 fire scars between 1562 and 1937, with most scars (81%) formed between 1700 and 1900 (Fig. 3). Compositing these dates by plot yielded 305 well-documented fire scar dates or an average of 10 dates per plot (range 2–19, excluding the plots that

Fig. 3. Chronologies of (*a*) fire occurrence, (*b*) climate, and (*c* and *d*) tree establishment. Horizontal lines show the calendar year life spans and fire occurrence for the composite fire record at each plot (i.e., fire scar dates composited for all trees within a plot, one to five trees sampled over about 2 ha plus the initial date of even-aged cohorts of trees) through time. Cohort dates are not annually accurate and may slightly predate their actual date if the corrections for distance to pith and years to reach coring height were too large. For plots with fire scars, nonrecorder years include those preceding formation of the first scar at a plot and periods during which any record of fire was consumed by subsequent fires or decay. For plots lacking fire scars, recorder years indicate the length of the tree-ring record. Inner dates are those of the earliest ring sampled at plots where pith was not sampled. Climate (PDSI) is the tree-ring reconstructed Palmer Drought Severity Index (Cook et al. 2004). Estimated tree establishment dates are summarized by decade across the study area by species and do not include trees <10 cm DBH (Figs. 3*c* and 3*d*). The *y*-axis scale for Douglas-fir (*Pseudotsuga menziesii*) is twice that for ponderosa pine (*Pinus ponderosa*).



lacked scars) (Fig. 3). Pooled across the study area, the mean plot-composite fire interval averaged 23 years (range 2–79 years) when computed over the entire period of record (from 1562 to 1937). This differed only slightly from the average computed over the period from 1700 to 1900 (average 21 years, range 2–60 years), when more trees were recording fire.

Inferring fire severity

We assigned most plots (27 of 41 or 66%) to a mixed-severity regime because they had fire scars *and* one or more cohorts (23 plots, e.g., the fire demography diagram in Fig. 4*c*) or a single cohort plus older residual trees (four plots, e.g., Fig. 4*d*). We assigned eight plots (20%) to a low-severity regime because they had fire scars but no cohorts

Fig. 4. Fire demography diagrams (Grissino-Mayer 2001; Brown et al. 2008) showing the range of fire severities that we assigned to six of our 41 plots. Each panel includes all of the trees that were cross-dated from a single plot. These plots were assigned to (*a* and *b*) high-severity regimes, (*c* and *d*) mixed-severity regimes, or (*e* and *f*) low-severity regimes based on the presence of cohorts and fire scars.

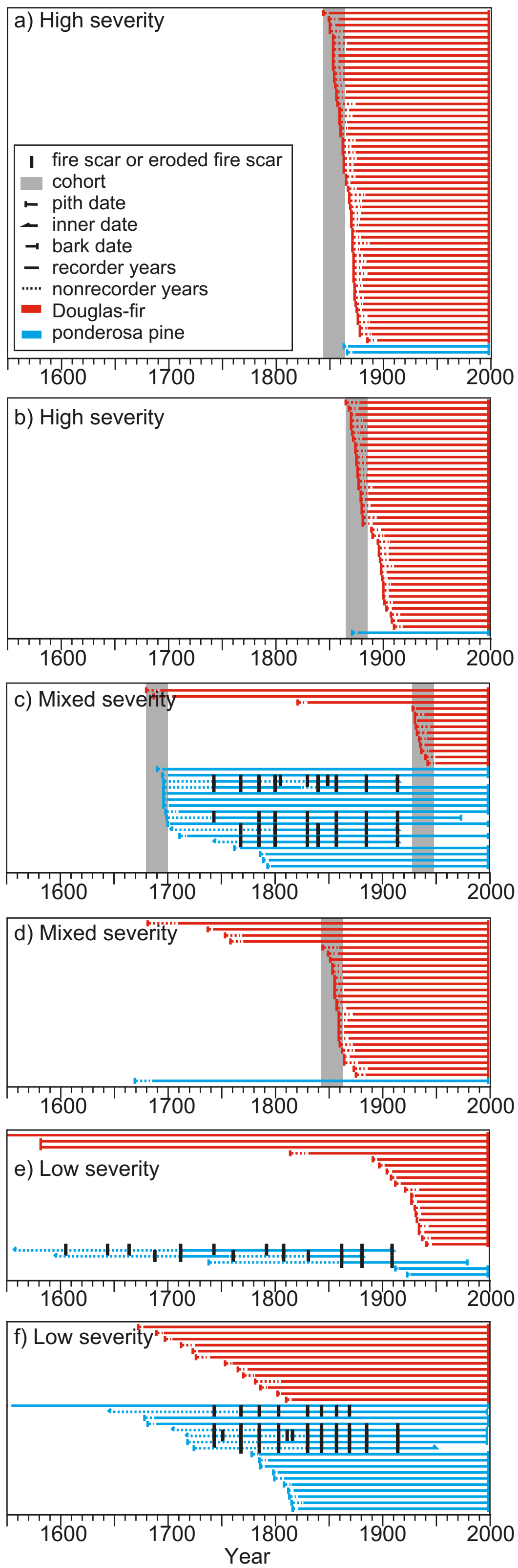
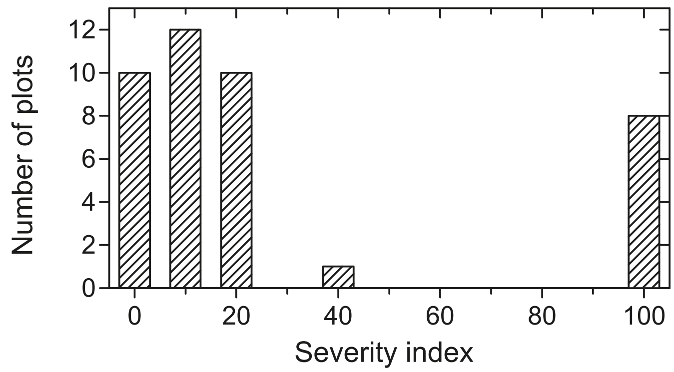


Fig. 5. Distribution of plots by our severity index (computed as the number of cohort dates divided by the number of fire scar plus cohort dates). A severity index below 50 indicates that there were more fire scar dates than cohort dates. A severity index of 100 indicates that all of the fire dates were derived from cohorts, but at half of our plots with this value, more than one cohort occurred and so we inferred a mixed-severity fire regime.



(e.g., Figs. 4*e* and 4*f*) and four plots (10%) to a high-severity regime because they had only a single cohort (e.g., Figs. 4*a* and 4*b*). Two plots had neither cohorts nor fire scars and so were not assigned a severity.

Our fire severity index ranged from 0 in low-severity plots to 100 in high-severity plots and also in mixed-severity plots in which a cohort was survived by older, residual trees (Fig. 2). The index at mixed-severity plots that contained both cohorts and fire scars averaged 12 (range 5–33) (Fig. 2). Most plots (80%) had a severity index less than 50 (Fig. 5). The dichotomous nature of the fire severity distribution is striking: plots were dominated either by low-severity fires or by one or more cohorts. None of the plots that had both fire scars and cohorts were dominated by the cohorts.

Our assignments of fire severity were not very sensitive to the criteria we used to identify cohorts. Compared to the criteria used in our analysis, Alternative A identified fewer cohorts, classified more plots as low-severity, and fewer as mixed- and high-severity (Table 1). The results from Alternative B were opposite. Averaged across all mixed-severity plots, the severity index varied by a maximum of 15%age points among criteria. Thus our conclusions are unlikely to be highly contingent on the classification criteria we used.

Spatial variation in fire regimes

Although structural and compositional variation was apparent on the ground both at the plot scale and across the study area as a whole, fire regimes did not vary systematically across the study area, as we had expected from our a priori understanding of the broad gradient in fire regimes along the full length of the Stein River Valley. Neither mean plot-composite fire intervals nor our index of fire severity was significantly correlated with distance along the river ($r = 0.15$, $p = 0.4275$ and $r = -0.28$, $p = 0.0823$, respectively). Furthermore, neither fire intervals nor the fire severity index was spatially autocorrelated ($p > 0.0217$). Instead of systematic geographic variation in these parameters of the fire regime (or in vegetation structure and composition), we found patchy

Table 1. Sensitivity of fire severity index to criteria used to identify postfire cohorts.

	Alternative A	Used in analysis	Alternative B
Criteria			
Length of cohort (years)	10	20	30
Prior gap (years)	20	30	40
Minimum number of trees	5	5	5
Results			
Cohorts (number)	27	31	33
Low-severity plots (number)	13	8	5
Mixed-severity plots (number)	24	27	28
High-severity plots (number)	3	4	5
Plots with unknown severity (number)	1	2	3
Severity index (average across mixed-severity plots) (%)	25	33	18

Note: Fire severity index is the percentage of cohorts at a plot (the number of cohorts divided by the number of cohorts plus fire scar dates for the entire period of record).

variability among plots. Fire regime and vegetation structure varied, but without an identifiable spatial pattern and not in the ways or at the scale that we expected.

Discussion

Mixed-severity fire regime: dominated by low-severity fires, punctuated by infrequent high-severity disturbances

Over the past several centuries, most of the plots (66%) that we sampled in dry forests of Douglas-fir and ponderosa pine in the middle Stein Valley sustained fires with a mix of severities over time. The mix that we reconstructed across our study area was dominated by low-severity fires with only occasional patches of high-severity disturbances that were small relative to the size of the study area. For the plots that we assigned to a mixed-severity regime, our fire severity index averaged only 25, i.e., only 25% of the events recorded in those mixed-severity plots were cohorts, which we assumed were evidence of high-severity fire. The widespread presence of old, fire-scarred trees in our study area also supports our inference that while high-severity patches certainly occurred in the dry forests of the Stein Valley, they were not extensive. The 37 fire-scarred trees that were alive when we sampled them (30% of fire-scarred trees) were 303 years old on average (range 181–487 years). Furthermore, 77% of plots with mixed- and low-severity fire regimes had trees that established before 1700.

The mix of severities did not vary systematically across the relatively consistent topography of our study area. Although the mix of severities in a fire regime can vary with topography (e.g., with elevation: Sherriff and Veblen 2006), our study area lacked substantial topographic gradients except in slope. However, we know that topography played a significant role in the behavior of individual low-severity fires and patterns in their frequency and extent over time within our study area. Jordan et al. (2008) showed that stream corridors within the study area were consistently associated with the boundaries of low-severity fires and that the incidence of these fires varied among landscape elements separated by streams. As well, Heyerdahl et al. (2007) showed that various aspects of a low-severity fire regime varied with aspect 20 km to the east near the mouth of the Stein Valley. Furthermore, outside the bounds of our study area, the mix of severities certainly varies along the entire length of the valley, with mesic forests to the west experiencing primarily high-severity fire regimes (Dorner et al. 2002). The mix is also likely to vary between our study area on south slopes and the adjacent north slopes on the other side of the Stein River that we did not sample.

We inferred that historically, the fire regime across our study area was one of frequent, often extensive low-severity fires but some small, high-severity disturbances also occasionally occurred. We derived this inference from fire scars and cohorts. While we have a high degree of confidence in our fire scar interpretation, it is significantly more challenging to identify even-aged cohorts of trees and to identify their forcing agents. Despite these challenges associated with cohorts, our overall inference about the historical fire regime across our study area is relatively robust. We may have overestimated the number of postfire cohorts because we assumed that none of our cohorts established after insect or disease outbreaks. However, while we could find little modern evidence of significant tree mortality due to insect outbreaks or windthrow, we found abundant evidence of frequent historical fire in the form of fire scars. Some of the cohorts that we assumed established after severe fire at a plot may have been shade-tolerant Douglas-fir trees that established in response to a low-severity fire or after the disruption of the low-severity fire regime in the late 1800s, although we did not find widespread, synchronous establishment of such trees during this period. Furthermore, our overall inference of a historical mixed-severity regime that was dominated by low-severity fires with relatively few patches of high-severity fire would still be valid even if we had overestimated the number of patches of high-severity fire.

Alternatively, we may have underestimated the number of high-severity fire patches for several reasons. First, cohorts that establish after severe fire can be killed by a subsequent fire so that the establishment dates of living trees are only a conservative estimate of past fires (Brown et al. 2008). For example, cohorts established in two plots around 1928 following the last low-severity fire recorded by fire scars in those plots in 1914. Historically, fires burned about every 20 years on average, so if another fire had occurred in the 1930s, then the small trees would have been killed and the evidence of the 1928 cohort would have been lost and not detected using our research methods. Second, we did not sample the establishment dates of dead trees and were unable to date some of the live trees in our plots. Seven of the undatable trees were from two of the four plots in which we identified a single cohort; one of these plots had five out of 37 large trees undatable and the other had two out of 28 large trees undatable, so it is unlikely that dating them would have identified another cohort at these plots. As a consequence, we may have failed to identify additional cohorts and so underestimated the occurrence of high-severity fires in the study area. However, even if the actual number of cohorts was an order of magnitude greater than we detected (i.e., 360 versus 36 cohorts), the number of high-severity fire dates would only comprise about half (54%) of the total fire dates at plots (305 fire dates from scars plus 360 fire dates from cohorts) and our inference of a historical mixed-severity regime with frequent, often extensive low-severity fires with patches of high-severity fire would still be valid.

We found evidence that fires of different severities occurred at individual plots through time in our study area (e.g., Fig. 4*c*), but it is also likely that individual fires were of mixed severity across space, as has been documented elsewhere for dry forests, both for modern fires (Lentile et al. 2005) and for historical ones (Brown et al. 1999, 2008). For example, an extensive 1843 fire was recorded by fire scars in 20 of our plots and likely by cohorts in five plots, four of which lacked scars (Fig. 3). Only two of the cohorts were in adjacent plots, suggesting that the patches of high-severity fire were small relative to the extent of the fire within the study area. Overall, given that most plots with a record of this fire (79%) had fire scars but no cohorts, this particular fire appears to have been dominantly low in severity with patches of high-severity fire within our study area. This emphasizes the complex nature of spatial and temporal patterns in the “mix” of a mixed-severity fire regime (Halofsky et al. 2011).

A few of the plots that we sampled had only evidence of high-severity fire. One of these plots in the southwestern corner of the study area was dominated by lodgepole pine and may be representative of high-severity fire regimes in lodgepole forests farther west toward the headwaters of the Stein River. Alternatively, these plots may have historically sustained a low- or mixed-severity regime, but with the most recent fire being of high severity. Some of the plots that we sampled initiated with a cohort several hundred years ago and then subsequently sustained frequent low-severity fires (Fig. 4*c*), similar to some locations in the Black Hills of South Dakota (Brown et al. 2008). However, if low-severity fires had been similarly frequent in our high-severity plots in the past, we would have expected to find some evidence of dead fire-scarred trees at those sites, but did not.

We could not determine whether the fire, or other disturbance, that resulted in a cohort was synchronous with a low-severity fire. While annually accurate fire dates can be obtained from fire scars, annually accurate fire dates cannot be obtained from postfire cohorts alone, although they can be obtained if fire scars are associated with these cohorts and fire intervals are long relative to the uncertainty in fire dates derived from the cohorts (Kaufmann et al. 2000; Kipfmueller and Baker 2000; Sibold et al. 2006; Margolis et al. 2007). The estimated dates of tree establishment do not typically yield accurate fire dates because coring rarely obtains the actual germination date of the trees; they are cored some distance up from the root collar and, as in our case, a correction is applied. Furthermore, there is often an unknown, climate-driven lag between the year of the fire and tree establishment. Where intervals between fires are long, cohorts may be assigned to a fire scar date (e.g., Brown et al. 1999). However, where fire scar dates are frequent relative to postfire lags in establishment, assigning cohorts to fire scar dates is not always possible. In our plots, fire scars were abundant and could be dated with annual accuracy, but we could not unequivocally assign a fire date to most cohorts, at least in part because low-severity fires were so frequent (Fig. 3).

Frequent, low-severity fires were not historically limited to sites with flat or gentle topography, as has been suggested for the southern interior of British Columbia (Klenner et al. 2008). While such fires did occur historically across our study area and at sites farther south with flat or gentle topography (e.g., Heyerdahl et al. 2001), they have also been observed at sites with steeper slopes (e.g., Heyerdahl et al. 2001; Wright and Agee 2004). Of the 35 plots to which we assigned a low- or mixed-severity fire regime, all historically sustained frequent low-severity fires. Three of these plots had gentle slopes (0%–20%), but most had moderate slopes (23 plots with slopes from 21% to 50%) or steep ones (nine plots with slopes from 50% to 90%). At the mouth of the Stein River (20 km from our study site), all but one of 37 plots had moderate to steep slopes (22%–67%) and sustained frequent low-severity fire regimes in the past (Heyerdahl et al. 2007).

We suggest that mixed-severity fire regimes that are dominated by low-severity fires were likely to be historically widespread in the Interior Douglas-fir and Ponderosa Pine zones elsewhere in the southern interior of British Columbia. This hypothesis is generally consistent with the conclusions of Klenner et al. (2008), although our data support a more significant role for low-severity fires than their analyses suggest. Unfortunately, there is little direct evidence published on fire regimes in the dry forests of the British Columbia interior that might be used to resolve how widespread the importance of low-severity fires actually is. The most pertinent comparison with the current study is with our own work 20 km to the east in the lower Stein Valley (Wong 1999; Heyerdahl et al. 2007). The historical frequency of low-severity fires in 2 ha plots in the middle Stein Valley was similar to that in the lower valley: mean plot-composite fire intervals in the middle valley averaged 20 years (range 2–60 years) versus 23 years (range 2–29) on south slopes in the lower valley during the same time period (1750–1950). In both study areas, older fire-scarred trees are common, but so are small, dense, Douglas-fir-dominated patches that appear to be the even-aged legacies of higher severity fire. However, our hypothesis of a mixed-severity fire regime dominated by low-severity fires likely cannot be extrapolated to riparian forests, even in our own study areas because we did not sample them. Such areas appear to often act as barriers to the spread of low-severity fires in the Stein Valley (Jordan et al. 2008), and these more mesic areas often accumulate substantially more fuels than nearby drier forests.

The broader landscape mosaic will comprise a complex mix of forests that owe their character not only to varying combinations of low-, mixed-, and high-severity fires but also to interactions between fires and other disturbance types of varying severity, including, insects, disease, fluvial and colluvial processes, and wind (Klenner et al. 2008). Resolving how this mix varies geographically is important because is has implications for a wide range of critical issues in ecosystem conservation and management (Klenner et al. 2008; Halofsky et al. 2011). This will require a substantial effort to build a geographically distributed network of studies such as ours that assess the nature and mix of disturbance severities across landscapes. Although such a research program will be challenging, it is the only way to resolve the complex management issues surrounding current debates on fire severity. This is made more urgent and challenging, however, because of the loss of historical records embedded in tree rings as a result of modern fires and the widespread mortality of ponderosa pine associated with the current mountain pine beetle outbreak.

Conclusions

In our study area, we inferred that low-severity fires have dominated the mixed-severity fire regime for at least several hundred years. Despite this dominance, fires of varying severities contributed to the suite of biological legacies and potential developmental pathways in the study area. Even when they occur in small patches, high-severity fires can be ecologically important (Collins and Stephens 2010) and patterns in forest structure represent a combination of the influence of high- and low-severity fires (Wong 1999). We expect that this kind of mixed-severity regime was widespread in the southern interior of British Columbia, but evaluating this hypothesis requires that additional studies of historical fire regimes be conducted elsewhere in the region.

Our a priori understanding of the gradient of fire regimes across our study area was challenged by our results. While the broader environmental gradient from the dry eastern end of the valley to the mesic western end within which our study area is embedded remains clear, at the finer scale represented by our 1105 ha study area, there were no consistent spatial patterns within the mix of fire severities either along the east–west gradient or from one plot to the next. This failure to identify spatial patterns suggests that even in an area of relatively consistent topography, such as ours, complex microgradients of topographic shading, fuel accumulation and drying, and topographic barriers can create a very complex pattern of historical fire behavior and severity. To resolve the geographic gradient in fire severity that we originally hypothesized would require reconstructing historical fires across a larger spatial scale that includes the more mesic and complex terrain to the west while maintaining the fine spatial resolution of the current study.

We suspect that, to some extent, the debates over the ecological significance of historical fires of varying severity arise from a combination of real geographic variation in the drivers of fire severity in time and space and the different messages provided by varying analytical approaches. For our study system, we would see distinct phenomena and come to different, incomplete conclusions if we looked only through the lens of fire scars or patterns in cohort establishment. In fact, while it is challenging, our approach illustrates more interesting, more complex ecological dynamics than we would see from either approach in isolation. We suggest that efforts to resolve the disputes over variation in historical fire severity and its management implications should be empirically based and grounded in methodological pluralism.

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