Spatially Explicit Quantification of Heterogeneous Fire Effects Over Long Time Series: Patterns from Two Forest Types in the Northern U.S. Rockies

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Introduction

Within the last decade, mixed-severity fire regimes (MSFRs) have gained increasing attention in both the scientific and management communities (Arno and others 2000, Baker and others 2007, Hessburg and others 2007, Perry and others 2011, Halofsky and others 2011, Stine and others 2014). The growing influence of the MSFR model derives from several factors including: (1) recent recognition of the wide geographic breadth of mixed severity fire regimes within western North America and elsewhere, (2) a lack of basic ecological data that spans sufficient temporal and spatial scales to sufficiently describe MSFRs for many regions, (3) debate about the appropriateness of using low- and high-severity fire regime models for MSFRs and (4) uncertainty regarding the implications of the MSFR model for describing ecosystem dynamics, predicting ecosystem responses to climate change and past management, designing ecological restoration treatments, and implementing future forest management and policy.

MSFRs have been documented in low to middle elevation forests of many regions within western, and parts of eastern, North America, including a diverse array of forest types comprised of ponderosa pine, Jeffrey pine, Douglas-fir, western larch, lodgepole pine, red fir, grand fir, white fir, jack pine and other species (Heinselman 1973, Taylor and Skinner 1998, Taylor 2000, Arno and others 2000, Wright and Agee 2004, Hessburg and others 2007, Sherriff and Veblen 2007, Klenner and others 2008, Perry and others 2011, Stine and others 2014). There is substantial variation in the dynamics of MSFRs for different vegetation types, between biogeographic regions, and along climatic, topographic, and successional gradients, but this variation is not yet well understood. In general, MSFR forests are thought to contain patches created by a mixture of surface fires, and active and passive crown fires that create a fine-scale mosaic of low, moderate and high severity fire effects (Agee 1993, Taylor and Skinner 1998, Lentile and others 2005, Baker and others 2007, Hessburg and others 2007 Halofsky and others 2011). The diversity and spatial arrangement of forest structure patches are thought to be key features of MSFR forests that create landscape memory (Peterson 2002) and influence the behavior of future fires (Moritz and others 2011, Perry and others 2011, Halofsky and others 2011). However, the relative importance of low versus high severity fire effects in structuring these landscape characteristics is actively being debated (Williams and Baker 2012, Fule and others 2013, Odion and others 2014). In addition, MSFRs exhibit high variability of fire return intervals (Brown and others 1999, Sherriff and Veblen 2007, Heyerdahl and others 2012), necessitating temporally resolved records of fire occurrence.

Although substantial datasets exist for MSFR forests in some regions, such as the Colorado Front Range (Sherriff and Veblen 2007, Schoennagel and others 2011), eastern Washington and Oregon (Hessburg and others 2007, Perry and others 2011), and parts of northern California and southern Oregon (Taylor 2000, Beatty and Taylor 2001, Taylor and Skinner 2003), there is a clear need for spatially explicit, temporally resolved data on the basic fire ecology of MSFR forests in other regions. Here, we present preliminary data from a study of fire history, tree establishment, and forest structure in pure Douglas-fir (*Psuedotsuga menziesii*) forests of the Greater Yellowstone Ecosystem (GYE) and mixed conifer forests of the Northern Continental Divide Ecosystem (NCDE), two of the dominant lower-mid elevation forest types of the northern U.S. Rockies thought to exhibit MSFRs. We combine extensive networks of dendroecological data with forest structure interpretations from historical aerial photographs to describe the fire history and landscape-scale patterns of fire severity produced by fires from the years 1600–present in one watershed within each of our two study regions. In addition to providing insight on the basic fire ecology of two widespread but poorly studied forest types, these data highlight some unique aspects of MSFRs that contrast with existing perceptions of low- and high-severity fire regimes.

Background

Douglas-fir forests of the GYE are characterized by gradients of open to closed canopy stands dominated by Douglas-fir, with small amounts of Rocky Mountain juniper (*Juniperus scopulorum*) and limber pine (*Pinus flexilis*) at lower elevations and lodgepole pine (*Pinus contorta*) at higher elevations (Figure 1a,c). A limited number of fire

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history studies exist in Douglas-fir forests of the GYE, primarily in stands at the forest-grassland ecotone, which show historically recurrent low severity fire and Douglas-fir expansion into grassland during the period of fire exclusion (Heyerdahl and others 2006, Barrett 1994, Arno and Gruell 1983). However, few studies document landscape-scale patterns of fire frequency and severity across the broader range of Douglas-fir forests.

Mixed conifer forests of the NCDE are comprised of Douglas-fir, ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), lodgepole pine, grand fir (*Abies grandis*), and occasional western white pine (*Pinus monticola*), Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) (Figure 1b,d). Numerous studies of this forest type have documented mixed severity fire effects (Arno and others 1995, Barrett and others 1991, Habeck 1990) in individual stands, but the relative importance of low and high severity fire effects and their landscape arrangement are poorly understood.

Methods

Following previously published methods (Hessburg and others 2007) we used stereo aerial photographs from the 1930s to 1950s to map forest structure across two watersheds: Six Mile Creek (21,800 acres) on the Gallatin National Forest in the GYE and Spotted Bear River (17,200 acres) on the Flathead National Forest in the NCDE (Figure 2). Forest structures were mapped across the full extent of each study area by delineating forest patches with uniform characteristics, to a minimum patch size of 4 ha. For each mapped entity, photo-interpreted structural attributes were assigned, including the percent canopy cover, cover type, and diameter class of overstory and understory canopy layers.

To characterize the age structure and disturbance history of patches in each watershed, during 2011-2013, we developed a network of 74 sample sites in a subset of patches, collectively comprising greater than 70% of each study area. These sites were spatially distributed across each watershed along topographical gradients and within different forest structural types mapped by aerial photo interpretation. At each sample site, increment cores were collected from all trees > 4 cm DBH, within fixed 0.04 ha circular plots, spaced along a transect at 50-100m, until a minimum of 40 trees were sampled. Fire history was reconstructed from a spatially distributed network of 180+ fire scar samples collected within each watershed. All increment cores and fire scars were cross-dated using master chronologies developed for each watershed using standard dendrochronological methods (Stokes and Smiley 1968). All cores used to create the master chronologies were measured to 0.001 mm and statistically crossdated using the program COFECHA (Grissino-Mayer 2001). All other increment cores and fire-scar samples were

Figure 1—Photographs depicting low (a-b) and high (c-d) density forest stands in the GYE (a, c) and NCDE (b, d).

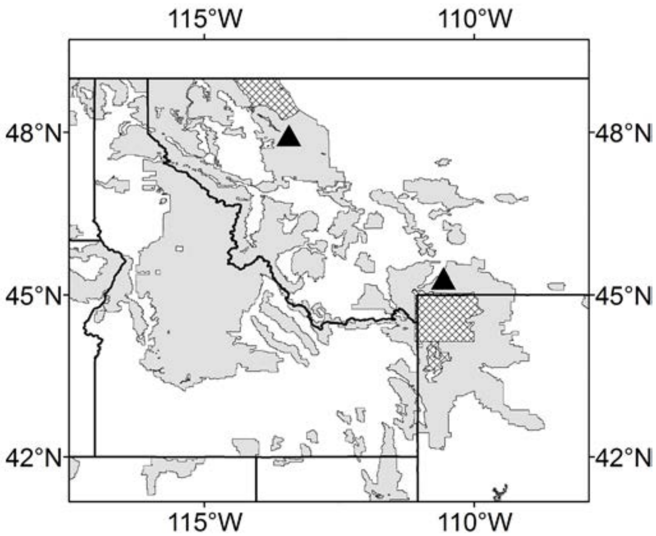

Figure 2—Map of the study region showing the study watersheds (black triangles), National Parks (crosshatched) and National Forests (grey).

crossdated using a combination of visual and statistical crossdating. Fire dates from all fire scars found within a patch were aggregated into one composite record that represented the fire history at that patch. For consistency with the aerial photo data and to minimize the influence of fire suppression on interpretations of age structure, tree establishment data were truncated at 1954, the date of the most recent aerial photograph used to map forest structures.

To determine historical fire severity, we compared the age structure of a patch with the composite fire history for that same patch to determine the percent of stand basal area (BA) that survived each fire. Similar to other studies we used the 20/70 percent threshold values of the percent BA surviving a fire to classify each fire as high, moderate, or low severity (Agee 1993, 1994, Hessburg and others 2007, Schoennagel and others 2011). To account for disturbances other than fire which might affect stand age structure, only contiguous establishment pulses following documented fires were included in the severity calculation. The time-integrated fire severity history of each patch was classified as low, mixed or high if all fires were of low severity, were a mix of low, moderate or high, or were all of high severity, respectively. According to these criteria, low severity sites are generally characterized by older, multi-cohort stands whereas high severity sites are even-aged young or old stands, depending on time since the last fire. Mixed severity sites encompass a diverse set of forest structures depending on the number of fires, the relative proportions of stand-replacing and non stand-replacing fire effects, and the time since stand-replacing fire.

Results

Forests in both regions exhibited moderate, but highly variable, stand density, with a median density of 530 trees ha^{-1} (min = 94, max = 3919) and 691 trees ha^{-1} (min = 209, max = 962) for the NCDE and GYE, respectively. Median canopy cover for both watersheds was similar, with a median

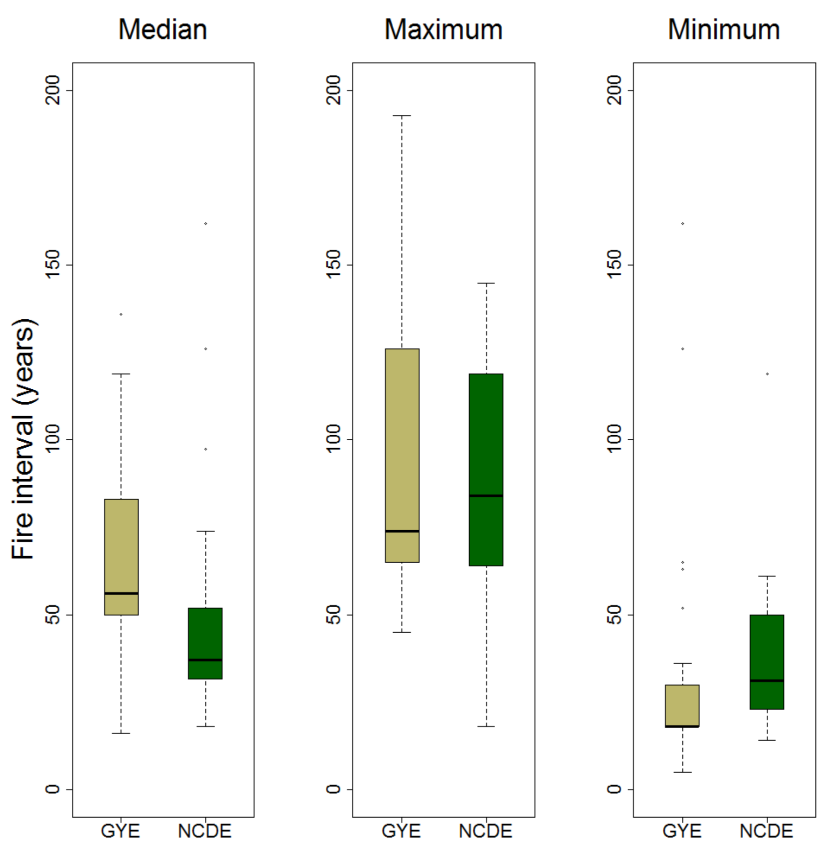

Figure 3—Boxplots of the median, maximum and minimum composite fire intervals for sites in the GYE and NCDE. Black horizontal bars within boxes represent the median, the box endpoints represent the 25th and 75th percentile values, and whiskers mark the 5th and 95th percentile values. Fire statistics were composited for all fire scars within the same patch, as defined by tree establishment patterns and forest structures identified in aerial photographs.

value of 70 percent ± 19 percent. Composite patch-level median fire intervals were 37 yr (max = 74, min = 18) and 56 yr (max = 84, min = 31) for the NCDE and the GYE, respectively (Figure 3). The age distribution of trees in both watersheds show a predominance of young trees less than 100 years old, especially in the NCDE, with greater than 80 percent of trees less than 225 years (Figure 4). Old trees greater than 225 years old are relatively rare throughout both watersheds. In both regions, forest patches were overwhelmingly classified as mixed severity (> 75 percent of sites), with no stand classified as low severity and less than 20 percent of stands classified as high severity (Figure 5).

Discussion

Relative to the mixed conifer forests of the NCDE, the Douglas-fir forests of the GYE were characterized by slightly higher median tree density, lower fire frequency and a lower percentage of high severity fire effects. However, striking similarities exist between the MSFRs in both of our study regions. Compared with forests in low severity fire regimes, where open stand conditions (stand density < 200 trees ha^{-1}) maintained by frequent fires (fire intervals of 5 to 25 yr) are common (Habeck 1990, Arno and others 1995, Williams and Baker 2012), the MSFR forests in our region were historically characterized by intermediate median stand density (> 500 trees ha^{-1}) and moderate, but highly variable, fire frequency. Forests in both study regions were dominated by mixed severity fire effects at the patch level, meaning that most patches (> 75 percent of all patches) experienced a high severity fire followed by one or more low to moderate severity fires that created multi-cohort stand structures. The other remaining 20% of stands were young forest that showed clear evidence of initiating after a high severity fire with no subsequent occurrence of low to moderate severity fire. Notably, none of the sampled stands exhibited a total absence of high severity fire or an old, low density forest structure, as would be expected in a low-severity fire regime model.

These findings suggest several unique characteristics of MSFRs that distinguish them from either low- or high-severity fire regime models, including:

- high severity fire was historically common in these MSFR forests, affecting most forest patches at some point in the last 100–300 years.
- at the patch sizes mapped in our aerial photo analysis (4 to 650+ ha), the studied MSFR forests are quite resilient to high severity fire.
- despite the widespread influence of high severity fire, the mix of stand-replacing and non stand-replacing fires experienced by most patches led to the predominance of young, multi-cohort forest patches.
- complex fire dynamics and diverse forest structures are evident in MSFRs despite moderate forest density and closed canopy forest conditions often presumed to lead primarily to high severity fire.

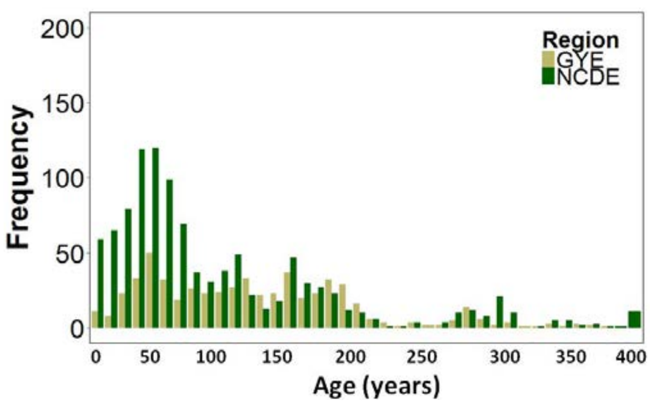

Figure 4—Age distribution of all trees sampled in the GYE and NCDE. Bars represent the frequency of ages in each 10 year bin.

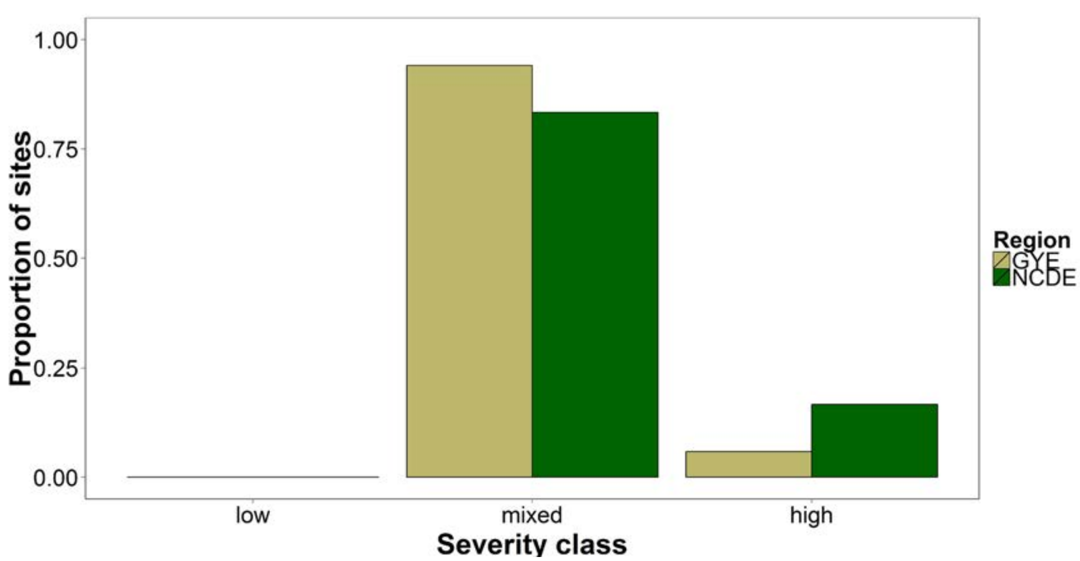

Figure 5—Proportion of sites in the GYE and NCDE classified in low, mixed, or high cumulative fire severity categories.

Consistent with previously published studies of MSFRs (Hessburg and others 2007, Sherriff and Veblen 2007, Halofsky and others 2011, Perry and others 2011, Odion and others 2014), our data support the use of a unique ecological model to describe MSFRs and to inform management in MSFR forests. Results from ongoing data analysis will expand our scope of inference to include a greater number of watersheds, assess the variability of MSFRs across topographic and climatic gradients, and examine the unique forest structural features and successional dynamics created by MSFRs.

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