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Differences in wildfires among ecoregions and land management agencies in the Sierra Nevada region, California, USA

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Abstract. Recent research has indicated that in most of the western United States, fire size is increasing, large fires are becoming more frequent, and in at least some locations percentage of high-severity fire is also increasing. These changes in the contemporary fire regime are largely attributed to both changing climate and land management practices, including suppression of fires and past timber harvesting, over the last century. Fire management, including suppression and using wildfire for resource benefits, varies among federal land management agencies, yet no published studies have directly compared fire statistics between federal land management agencies in our study area. The primary response to wildfire on Forest Service areas is immediate suppression, while the National Park Service is more likely to use wildfire for resource benefits. We use fire perimeters and satellite-derived estimates of fire severity to compare fire statistics for wildfires (fire size, percentage of high-severity fire and high-severity patch size) among ecoregions, forest types, and land management agencies 1984–2009 in the Sierra Nevada, Southern Cascades, and Modoc Plateau of California, USA. High-severity patch size and percentage of high-severity fire, regardless of forest type, were less ($P < 0.05$) in Yosemite National Park than on Forest Service lands. Yosemite fires were smaller on average than fires on Forest Service lands on the east side of the Sierra Nevada, southern Cascades and Modoc Plateau. Depending upon whether fires that crossed boundaries were included or not, mean size of Yosemite fires was either smaller or not significantly different from Forest Service fires on the west side of the Sierra Nevada. Even under current conditions, it appears that fire management practices that emulate those used in Yosemite could moderate effects of past land management, restoring and helping to maintain old forest conditions within the greater Sierra Nevada region, including the southern Cascades and Modoc Plateau.

Key words: fire effects; fire severity; fire suppression policy; Forest Service; National Park Service; RdNBR; Sierra Nevada, USA; wildfire.

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INTRODUCTION

In dry forest types throughout the western United States fire is the dominant process driving acute change in forest structure and species composition (Pyne et al. 1996). However, not all fire is equal; fire-caused change, or fire severity, can vary considerably. Species associated with dry forest types evolved largely with low to moderate-severity fire, and in those forest types post-fire landscapes are characterized by survival of fire-tolerant, large-diameter individuals (Agee 1993, Stephens et al. 2008, Larson and Churchill 2012). Because large-diameter trees provide a seed source and ameliorate environmental stress, these forests can withstand or recover rapidly following low to moderate-severity fire. Furthermore, dry forest tree species generally have limited capacity to recover naturally following extensive high-severity fire (Allen et al. 2002, Savage and Mast 2005).

Increases in tree density, especially of fire intolerant species, and decreases in the area of patchy forest cover resulting from past and current land management practices (e.g., widespread grazing, extensive timber harvesting, fire suppression) have rendered large tracts of dry forests susceptible to extensive and uncharacteristic high-severity fire (Fulé et al. 2004, Hessburg et al. 2005, Naficy et al. 2010, Collins et al. 2011). This increased susceptibility, combined with the limited capacity to recover naturally from high-severity fire, has created great concern for federal land management agencies responsible for managing areas with these forest types (HFRA 2003, USDA 2011).

Developments in acquiring and analyzing spatial data to capture not only fire extents, but fire effects as well, have led to robust characterizations of contemporary fire patterns (e.g., Morgan et al. 2001, Key and Benson 2006*b*, Miller and Thode 2007). These characterizations have allowed for a number of analyses investigating factors influencing fire severity both within individual fires (Finney et al. 2005, Collins et al. 2007, Román-Cuesta et al. 2009, Collins and Stephens 2010, Prichard et al. 2010) and among numerous fires within particular regions (Holden et al. 2007, Miller et al. 2009*b*, Miller et al. 2012, van Wagtendonk et al. 2012, Kolden et al. *In press*). Additionally, fire extent and severity data have been used to compare fire patterns among regions (Dillon et al. 2011) and forest types (Miller et al. 2009*b*, Miller et al. 2012). Such comparisons are useful for identifying potential differences in the processes driving fire (e.g., climate, forest structure, topography). To date however, no previous studies have examined whether differences in land management practices between land management agencies within a given region could be contributing to differences in the fire regime (but see van Wagtendonk and Lutz [2007] for a comparison of fires used for resource benefit and prescribed fires with wildfires).

Characterizing contemporary fire patterns (fire extent and effects) often involves an assessment of whether or not current patterns are within the historical or natural range of variability (Landres et al. 1999, Schoennagel et al. 2004). However, issues associated with those types of assessments can lead to considerable uncertainty: (1) data from historical forest and fire reconstruction studies can never achieve the level of detail or spatial coverage that contemporary characterizations can, (2) historical reconstructions are inherently incomplete because they are based on extant data (i.e., some data are lost from fire and decomposition; Heinselman 1973), and (3) due to a fairly ubiquitous and long-established policy of fire exclusion, there are very few contemporary reference sites with historic and intact fire regimes (Stephens et al. 2008, Scholl and Taylor 2010), and the few that there are have been impacted by early fire suppression efforts (see Rollins et al. 2002, Collins and Stephens 2007, Holden et al. 2007).

Because of these challenges, there is no perfect method for assessing current fire effects on forests relative to pre-settlement forest–fire dynamics. However, some comparisons can provide insight into the potential alteration of contemporary fire patterns. One such comparison is between lands managed by the Forest Service (FS) and National Park Service (NPS) in the Sierra Nevada. Comparing fire patterns between the two agencies within the same region allows for partial identification of past and current management impacts on contemporary fire patterns. Although both NPS and FS policies have allowed the use of wildland fire for resource benefit since the late 1960s and early 1970s, respectively, implementation has varied between the two agencies (van Wagtendonk 2007). While immediate suppression is the most common response on all FS lands in our study area, managing fire for resource benefit has occurred to some extent since 1999, primarily in wilderness areas. In 2009, the US Department of Agriculture and the US Department of the Interior issued updated guidance for implementing federal wildland fire policy (USDA-USDI 2009). The guidance provides for the use of wildland fire for resource benefits specified in land or resource management plans. National parks in the Sierra Nevada, which were subjected to fire exclusion policies similar to FS lands prior to the early 1970s, use both prescribed fire and managed wildfire on most NPS lands. In addition to the increased use of wildfire for resource benefit starting in the 1970s, NPS lands have not experienced extensive timber harvesting or recent livestock grazing since the current park boundaries were established (Collins et al. 2011), making NPS lands at least partially capable of serving as contemporary reference forests.

Our objectives with this study were to: (1) characterize fire patterns (effects, extents) for all fires > 80 ha that occurred between 1984 and 2009 in the Sierra Nevada, southern Cascades and Modoc Plateau; (2) summarize and compare fire patterns among ecoregions and land management agencies, particularly FS and NPS lands; and (3) summarize and compare fire patterns by forest type within ecoregions, wilderness vs. nonwilderness, and agencies. Specifically, we wanted to examine the similarities or differences in high-severity fire among ecoregions, forest types, and fire management strategies.

METHODS

Study area

The study area, which encompasses the extent of the Sierra Nevada Forest Plan Amendment (SNFPA), is divided by three ecoregions as defined by Bailey et al. (1994): the Sierra Nevada proper, portions of the Modoc Plateau including the Warner Mountains, and the eastern portion of the southern Cascades (Bailey et al. 1994, Miles and Goudey 1997, USDA 2004). The ecoregion classification system developed by Bailey et al. (1994), based upon climate, elevation and landform, has been used as a basis for examining differences in fire regimes (e.g., Sugihara and Barbour 2006). The fire regime concept was developed to provide a framework for investigating differences in the way fire influences ecosystems (Heinselman 1981). Because climate and the distribution of forest types vary throughout our study area, we use the fire regime concept and Bailey's ecoregions to define regions within our study area and examine differences in fire statistics.

Climate throughout the study area is Mediterranean, characterized by warm, dry summers and cool, wet winters with almost all precipitation falling between October and April. Depending upon elevation, much of the precipitation is in the form of snow. Variation in precipitation and vegetation is primarily due to elevation and rain shadow effects. The crest of the range, which generally runs north-to-south, divides the Sierra Nevada ecoregion into two distinct precipitation subregions usually denoted as the eastside and westside (Major 1988). Precipitation on the westside of the Sierra Nevada varies from about 500 mm in the foothills to over 2000 mm at the crest in the northern end of the ecoregion. The Modoc Plateau and most of the eastern portion of the southern Cascades ecoregions have precipitation amounts similar to the eastside of the Sierra Nevada, generally less than 1000 mm, due to rain shadow effects from Mt. Shasta and Mt. Lassen (Major 1988, Minnich 2006, Skinner and Taylor 2006).

Vegetation on the westside of the Sierra Nevada crest is dominated by ponderosa pine (*Pinus ponderosa*) at lower elevations; white fir (*Abies concolor*), incense-cedar (*Calocedrus decurrens*), sugar pine (*P. lambertiana*), ponderosa pine, and Douglas-fir (*Pseudotsuga menziesii*) at intermediate elevations; and Jeffrey pine (*P. jeffreyi*) and red fir (*A. magnifica*) at higher elevations. Eastside forests are characteristically more open than westside forests. Pinyon pine (*P. monophylla*) is common at lower elevations on the eastside of the Sierra Nevada, especially south of Lake Tahoe. Jeffrey and ponderosa pine dominate mid-elevations, transitioning to mixed white fir and pine forests at higher elevations. Douglas-fir, most common on the westside, reaches its southern extent within Yosemite National Park (NP) and only occurs in small amounts on the eastside (Lanner 1999, van Wagtendonk and Fites-Kaufman 2006, Sawyer et al. 2008). The crest is higher in the southern portion of the range, reaching its maximum at Mt. Whitney, the highest peak in the continental US. The western slopes are therefore generally steeper in the southern portion of the range due to the higher elevation of the crest, leading to much shorter transitions between forest types.

Similar to the Sierra Nevada, in the southern Cascades mixed conifer forests dominate mid-elevations west of the crest; and east of the crest Jeffrey and ponderosa pine dominate. At higher elevations forests transition to mixed white fir, red fir and pine forests, but species dominance varies widely, influenced by precipitation, topography, and substrate (Skinner and Taylor 2006). Further to the east, forests on the Modoc Plateau are dominated by ponderosa pine at lower elevation and transition to mixed ponderosa pine, Jeffrey pine and white fir as elevation increases. At upper elevations white fir can occur in almost pure stands but also mixes with western white (*P. monicola*), ponderosa, Jeffrey, and Washoe (*P. washoenis*) pines. Red fir does not occur within the ecoregion, and Douglas-fir and sugar pine only occur on the extreme western edge (Riegel et al. 2006).

Conifer forests throughout the region historically experienced low to moderate-severity fire, falling into either fire regime group I or III (Table 1; Sugihara et al. 2006*b*, Hann et al. 2010). Yellow pine forests dominated by either ponderosa or Jeffrey pine and mixed conifer forests historically experienced low-severity fires with mean fire return intervals of 11 to 16 years (fire regime group I; Perry et al. 2011). Red fir forests experienced low to moderate-severity fires with mean fire return intervals of 40 years (fire regime group III; van Wagtendonk and Fites-Kaufman 2006, Stephens et al. 2007, Van de Water and Safford 2011).

Four national parks exist within the study area: Lassen, Yosemite, Sequoia and Kings Canyon. Yosemite, Sequoia and Kings Canyon NPs occur on the westside of the Sierra Nevada. Yosemite is most centrally located north-to-south and Sequoia and Kings Canyon are the most southern of the parks. Lassen is the most northern park, occurring in the Southern Cascades ecoregion. Although the adjacent Sequoia and Kings Canyon NPs have the longest history of allowing naturally ignited fires to burn (van Wagtendonk 2007), an extensive fire severity database, matching the one we have compiled for fires on FS lands (see *Data: Fires and severity* section below), has not yet been assembled for those parks. In addition, most of the area comprised by those two parks falls above the red fir zone and is not forested. The forests that do occur in the two parks occupy only a narrow band due to relatively steeper slopes west of the crest in comparison to the northern portion of the range. Lassen, the smallest of the parks, occupies the higher elevations in the southern Cascades ecoregion and falls almost exclusively into the red fir zone. Lassen has had only a few large (>400 ha) wildfires in the last two decades, and extensive areas in most of those fires were a result of firing operations, i.e., ignitions used to manage the fires (C. Farris, *personal communication*). Of all the parks, Yosemite is the most centrally located, and therefore best represents the forest types within our study area. Also, the current fire management plan for Yosemite allows naturally ignited fires to burn under prescribed conditions over 83% of the park (van Wagtendonk 2007). As a result, Yosemite provides the best, though perhaps not perfect, comparison of the cumulative effects of the primarily suppression based management philosophy of the FS, and the primarily fire use suppression policy of the NPS on forests in our study area.

We defined four ecological/management regions: Cascade-Modoc, eastside Sierra Nevada (eastside), westside Sierra Nevada (westside) and Yosemite National Park (Yosemite) (Fig. 1). Although the east and west sides of the Sierra Nevada are delineated in the same ecoregion section by Bailey et al. (1994), we hypothesized that the distinctly different precipitation patterns result in fires of different severity and size and should be designated as separate regions in our study. However, we could find no formal boundary defining east and west sides. We therefore used Bailey's ecoregion subsections and annual precipitation to define the boundary between the eastside and westside. Overlaying a spatial model of annual precipitation on the ecological subsections, we designated subsections east of the Sierra Nevada crest with

Table 1. Fire regime groups (from Hann et al. 2010).

Fire regime group	Description
I	≤35-year fire return interval, low and mixed severity
II	≤35-year fire return interval, replacement severity
III	35–200-year fire return interval, low and mixed severity
IV	35–200-year fire return interval, replacement severity
V	>200-year fire return interval, any severity

Notes: Hann et al. defined mixed and replacement severity as corresponding to 25–75% mortality and greater than 75% mortality over an entire fire, respectively. In contrast, the moderate and high categories in this manuscript are descriptive at the 30-m Landsat pixel level.

generally less than 1000 mm annual precipitation as eastside (Daly et al. 1994, Miles and Goudey 1997). We combined the southeastern Cascades and Modoc Plateau into one region due to their similarity in precipitation and vegetation.

Data

Fires and severity.—The Forest Service Pacific Southwest Region maintains a database of vegetation severity data for wildfires due to lightning and human ignitions that have occurred at least partially on FS lands in California since 1984 (available online at http://www.fs.usda.gov/wps/portal/fsinternet/main/r5/landmanagement/gis). For our study area the database contains all wildfires larger than 80 ha between 1984 and 2009 that at least partially occurred on the ten national Forests in the Forest Service's Pacific Southwest Region, and fires over 400 ha on the one national Forest in the Intermountain Region for a total of 280 fires, eight of which overlap boundaries with Yosemite NP. Moderate resolution (30 m) Landsat thematic mapper (TM) satellite images used to develop these severity data came from a number of sources including the Monitoring Trends in Burn Severity (MTBS) program (http://www.mtbs.gov/) and Rapid Assessment of Vegetation Condition (RAVG) program (http://www.fs.fed.us/postfirevegcondition/index.shtml). Both MTBS and RAVG programs only map fires larger than 400 ha. To capture smaller fires Landsat images were acquired and methods identical to those used by MTBS and RAVG were used to process the images. To permit inter-fire comparisons of severity, the severity data we used were developed from the relativized differenced normalize burn ratio (RdNBR) data, which compensates for different pre-fire vegetation and surface conditions (Miller and Thode 2007). We categorized the RdNBR data into four levels of severity based on calibrations derived of RdNBR to the plot-level Composite Burn Index (CBI) severity measure (unchanged = 0–0.1, low = 0.1–1.24, moderate = 1.25–2.24, and high = 2.25–3.0; Key and Benson 2006*a*, Miller and Thode 2007, Miller et al. 2009*a*). Based upon regression analysis, our high-severity threshold is approximately equal to 95% change in canopy cover ($r^2 = 0.56$, $P < 0.0001$; Miller et al. 2009*a*). FS vegetation classification standards specify that 10% pre-fire tree canopy cover is required for an area to be mapped as forested (Brohman and Bryant 2005). In forested areas, our high-severity category therefore generally describes a conversion of forest to a non-forested condition. For Yosemite, we augmented the severity data we had previously developed to match the size (>80 ha) and time period (1984–2009) of the FS data (Collins et al. 2009, Lutz et al. 2009). The Yosemite fire severity database includes data for management ignited fires and wildfires that were either lightning or human caused. We eliminated all management ignited fires for this study because those fires were ignited and burned under conditions that produce lower severity effects than wildfires, leaving a total of 72 fires (van Wagtendonk and Lutz 2007). Forty-seven of the fires were managed for resource benefit for their duration. Twenty fires were actively suppressed from the time of ignition, and five fires that started out being managed for resource benefit were suppressed when they exceeded their prescriptions. The Yosemite severity data were processed to match the severity categories used for the fires on FS lands. All severity data were converted from raster to polygons using standard geographic information system (GIS) procedures to consolidate individual pixels into homogeneous patches. Severity data on FS lands were constrained to those administrated by the FS to eliminate effects from private managed in-holdings.

Vegetation.—Most previous studies that have examined severity by forest type have used maps based upon existing vegetation (but see Holden et al. [2007] and Dillon et al. [2011] who used potential vegetation type derived from environmental site potential). Because high-severity fire events cause at least temporary vegetation type change, using maps of current vegetation as a pre-fire condition to analyze severity by vegeta-

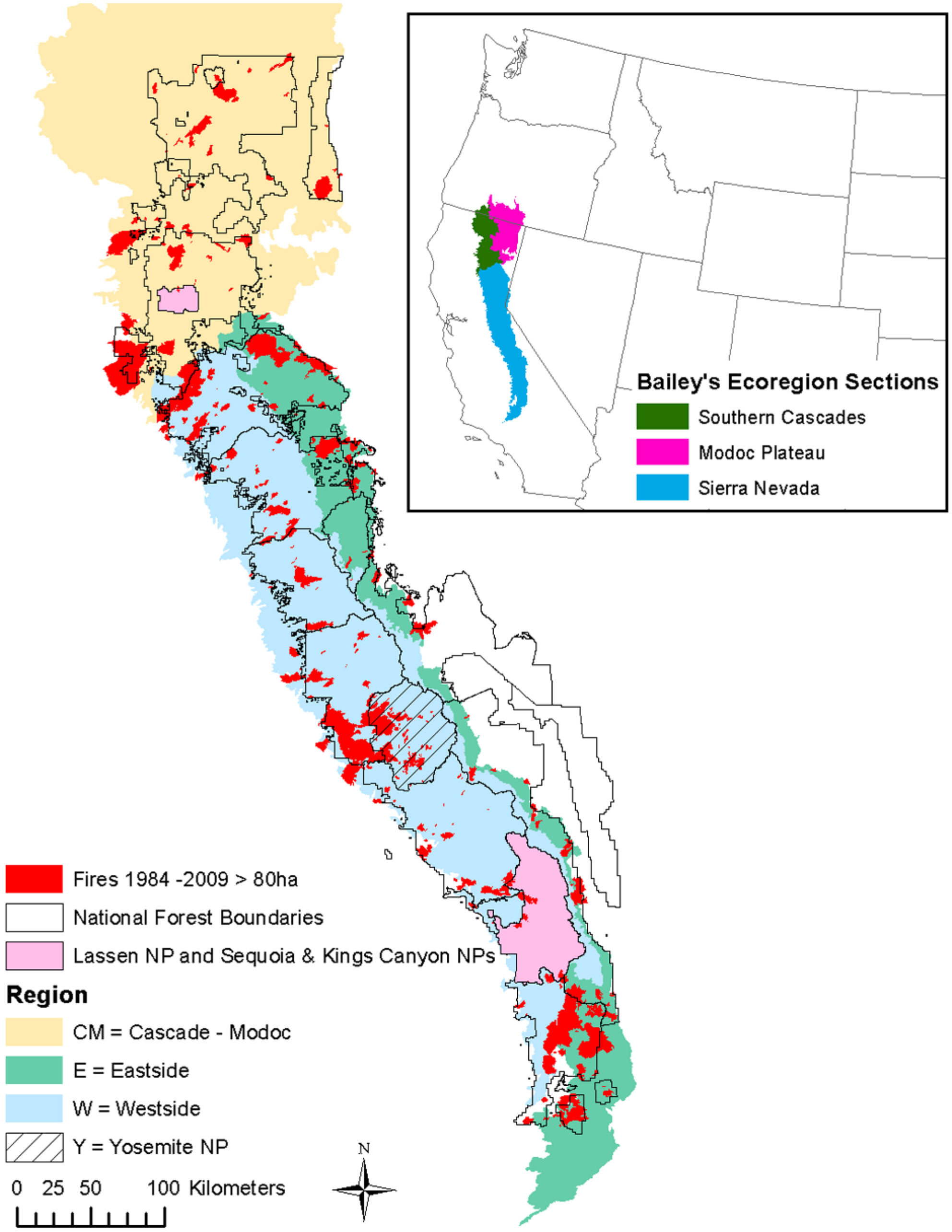


Fig. 1. Map of the study area. The regions used for comparing fire statistics: Cascade-Modoc, westside, eastside, and Yosemite. National Forests in the study listed from north-to-south are the Modoc, Lassen, Plumas, Tahoe, Lake Tahoe Basin Management Unit, Eldorado, Stanislaus, Sierra, Inyo, and Sequoia National Forests. Red polygons represent 352 fires larger than 80 ha that occurred 1984–2009 included in this study.

tion type leads to an analysis of potential type conversion (e.g., conversion of forest to a non-forested condition). But when characterizing fire regime characteristics over broad scales it may make more sense to stratify with map data that describe the geographic distribution of vegetation type regardless of stand development (seral stage) (Van de Water and Safford 2011). For example, a site that was able to support a mature forest (beyond stand initiation) prior to high-severity fire would always retain the same type label given that it could return to a forested condition provided that the fire return interval was of sufficient length, subsequent fire intensity was low enough, seeds were available, and competition and herbivory allowed seedlings to establish and grow back to mature trees (Oliver and Larson 1996).

For this study we used LANDFIRE-generated Biophysical Settings (BpS) vegetation layer to stratify the fire severity data (data available online at www.landfire.gov). The BpS data are advertised to provide a spatially explicit representation of the vegetation that may have been present prior to Euro-American settlement (Rollins 2009). The data are based on the current biophysical environment (climate, soils and topography) and best estimate of the pre-Euro-American fire regime. BpS vegetation types are based on Nature Serve's Ecological Systems classification system, and are more broad in definition and scale than National Vegetation Classification System (NVCS) floristic units (alliances and associations) used by the FS's Classification and Assessment with Landsat of Visible Ecological Groupings (CALVEG) vegetation classification system (Comer et al. 2003, Keeler-Wolf 2007, USDA 2008). Each BpS vegetation type is linked to state and transition models developed from published literature and expert opinion, which through a modeling process, resulted in estimated proportions of each successional stage that should have occurred on the landscape, from early seral (stand initiation) through late-closed (old growth) (Rollins 2009).

Because of the broad scale of the BpS data, we decided to perform an error analysis using forest inventory and analysis (FIA) intensification plots previously established for CALVEG accuracy assessment before determining which BpS forest types to include in our analysis. The intensification plots are based on a stratified random sample of ecologically significant CALVEG vegetation types within each bioregion. The FIA intensification plots that occurred only on FS managed lands were selected for use in the error analysis of BpS. Plots that fell within fires that occurred 1984–2009 were eliminated, leaving 1190 plots for error analysis.

Analyses

Percentage of high-severity fire in wilderness vs. non-wilderness by region.—To determine whether percentage of high-severity fire differed due to wilderness designation, which can result in different fire management strategies, we stratified the high-severity data by wilderness boundaries for FS lands. For Yosemite, we used the fire management unit boundaries that indicate where all wildfires are either fully suppressed or, if they are in prescription, are allowed to be managed for resource benefit. For the sake of brevity, throughout the remainder of this manuscript we use "wilderness designation" to mean wilderness vs. non-wilderness for FS lands, and suppression vs. fire-use fire management units for Yosemite. Distribution analysis of the percent high-severity data indicated they would best be fit by a gamma function due to the number of fires with no or low percentages of high severity. We therefore chose to use a Generalized Linear Mixed Model (GLMM) because this method does not require the dependent variable to be normally distributed, but rather one of several probability distribution functions can be used to describe the dependent variable (Bolker et al. 2009). Region crossed by forest type and wilderness designation was the fixed effect, and because the percentage of high severity at which a given forest type will burn can differ between fire events, fires were considered a random effect. A post hoc test was used to compare differences in mean percentage of high severity per fire between wilderness designations. We set $\alpha = 0.05$, and used the Tukey-Kramer adjustment to account for multiple comparisons (Kramer 1956).

Percentage of high-severity fire by forest type and region.—We calculated total area burned, total area burned at high severity and fire rotation periods for each forest type per region. Fire rotation, defined as the length of time necessary to burn an area equal to the area of interest (in this case, our study area) was calculated by dividing the time period of our severity data (26 years) by the proportion of the study area burned in that time period (Heinselman 1973).

Similar to the wilderness vs. non-wilderness analysis, the severity data were best fit by a gamma function and we chose to use a GLMM. Region crossed by forest type was the fixed effect, and fires were considered a random effect.

Post hoc tests were used to compare differences in mean percentages of high severity per fire between and among regions. The GLMM was therefore run twice, partitioning the interaction effects by region and forest type in separate runs, and the Tukey-Kramer adjustment was used to account for multiple comparisons.

Fire size.—We used a one-way analysis of variance (ANOVA) to test for differences in mean fire size among regions. We used a Ryan-Einot-Gabriel-Welsch multiple range test because the number of samples among regions was uneven. Distribution analysis indicated that log transformed fire sizes best fit a normal distribution. In several instances fire perimeters crossed region boundaries. We therefore ran the ANOVA on two different sets of fires. First, we counted fires that crossed region boundaries in each region; second, we deleted fires that crossed region boundaries from the analysis.

High-severity patch size.—The BpS data were not derived through an object oriented classification methodology that would identify forest stands, but rather the data were based upon a modeling exercise at the pixel level. As a result, we did not think the BpS data were conducive to analyzing patch dynamics due to the high degree of confusion among forest types. As a result, we did not stratify high-severity patches by forest type. We used a mixed model ANOVA to test for differences in high-severity patch size among regions. Based upon the distribution analysis we converted patch sizes to m^2 and log transformed them before running the ANOVA to satisfy normality assumptions. Region was the fixed effect and fires were considered a random effect. We considered patches smaller than 900 m^2 corresponding to the Landsat pixel size used to create the severity data were slivers created by GIS clipping operations, and we eliminated them from the analysis.

RESULTS

Assessment of BPS vegetation data

Most of the FS FIA intensification plots (81.9%) coincided with four BpS forest types: dry-mesic mixed conifer, mesic mixed conifer, Jeffrey pine–ponderosa pine, and red fir (Table 2). There was no clear distinction between dry-mesic and mesic mixed conifer BpS types (results not shown). For example, plots identified as Pacific Douglas-fir and Douglas-fir–ponderosa pine CALVEG types should have appeared in the BpS mesic mixed conifer type, but instead most were classed as dry-mesic. Thus, we combined the dry-mesic and mesic mixed conifer BpS types and focused only on the three major forest types: mixed conifer, yellow pine (Jeffrey and ponderosa pine) and red fir. Mixed conifer had the highest accuracy at 70.5%, and red fir was the least accurate at 29.8%. Most plots mis-mapped in BpS were mapped in types that are normally geographically adjacent. For example, there were more ponderosa pine plots mapped as mixed conifer than yellow pine, but ponderosa pine elevational range overlaps with mixed conifer. The BpS red fir type had the lowest accuracy primarily because lodgepole pine and subalpine conifer plots were more often mapped as red fir even though those types also occur within the BpS classification system. Mixed conifer is the dominant forest type mapped on the westside (54.2%) and in the Cascade-Modoc region (45.9%), although in the Cascade-Modoc region yellow pine almost covers an equivalent area (43.1%, Table 3). Red fir is the dominate forest type mapped in Yosemite (66.3%), and yellow pine is dominant on the eastside (65.4%).

Percentage of high-severity fire in wilderness vs. non-wilderness by region

There were only two cases where the percentage of high-severity fire differed by wilderness designation within a given region: mixed conifer and red fir on the eastside ($P = 0.003$ and $P = 0.039$, respectively, results not shown). Most of the area burned in eastside wilderness in those two forest types occurred in two fires (61% and 73%, respectively), both of which were fully suppressed (B. Skaggs, *personal communication*). Since we found no other significant difference between wilderness and non-wilderness, we did not account for a wilderness effect in any of the remaining analyses.

Percentage of high-severity fire by region and forest type

The westside and Cascade-Modoc regions had the lowest percentage of total area burned in each forest type (Table 3). The eastside experienced the

Table 2. Confusion matrix of BpS forest type to CALVEG type as determined by FIA intensification plots.

CALVEG type	Mixed conifer	Yellow pine	Red fir	Lodgepole pine	Subalpine conifers	Other	Total
Mixed conifer types							
Pacific Douglas-fir	26	0	0	0	0	7	33
Douglas-fir–ponderosa pine	24	3	0	0	0	5	32
Mixed conifer–giant Sequoia	21	3	0	0	0	1	25
Incense cedar	8	0	0	0	0	5	13
Mixed conifer–fir	43	40	39	0	0	16	138
Mixed conifer–pine	144	35	4	0	0	22	205
Ponderosa pine–white fir	12	1	0	0	0	1	14
White fir	42	12	18	0	0	15	87
Subtotal	320	94	61	0	0	72	547
Yellow pine types							
Eastside pine	22	62	2	0	0	25	111
Jeffrey pine	11	73	20	0	0	8	112
Ponderosa pine	55	34	0	0	0	8	97
Yellow pine–western juniper	7	8	0	0	0	9	24
Subtotal	95	177	22	0	0	50	344
Red fir	0	1	68	0	0	3	72
Other							
Lodgepole pine	3	4	22	3	1	9	42
Whitebark pine	0	0	0	0	6	2	8
Subalpine conifers	5	0	39	2	1	8	55
Montane shrubs	5	7	8	0	0	2	22
Other	26	10	8	0	2	54	100
Subtotal	39	21	77	5	10	75	227
Total	454	293	228	5	10	200	1190
Percent accurate	70.5	60.4	29.8	60.0		37.5	

Note: BpS names: Mixed Conifer = Mediterranean California Dry-Mesic Mixed Conifer Forest and Woodland or Mediterranean California Mesic Mixed Conifer Forest and Woodland; Yellow Pine = California Montane Jeffrey Pine (-Ponderosa Pine) Woodland; Red Fir = Mediterranean California Red Fir Forest; Lodgepole pine = Sierra Nevada Subalpine Lodgepole Pine Forest and Woodland; and Subalpine conifers = Mediterranean California Subalpine Woodland.

highest percentage of total area burned at high severity in every forest type. Percentage of total area burned at high severity for eastside mixed conifer and yellow pine, and Cascade-Modoc yellow pine were all well over 40%. In addition to having the highest percentage of high severity (47.6%), eastside mixed conifer also had a fire rotation period of 95 yrs. In contrast, Yosemite had the highest percentage of area burned, and subsequently the lowest fire rotation period for all forest types; all <100 yrs. Percentage of total area burned at high severity in Yosemite was also the lowest of any other region regardless of forest type: <15% for mixed conifer and yellow pine,

Table 3. Total area, total area burned, total area burned at high severity and rotation periods during 1984–2009 by BpS forest type and region.

BpS forest type	Region	Total area (ha)	Total burned area (ha)	Area burned (%)	Fire rotation (yr)	High severity (ha)	High severity (%)	High-severity rotation (yr)
Mixed conifer	CM	323,592	23,670	7.3	355	5,302	22.4	1587
	E	61,280	16,770	27.4	95	7,989	47.6	199
	W	905,314	99,992	11.0	235	21,283	21.3	1106
	Y	40,721	19,160	47.1	55	2,626	13.7	403
Yellow pine	CM	303,643	15,297	5.0	516	6,706	43.8	1177
	E	421,446	95,548	22.7	115	42,692	44.7	257
	W	192,141	18,619	9.7	268	5,815	31.2	859
	Y	11,199	5,300	47.3	55	773	14.6	376
Red fir	CM	77,527	4,286	5.5	470	572	13.3	3525
	E	162,100	21,442	13.2	197	3,832	17.9	1100
	W	571,367	19,170	3.4	775	3,195	16.7	4650
	Y	101,978	27,501	27.0	96	2,159	7.9	1228

Note: CM = Cascade-Modoc, E = Eastside, W = Westside, Y = Yosemite National Park.

Table 4. Descriptive statistics for percentage of high-severity per fire by BpS forest type and region.

			High severity (%)					95% confidence level of mean (%)	
BpS forest type	Region	No. fires	Mean	SE	Minimum	Maximum	Median	Lower	Upper
Mixed conifer	CM	49	26.6	3.37	0	100.0	20.1	19.8	33.4
	E	65	23.9	2.76	0	86.1	22.5	18.4	29.4
	W	152	15.6	1.54	0	79.5	6.1	12.6	18.7
	Y	55	10.6	2.19	0	90.2	4.3	6.2	15.0
Yellow pine	CM	46	31.6	3.63	0	96.6	32.9	24.3	39.0
	E	82	27.5	2.37	0	83.8	24.2	22.8	32.2
	W	144	22.9	2.01	0	97.2	16.6	18.9	26.9
	Y	69	12.7	1.80	0	66.9	6.6	9.1	16.3
Red fir	CM	13	33.1	10.05	0	100.0	25.4	11.2	55.0
	E	50	16.3	2.69	0	80.7	10.3	10.9	21.7
	W	60	12.1	1.64	0	47.7	8.1	8.8	15.4
	Y	69	7.1	1.15	0	53.4	2.6	4.8	9.4

Note: CM = Cascade-Modoc, E = Eastside, W = Westside, Y = Yosemite National Park.

and <8% for red fir. Mean percentage of high severity per fire followed a similar pattern with Cascade-Modoc and eastside experiencing the highest percentages and Yosemite the lowest (Table 4). Mean percentage of high severity per fire was significantly less ($P < 0.05$) in Yosemite than all other regions regardless of forest type (Fig. 2). Differences in mixed conifer or yellow pine between the Cascade-Modoc, eastside and westside regions were not significant. Mean percentage of high severity per fire for red fir tended to be lower than any other type within the same region, except Cascade-Modoc and westside mixed conifer. There were no significant differences in mean percentage of high severity among any of the forest types within the Cascade-Modoc region.

Fire size

When fires that crossed region boundaries are not considered, Yosemite fires were significantly smaller ($P < 0.05$) on average than fires in any of the other regions (Table 5). When fires that crossed region boundaries were included in the analysis, Yosemite fires were still smaller than Cascade-Modoc or eastside fires, but were not significantly different than westside fires even though the mean size of westside fires was more than double that of Yosemite fires (2907.9 ha and 1416.8 ha, respectively).

High-severity patch size

Yosemite mean high-severity patch size was significantly smaller ($P < 0.005$) than mean patch sizes in all other regions (Table 6). Westside, Cascade-Modoc and eastside mean high-severity patch sizes were 2.12, 3.08, and 3.89 times larger, respectively, than the 4.2 ha mean Yosemite patch size (Table 7). Cascade-Modoc and eastside, and eastside and westside were the only two region pairs where the null hypothesis of equal mean patch sizes could not be rejected (Table 6). While the percentage of patches <5 ha was similar on FS lands and Yosemite (86.0% and 88.9%, respectively), the percentage of patches >100 ha and mean patch size was almost three times higher on FS lands (1.96% vs. 0.69% and 12.16 ha vs. 4.24 ha, respectively; Fig. 3).

DISCUSSION

Our study is the first to contrast fire statistics in the Sierra Nevada among ecoregions, and between federal land management agencies. Our findings indicating lower percentages of high-severity fire in Yosemite relative to FS lands in the three ecoregions suggest a fundamental distinction due to the differing land management and fire management policies of the FS and Yosemite (Fig. 2). Although fire regime characteristics can vary due to fine scale topography and variation in stand history (Perry et al. 2011), the forest types we use are considered to have generally similar fire regime characteristics at the broad scale of the study area (Sugihara et al. 2006*b*, Stephens et al. 2007, Van de Water and Safford 2011). Therefore, the differences in land management and fire management histories between the two agencies are likely the major factor driving the distinction in high-severity fire percentages.

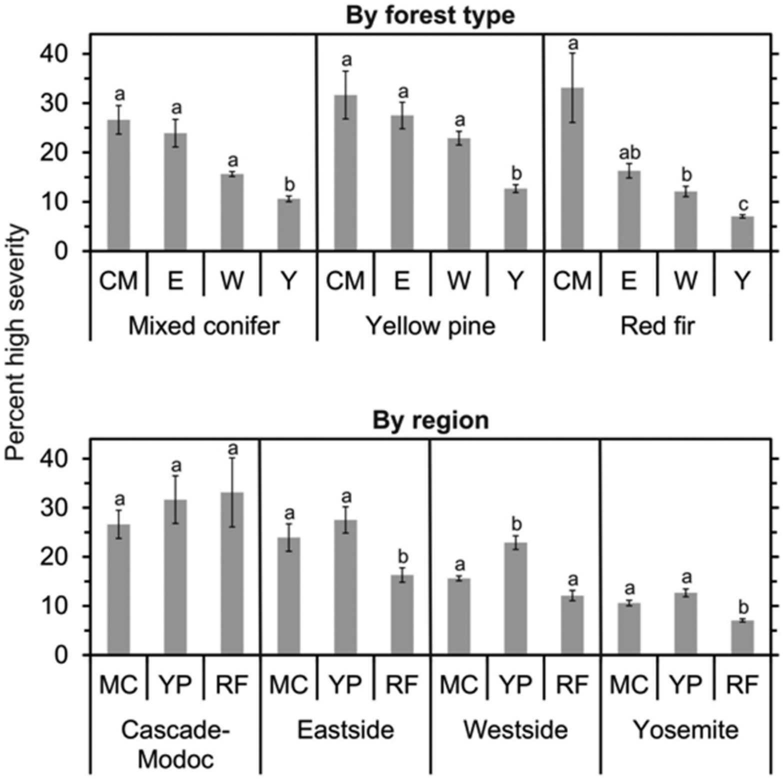


Fig. 2. GLMM results comparing percentage of high severity sliced two ways; top are results by forest type, bottom are results by region. Percent high-severity values were weighted by total area of the forest type within each fire constrained by region. Fires were a random effect and region crossed with forest type was the fixed effect. A gamma function was used as the probability distribution in the model. Bars labeled with different letters indicate *P*-values using a Tukey-Kramer adjustment are significant at $P < 0.05$. CM = Cascade-Modoc, E = Eastside, W = Westside, Y = Yosemite National Park; MC = mixed conifer, YP = yellow pine, RF = red fir.

Table 5. Descriptive statistics and one-way ANOVA results for comparing mean fire size among regions.

			Fire size (ha)					95% confidence level of mean (ha)	
Analysis group	Region	No. fires	Mean	Mean log†	SE	Maximum	Median	Lower	Upper
All fires‡	CM	54	4690.9	3.1366^{A}	1233.15	51907.3	1232.2	2217.5	7164.3
	E	85	3656.6	3.0429^{A}	910.96	61516.1	1170.5	1845.1	5468.2
	W	165	2907.9	2.9193^{AB}	508.51	61516.1	785.9	1903.9	3912.0
	Y	72	1416.8	2.7062^{B}	432.28	24123.1	441.5	554.8	2278.7
No multi-region fires§	CM	52	4399.3	3.1111^{A}	1229.79	51907.3	1226.3	1930.4	6868.2
	E	70	2781.7	3.0172^{AB}	621.37	32060.6	1075.9	1542.1	4021.3
	W	142	1998.2	2.8565^{B}	284.16	21054.3	692.4	1436.5	2556.0
	Y	64	674.1	2.6150^{C}	92.33	3583.8	397.3	489.6	858.6

Note: Means for each analysis group were compared using a Ryan-Einot-Gabriel-Welsch multiple range test. Fire sizes were log transformed before running the ANOVA. CM = Cascade-Modoc, E = Eastside, W = Westside, Y = Yosemite National Park.

†Means with the same superscript letter were not significantly different ($P < 0.05$).

‡Fires that crossed region boundaries were counted in each region.

§Fires that crossed region boundaries were deleted.

Table 6. ANOVA results comparing differences in mean high-severity patch size between regions.

Region comparison	Estimate	SE	*P*	Adjusted *P*†
CM–E	0.1097	0.0825	0.1838	0.5442
CM–W	0.1865	0.0766	0.0149	0.0706
CM–Y	0.3652	0.0901	<0.0001	0.0003
E–W	0.0768	0.0345	0.0260	0.1161
E–Y	0.2555	0.0622	<0.0001	0.0002
W–Y	0.1787	0.0536	0.0008	0.0047

Notes: Polygons smaller than the 900 m^2 Landsat pixel size were removed from the analysis. Fires were a random effect and region a fixed effect in the ANOVA. Patch sizes were converted to m^2 and log transformed before running the ANOVA. CM = Cascade-Modoc, E = Eastside, W = Westside, Y = Yosemite National Park.

†*P*-values using a Tukey-Kramer adjustment.

The comparison of fire patterns among the three ecoregions and Yosemite is imperfect for two reasons. First, Yosemite is considerably smaller than the three ecoregions and as a result does not encompass the topographic or geographic variability that the ecoregions do. Second, there are unequal proportions of area in BpS vegetation classes among the ecoregions and Yosemite (Table 3). Despite these issues, the differences in fire patterns among the three ecoregions and Yosemite (lower proportion of high-severity fire, smaller high-severity patches, and smaller fire sizes in Yosemite) are most likely due to the NPS fire management policies, and not the discrepancies among regions. First, the total number of fires (>80 ha) in Yosemite over our study period is comparable to that of the Eastside, and in excess of that for the Cascade-Modoc (Table 5), which implies relatively similar ranges of burning conditions among the regions. Second, there are no consistent trends in percentage of high severity among dominant forest types, i.e., there is no forest type that is consistently the highest or lowest across all regions. Red fir does comprise a larger percentage of Yosemite than the other regions, and Yosemite red fir had the lowest percentage of high severity in comparison to all forest types across all the other regions. But, 91% of Yosemite's red fir occurs in their fire use zone. Moreover, there was no difference in percentage of high severity between mixed conifer and red fir on the westside, whose forests are most similar to Yosemite's. Therefore, the unequal proportions of forest types among regions do not appear to be driving the differences in fire patterns among regions.

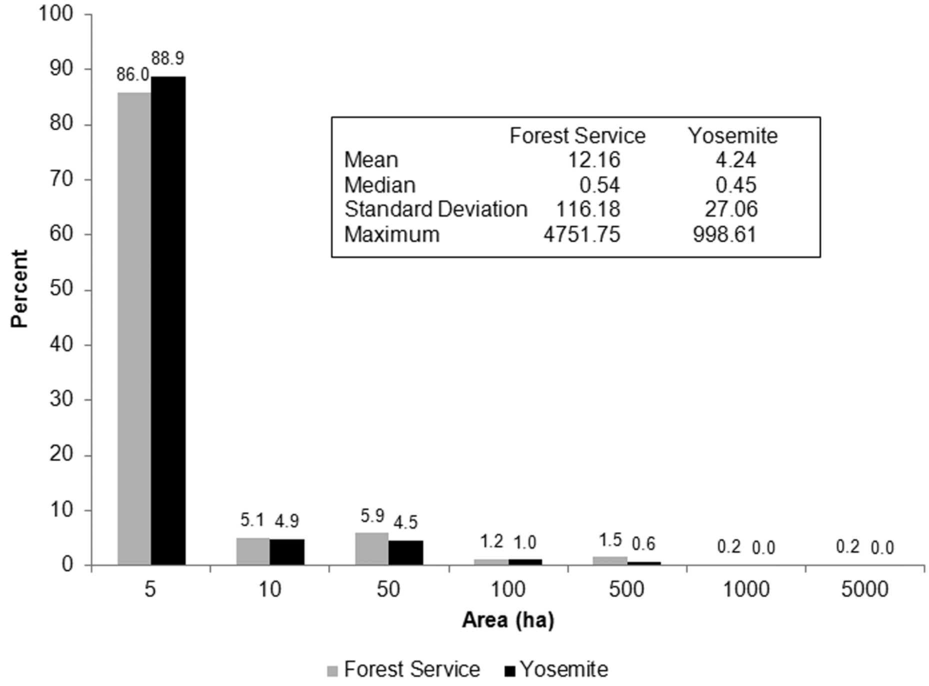
Although the FS in recent years has begun to manage more wildfires in wilderness areas for resource benefit, a policy of full suppression was in effect on most fires that occurred during our study period. In contrast, Yosemite has had a policy of only suppressing lightning-ignited fires when they occur outside their fire use zone or are out of prescription (van Wagtendonk 2007, van Wagtendonk 2012*b*). We were surprised not to find any significant difference in the percentage of high-severity fire between Yosemite fire management zones, especially since van Wagtendonk and Lutz (2007) found a distinct difference between suppressed fires and resource benefit fires. However, our analysis differed from van Wagtendonk and Lutz's; we stratified by fire management unit, not by how individual fires were managed. Yosemite's extensive use of management ignited fire (i.e., prescribed fires) may have also played a part in influencing the severity of their suppression zone fires by moderating fire effects in some wildfires (Vaillant et al. 2009, Arkle et al. 2012, van Wagtendonk 2012*b*).

By allowing most lightning-fires to burn relatively unimpeded, and perhaps due to their extensive use of prescribed fire, it appears

Table 7. Descriptive statistics of high-severity patch size by region.

		Patch size (ha)					95% confidence level of mean (ha)	
Region	No. patches	Mean	SE	Minimum	Maximum	Median	Lower	Upper
CM	1442	13.0	2.40	0.09	1696.7	0.54	8.3	17.7
E	4675	16.5	2.34	0.09	4751.8	0.45	11.9	21.1
W	6784	9.0	0.96	0.09	4719.2	0.63	7.1	10.9
Y	2031	4.2	0.60	0.09	998.6	0.45	3.1	5.4

Notes: Polygon size was not constrained by forest type. Polygons smaller than the 900 m^2 Landsat pixel size were removed from the analysis. CM = Cascade-Modoc, E = Eastside, W = Westside, Y = Yosemite National Park.



	Forest Service	Yosemite
Mean	12.16	4.24
Median	0.54	0.45
Standard Deviation	116.18	27.06
Maximum	4751.75	998.61

Fig. 3. Frequency distribution of high-severity patches in fires 1984–2009 on Forest Service lands (all regions combined) and Yosemite NP.

Yosemite has been able to achieve high-severity proportions and patch sizes closer to what may have occurred historically in the forest types in our study (Stephens et al. 2007). Consequently, Yosemite fire statistics are likely more representative of a "historic" fire regime than FS fires. It should be noted that a "historic" fire regime under today's climate conditions may not necessarily be representative of the period immediately preceding Euro-American settlement due to differences in climate (Stephens et al. 2010), and current lack of native American ignitions (Anderson 1996). However, it is interesting to compare percentages of high severity by forest type we measured for Yosemite fires to estimates of early seral conditions as detailed in the Landfire BpS vegetation descriptions (measured vs. BpS description: mixed conifer = 10.6% vs. 20%, yellow pine = 12.7% vs. 15%, southern Sierra Nevada red fir = 7.1% vs. 10%). Our results, based on the relatively short fire record permitted by the Landsat TM period of record, appear to be similar to Landfire estimates for yellow pine and red fir, but for mixed conifer they disagree by nearly a factor of two. That may suggest that the Landfire mixed conifer model may need to be reevaluated. Our results also suggest that Yosemite fires display characteristics more similar to those necessary to maintain old-forest conditions than do FS fires (Kaufmann et al. 2007).

Another factor that also may explain the difference in proportion of high-severity fire and high-severity patch size between Yosemite and FS lands is the difference in land management histories, particularly with respect to timber harvesting. Most FS lands in the Sierra Nevada were subjected to intensive harvesting in the 1920s and 1930s ("railroad logging") (Laudenslayer and Darr 1990). Subsequent timber harvesting has occurred sporadically up through the early 1990s, which consisted largely of selection harvests targeting larger "over mature" trees. Yosemite has had no large-scale timber harvesting. Only limited harvesting occurred in the western portion of the park before being incorporated within the current park boundaries in 1930 (Collins et al. 2011). These different timber harvest histories, coupled with decades of fire suppression, have contributed to different overall forest structures, mainly more small trees and fewer large trees on FS lands, which lead to increased susceptibility to crown fire (Stephens and Moghaddas 2005).

Ecological theory dictates that high fire frequency and the self-organizing dependent nature of burn patterns create a fine scale heterogeneous forest-patch structure that is characteristic of old forest conditions in mixed conifer forests of the Sierra Nevada (Sugihara et al. 2006*a*, Beaty and Taylor 2007, Collins et al. 2009, Perry et al. 2011, Lutz et al. 2012, North et al. 2012). Topography however, often influences severity with smaller areas of high severity on lower, mesic slopes and larger areas on upper, xeric slopes (Beaty and Taylor 2001). Climate variations and short-term weather patterns can also influence the amount and size of high-severity patches. Large high-severity patches can occur under dry and windy weather conditions, but can be exacerbated by the dense forest conditions and high fuel loads that have developed during the fire suppression period (Scholl and Taylor 2010, Perry et al. 2011, Lutz et al. 2012). Our results, therefore, likely do not apply evenly across the landscape, but do demonstrate that at least some contemporary fire regime characteristics differ among Sierra Nevada regions. For example, percentage of high-severity fire in red fir forests was higher in Cascade-Modoc than westside fires during 1984–2009 (Fig. 2). We believe short term climate patterns (e.g., the El Niño Southern Oscillation) were not a significant factor in our results because the data span a wide range of year-to-year variation in annual (October–September) precipitation conditions over the twenty-six year period, incorporating a full range of climatic conditions (Western Regional Climate Center Sierra Nevada region: mean = 944 mm, minimum = 527 mm, maximum = 1625 mm [Abatzoglou et al. 2009, WRCC 2012]).

In contrast, some researchers have recently suggested that large contemporary fires within the study area, which exhibited very large (1000–5000 ha) high-severity patches, fall within the natural range of variation, and therefore are typical of the historic fire regime (Odion and Hanson 2006). However, variation of fire regime characteristics is better described by traditional statistics (i.e., mean, mode and standard deviation) rather than maxima, because maxima by definition represent rare events (Burt and Barber 1996, Landres et al. 1999, Sugihara and Barbour 2006). It is much more likely that fire effects seen in the contemporary fires in the Odion and Hanson (2006) study were actually rare historically (Perry et al. 2011). For example, for the three fires analyzed by Odion and Hanson (2006) mean high-severity patch size was more than twice as large as the mean high-severity patch size in Yosemite fires from 1984–2009 (9.5 ha vs. 4.2 ha), and patches larger than 100 ha occurred more than twice as often (1.49% vs. 0.69%). Any increase in the distribution of large patch size and occurrence, both in time and space, in comparison to historical conditions has important implications to forest recovery and species habitat (Pickett and White 1985, Roberts et al. 2008, Roberts et al. 2011). Large proportions of two of the three fires Odion and Hanson studied occurred on the westside (1/3 and 2/3), but mean percentages of high severity by forest type in the Odion and Hanson study (mixed conifer = 25.8%, yellow pine = 34.2%, and red fir = 13.4%) were more representative of percentages of Cascade-Modoc and eastside fires that were more than two times higher and significantly different than percentages in Yosemite fires (Table 4 and Fig. 2). Historic regime characteristics for the westside may have been different from Cascade-Modoc and eastside due to the differences in precipitation patterns, but we have no analog for Yosemite in those regions for comparison. Regardless, current eastside fire regime characteristics are likely not representative of "historic" conditions that result in old-forest conditions in frequent fire dry forests (Smith 1991, Stephens et al. 2008, Larson and Churchill 2012).

Retention of forests with conditions indicative of a late successional stage of forest development is desirable to maintain wildlife habitat, biological diversity, carbon sequestration, and other ecosystem values (Binkley et al. 2007, Luyssaert et al. 2008, Stephens et al. 2012*a*). Forest successional stages are most often described using structural characteristics such as tree size, density by tree size class, number of canopy layers, tree cover as well as the distribution of understory species and downed wood (Franklin and Fites-Kaufmann 1996, Oliver and Larson 1996). Stand age is less often used to describe successional stages because the rate of stand development also depends upon site conditions and fire history. However, if a “historic” fire regime were to be maintained, stand age could be indicative of developmental stage (Fites et al. 1992). Our results indicate that eastside mixed conifer and yellow pine high-severity fire rotations (199 years and 257 years respectively; Table 3) over the 1984–2009 period are likely shorter than those required to maintain old-forest conditions (Smith 1991, Fites et al. 1992, Beardsley et al. 1999). However, most of the high severity in eastside types occurred on the east side of the Plumas National Forest in the northern portion of the region, and on the Kern Plateau in the southern portion of the region. As a result, fewer forests have been retained in those areas that have the potential for exhibiting old forest conditions, while other eastside locations (e.g., the Lake Tahoe Basin) have seen relatively little fire (Fig. 1). In contrast, high-severity rotations may be too long in most Cascade-Modoc and westside FS locations, especially in comparison to Yosemite, leading to a homogenization of dense forest conditions, which is also uncharacteristic of old forest conditions (Perry et al. 2011). However, when high-severity patches are uncharacteristically large, forest homogenization can also occur (Perry et al. 2011). When Sierra Nevada conifer forest types are converted to montane chaparral by high-severity fire, there is a high probability of subsequent fires also burning at high severity, perpetuating or enlarging the montane chaparral patch (Nagel and Taylor 2005, Collins and Stephens 2010, van Wagtendonk et al. 2012, van Wagtendonk 2012*a*). Therefore, large high-severity patches could be a management concern where old-forest conditions are desired.

Our use of the Landfire BpS vegetation data to stratify by forest type likely impacted our results for red fir more than mixed conifer and yellow pine. Classification accuracies for mixed conifer and yellow pine were similar to those achieved by other researchers using similar techniques to Landfire, but the red fir classification accuracy was low (Cairns 2001, Rollins et al. 2004). Also, historical mixed conifer and yellow pine fire regimes were similar (Sugihara et al. 2006*b*, Van de Water and Safford 2011), and, therefore, even though those two types were confused most often, it likely did not make very much difference when interpreting our results. However, red fir was confused with mixed conifer–fir types and subalpine conifers, both of which historically had fire regimes that were different from red fir (shorter and longer, respectively) (Sugihara et al. 2006*b*, Van de Water and Safford 2011).

Our results support the hypothesis that the current patterns of large wildfires and large high-severity patch sizes in the dry forest types on FS lands in the greater Sierra Nevada region, including the southern Cascades and Modoc Plateau, is to a large extent due to the lack of an agent to remove forest fuels at a rate commensurate with their accumulation (Abella et al. 2007, Miller et al. 2009*b*, Collins et al. 2011). Smaller Yosemite fire size and high-severity patch size in comparison with FS fires also suggests that the larger percentages of high severity on FS lands are not due to suppression limiting the amount of low severity in individual fires. Rather, it is the cumulative effect of suppression that has led to an accumulation of fuels, and subsequent higher percentages of high severity. As a corollary, our results support the hypothesis that restoring ecological processes, e.g., allowing more wildfires to burn under weather conditions less conducive to producing high intensities and severe effects, would reduce fuel loads and stand densities across broad scales even under current climate conditions, resulting in forests that may be more resilient to future climate change (Miller and Urban 2000, Stephens et al. 2010). Federal fire management policy allows for fires to be managed for resource benefit, provided such fire management strategies are identified in the Land and Resource Management Plans (LMP) and Fire Management Plans (FMP) (USDA-USDI 2009). Current LMPs and FMPs that call for suppressing all wildfires would need to be altered to allow for increasing the number and extent of wildfires managed for resource benefit (Steelman and McCaffrey 2011). There is an opportunity to do so with the new 2012 forest planning rule, and upcoming LMP and FMP revisions scheduled for the Forests in the greater Sierra Nevada region (North et al. 2012, USDA 2012).

Numerous challenges remain, however. Often social–political pressures are placed upon fire managers and land managers to quickly extinguish fires. As a result, there is a tendency for managers to avoid long-duration fires and risk fires escaping onto private lands. Some central and northern Sierra Nevada Forests are a checker-board of Federal and private ownership, and extensive co-operation between private land owners and federal, state and local fire managers will be required before allowing more wildfires to burn (Black et al. 2008, Canton-Thompson et al. 2008, Steelman and McCaffrey 2011). Public concern over air quality and air quality regulatory issues have also been a factor in limiting the use of prescribed fires or amount of time wildfires are allowed to burn (Winter et al. 2002, Quinn-Davidson and Varner 2012). To alleviate smoke concerns, managing fuels through mechanical treatments has been proposed as an option for meeting restoration objectives in some locations (Dombeck et al. 2004). Mechanical treatments are also usually preferred by the general public for meeting fuels management objectives in wildland-urban interface areas (Winter et al. 2002). Moreover, a recent study found few, if any, undesirable effects from mechanical fuels treatments (Stephens et al. 2012*b*). Mechanical treatments are not allowed in wilderness areas; nevertheless, using fire for resource benefit could be further emphasized. Regardless of where mechanical treatments potentially could be used, currently there is limited infrastructure that could economically treat enormous quantities of biomass material (Nicholls et al. 2008). Therefore, managing wildfire for resource benefit is likely the best option for fuels reduction and forest restoration over a large proportion of the landscape.

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