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Quantifying the fire regime distributions for severity in Yosemite National Park, California, USA

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Abstract. This paper quantifies current fire severity distributions for 19 different fire-regime types in Yosemite National Park, California, USA. Landsat Thematic Mapper remote sensing data are used to map burn severity for 99 fires (cumulatively over 97 000 ha) that burned in Yosemite over a 20-year period. These maps are used to quantify the frequency distributions of fire severity by fire-regime type. A classification is created for the resultant distributions and they are discussed within the context of four vegetation zones: the foothill shrub and woodland zone; the lower montane forest zone; the upper montane forest zone and the subalpine forest zone. The severity distributions can form a building block from which to discuss current fire regimes across the Sierra Nevada in California. This work establishes a framework for comparing the effects of current fires on our landscapes with our notions of how fires historically burned, and how current fire severity distributions differ from our desired future conditions. As this process is refined, a new set of information will be available to researchers and land managers to help understand how fire regimes have changed from the past and how we might attempt to manage them in the future.

Additional keywords: burn severity, dNBR, Landsat, RdNBR, Sierra Nevada.

Introduction

Recent studies of western North America have shown increases in the area burned annually and the size of individual fires (McKenzie *et al*. 2004; Westerling *et al*. 2006). A decade earlier, McKelvey *et al*. (1996) reported that fires in the Sierra Nevada of California were generally thought to have become less frequent and more severe, and that recent fires burned larger contiguous areas at higher intensities, resulting in a larger proportion of the burned area having severe effects. However, there were few or no direct data on fire regimes, which describe the way fire burns in different ecosystems, to support these statements. One important component of a fire regime is severity, defined as the magnitude of the effect of the fire on the ecosystem (Agee 1993; Lentile *et al*. 2006; Sugihara *et al*. 2006) or the degree to which a site or ecosystem has been changed owing to the fire (DeBano *et al*. 1998; Morgan *et al*. 2001; National Wildfire Coordination Group 2007). To determine if current fires are burning larger contiguous patches resulting in a larger proportion of the landscape burning at high severity, historical and current data need to be compared. Historical severity frequency distributions and patterns are difficult to reconstruct, because the principal data currently available to assess these fire regime attributes are dendrochronology studies of fire history, stand-age analysis and current patterns of vegetation on the landscape (Skinner 1995; Taylor and Skinner 1998, 2003; Moody *et al*. 2006). However, our ability to infer detailed geographic features of fires is limited and becoming more difficult with older fires. Time erases the fire history record left in older trees and snags, and current fires continue to change our stands and the vegetation patterns on the landscape.

To know if fire severity is changing across the landscape, we also need to be able to quantify the severity and patchiness of recent fires. This assessment has been difficult and impractical in the past owing to the size and number of fires across the landscape through space and time and the lack of a consistent way to quantify and map burn severity from fire to fire. In this paper, we describe the use of remote sensing to quantify the frequency distribution of fire severity in the vegetation types in Yosemite National Park, California, USA, for a 20-year period. Knowledge of the range of variation for fire severity allows us to create frequency distributions that can be compared with conceptual distributions of historic severity.

Recently, fire regimes have been given considerable attention in the federal land management agencies. The numerous major fire events over the last decade have caused changes in policy and management (Stephens and Ruth 2005). These

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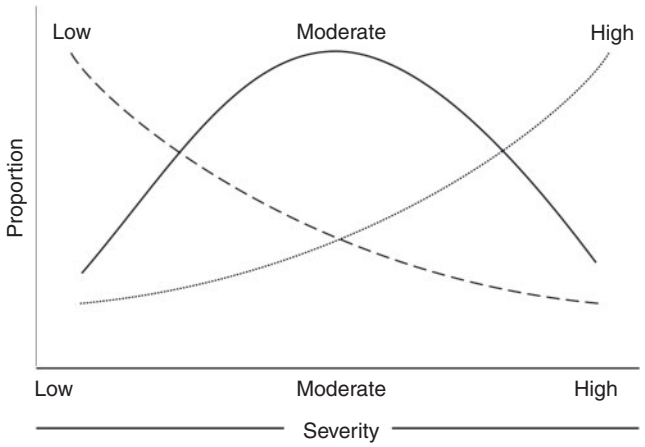

Fig. 1. Variation in fire severity within a general fire-severity type. The general fire-severity types differ in the proportion of the area burned at each fire-severity category. (Redrawn from Agee 1993.)

changes led to additions and improvements to our fire suppression forces, as well as renewed interest in fire regimes. The focus shifted to determining how current wildland conditions differ from historical conditions.

Agee (1993) defines a fire regime as 'a generalised description of the role fire plays in an ecosystem', whereas Heinselman (1981) states that a fire regime is the 'kind of fire history that characterised an ecosystem'. To discuss fire regimes in a meaningful manner, classifications have been created to simplify the complex patterns seen on landscapes (Sugihara *et al*. 2006). Fire regimes were first presented by Heinselman (1978) and his classification included the attributes of fire type, intensity, size and frequency. Kilgore (1981) also included fire frequency and intensity (Sando 1978; Heinselman 1981) in his definition and added season (Gill 1975), pattern (Keeley 1977) and depth of burn (Methven 1978). Hardy *et al*. (2001) added severity as a fire regime attribute and modified Heinselman's (1978) fire regime classification to have five groups based on only frequency and severity. This classification is currently used to determine natural and current fire regimes across the United States (Hann and Bunnell 2001).

Fire regime groups can be created by combining vegetation types based on the response of the dominant vegetation to fire, the frequency of fire, and similarities in post-fire succession (Davis *et al*. 1980; Sugihara *et al*. 2006). Agee (1993) built on these ideas to present a new classification method of fire regimes based on the severity of fire effects on the dominant vegetation. He noted that over large scales of space and time, all categories of fire severity can be expected to occur on any site. To display this variability in fire effects, he used a set of distributions to represent the different proportion of area burned along the gradient of fire severity. For example, in Fig. 1, Agee (1993) shows distribution curves for low-, moderate- and high-severity types. As these distributions represent fire severity by dominant vegetation types over large scales of space and time, they incorporate variations in weather, which in turn incorporates variation in fuel moistures.

Sugihara *et al*. (2006) developed a new framework that builds on both Agee's (1993) concept of distributions and the different fire regime attributes described by Heinselman (1978) and Kilgore (1981). Sugihara *et al*. (2006) describe fire regimes for California's vegetation types using a series of conceptual distributions that represent the variability of seven attributes over space and time for the ecosystem being described (Table 1). Each attribute can have several curves that represent the variability in different ecosystems (Fig. 2). The specific shapes of these curves can have specific ecological meaning and are described in detail in Sugihara *et al*. (2006).

For the purposes of this study, we focus specifically on the distributions for the fire regime attribute of severity in Yosemite National Park. Quantification of burn severity has been done for individual and multiple fires within the park (van Wagtendonk *et al*. 2004; van Wagtendonk and Lutz 2007; Lutz *et al*. 2009), but the frequency distributions of severity for multiple fires burning in different vegetation types has not been examined. Theoretical fire regime attribute distributions for the most common vegetation types of the Sierra Nevada have been presented by van Wagtendonk and Fites-Kaufman (2006) based on expert knowledge of the vegetation types and available fire history and fire effects data. These distributions were created for all seven fire regime attributes including seasonality, fire return interval, size, spatial complexity, fireline intensity, severity and fire type. However, there are few quantitative data available to test the predicted distributions. This is particularly true for the severity curves. Assessing severity for many fires through time and across large landscapes has been difficult to impossible in the past.

Over the last 20 years, development of methods for mapping burn severity using remote sensing has been an active area of research around the world (White 1985; Milne 1986; Jakubauskas *et al*. 1990; Lopez-Garcia and Caselles 1991; White *et al*. 1996; Rogan and Franklin 2001; Rogan and Yool 2001; van Wagtendonk *et al*. 2004; Key and Benson 2006). In the national parks in the Sierra Nevada, research on burn severity mapping has been active since 1999 (Key 2006). Based on this previous work, burn severity has been mapped in Yosemite dating back to 1984 using Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery and from 1974 through 1983 using Landsat Multispectral Scanner System (MSS) imagery (van Wagtendonk *et al*. 2002). Owing to different processing needs for the different sensors, the present study uses only fires greater than 40 ha from 1984 through 2003 to create current quantitative fire regime frequency distributions for severity.

Our objective was to use the 20 years of Landsat TM data collected from 1984 through 2003 in Yosemite National Park to create quantitative frequency distributions for the fire regime attribute of severity for different fire-regime types. These distributions were chosen as meaningful and readily quantified measures to represent current fire regimes in Yosemite.

Methods

Vegetation data

Yosemite National Park is located in the central Sierra Nevada in California (Fig. 3). The park contains over 300 000 ha that span the range from 600 to 4000 m in elevation. Vegetation in this section of the Sierra Nevada occurs in broad zones that separate out by climate and elevation from foothill shrub and

Table 1. Fire regime groups and attributes
The definitions of the different fire-regime attributes as described by Sugihara *et al*. (2006). These definitions are specific to the fire-regime distributions used in the present study

Fire regime groups and attributes
Temporal
Seasonality. Time of year when fire occurs
Fire return interval. Length of time between fires on a particular area
Spatial
Fire size. The area inside the perimeter of the fire
Spatial complexity. The patchiness or spatial variability in fire severity within the perimeter
Magnitude
Fireline intensity. The energy released per unit length of fire front
Fire severity. The magnitude of the effect of the fire as a measure of biomass consumed
Fire type. Ground, surface, passive crown, active crown, or independent crown fire

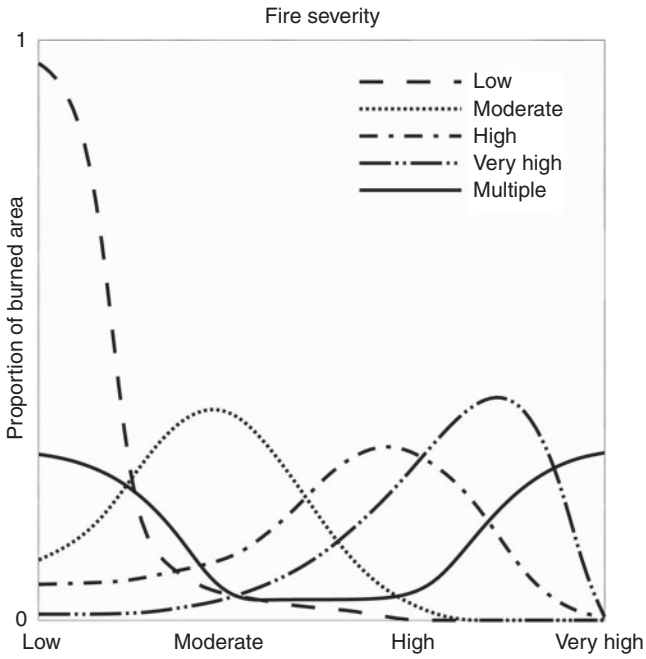

Fig. 2. Theoretical severity distributions. The *x* axis is severity from low to very high. The *y* axis is the proportion of burned area. The area under each curve is equal to 1. The low, moderate, high and multiple curves are the theoretical curves that apply to the fire-regime types assessed in Yosemite National Park. (Redrawn from Sugihara *et al*. 2006.)

woodlands, through lower and upper montane forests, subalpine forests, and alpine meadows and shrublands up to the crest.

The vegetation types of the Yosemite region were mapped in 1997 to the association or alliance level where possible, or to combined super-associations or super-alliances (Maybury 1999). Fire-regime types were created by grouping vegetation types that burn in a similar manner from the perspective of the seven different fire-regime attributes (Table 1, van Wagtendonk and Fites-Kaufman 2006). Although our fire-regime types are closely related to vegetation types, our classification is based on an assessment of how fire moves through these systems, primarily from the perspective of the amount of available fuel and ladder fuels.

The foothill shrub and woodlands zone occurs in the foothills of the Sierra Nevada between 500 and 1500 m. The zone contains foothill chaparral, conifer patches, live oak and oak woodlands fire-regime types. Vegetation associations and alliances included in these fire-regime types are listed in Table 2.

The lower montane forest zone occurs just above the foothill zone from 1500 to 1800 m. Vegetation varies with elevation and landscape position, and includes the lower montane chaparral, ponderosa pine (*Pinus ponderosa*), ponderosa pine–shrub, black oak (*Quercus kelloggii*), white fir (*Abies concolor*), white fir–shrub, giant sequoia (*Sequoiadendron giganteum*), and riparian fire-regime types (Table 3).

The upper montane forest zone is found just above the lower montane forest between 1800 and 2500 m. Extensive stands typical of the upper montane forest zone occur on relatively moderate terrain. The fire-regime types include upper montane chaparral, red fir, Jeffrey pine (*Pinus jeffreyi*)–shrub, Jeffrey pine–western white pine (*P. monticola*) and aspen (*Populus tremuloides*) (Table 4).

The subalpine forest zone extends up to the treeline at ~3450 m. As with the upper montane zone below, the terrain is moderate with increasing steepness as the treeline is approached. Within the subalpine forest zone are the whitebark pine (*Pinus albicaulis*)–mountain hemlock (*Tsuga mertensiana*) and lodgepole pine fire-regime types (Table 5).

Fire data

The park maintains and annually updates a GIS layer of fire perimeters for all suppressed wildfires, wilderness fires and prescribed fires going back to 1930 (van Wagtendonk *et al*. 2002). The perimeters from this GIS layer were used to identify 99 fires greater than 40 ha that burned between 1984 and 2003, representing over 97 000 ha that have burned during the 20-year period. The vegetation data layer was intersected with all post-1984 fire perimeters greater than 40 ha, including fires that burned across park boundaries. All portions of fires that intersected the vegetation map were included in the study.

Image processing

We estimated burn severity using the Relative Differenced Normalised Burn Ratio (RdNBR) (Miller and Thode 2007) with Landsat imagery. The RdNBR uses a pre- and 1-year-post-fire

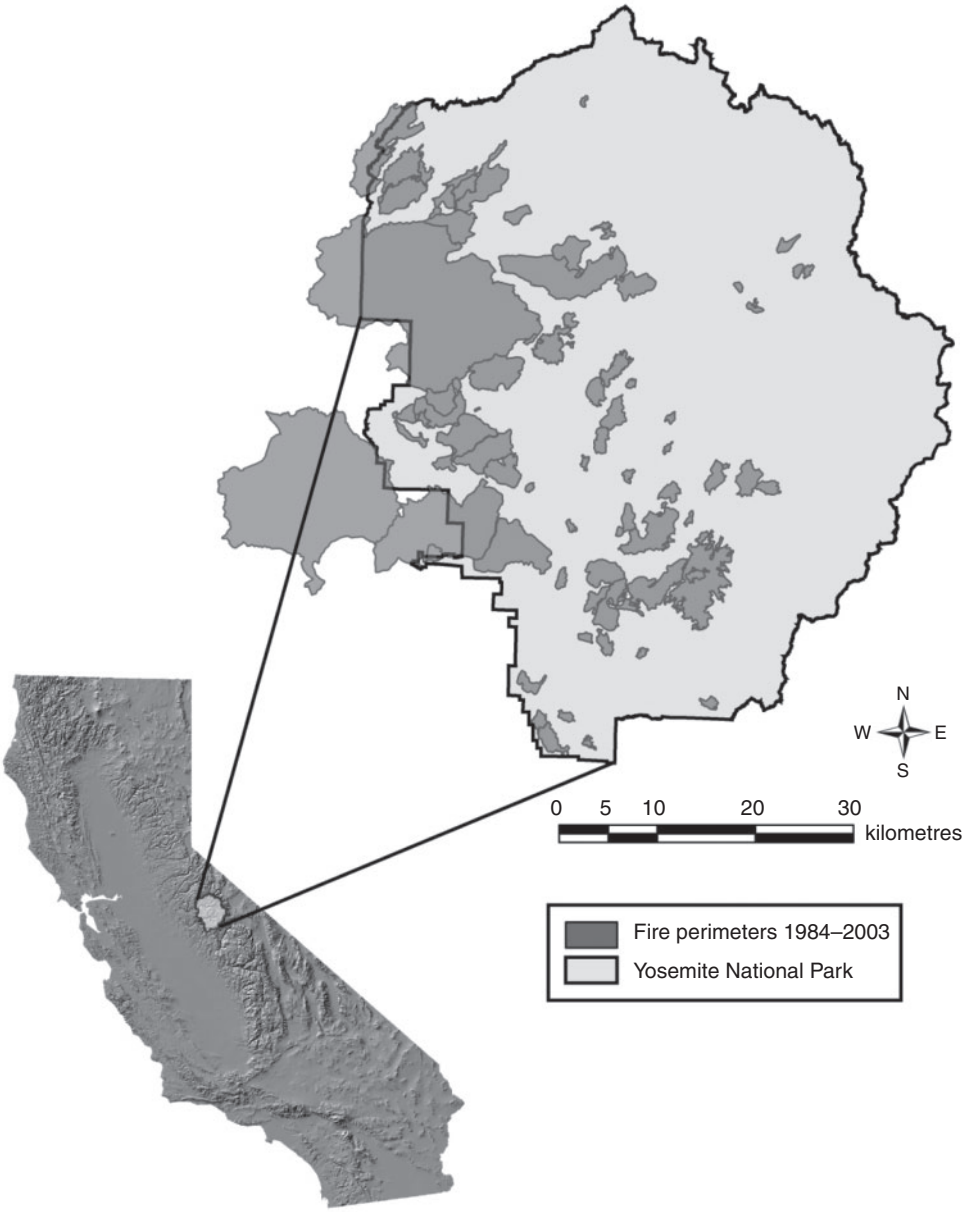

Fig. 3. Yosemite National Park locator map showing fire perimeters from 1984 to 2003.

image to measure the relative change in the burned area. The NBR (Lopez-Garcia and Caselles 1991; Key and Benson 2006) is calculated for each image using the reflectance values for bands 4 and 7:

$$\mathrm{NBR} = \frac{(R4 - R7)}{(R4 + R7)}$$

To calculate the RdNBR, the post-fire NBR is subtracted from the pre-fire NBR and then divided by the square root of the pre-fire NBR:

$$\mathrm{RdNBR} = \frac{(\mathrm{NBR}_{\text{pre-fire}} - \mathrm{NBR}_{\text{post-fire}})}{\left(\sqrt{\mathrm{NBR}_{\text{pre-fire}}}\right)}$$

All images used in this study were orthorectified using a terrain correction algorithm. The Landsat 5 images were orthorectified by the US Geological Survey. Landsat 7 images were orthorectified using existing orthorectified images as base images. The US Geological Survey 7.5-min National Elevation Dataset for California was used in the terrain correction algorithm in *ERDAS Imagine*. To reduce storage and image processing times, each image was clipped to include an unburned rectangle around each fire. All subsequent processing was performed only on the clipped area. The pre- and post-fire clipped images for each fire were coregistered to within a pixel.

The NBR algorithm incorporates only the near-infrared and mid-infrared wavelengths, in which atmospheric scattering is reduced (Avery and Berlin 1992). Therefore atmospheric

Table 2. Dominant species in the foothill shrub and woodland zone
Species are organised by the fire-regime types in the zone

Foothill shrub and woodland fire-regime type	Scientific name
Dominant species	
Chaparral	
Chamise	*Adenostoma fasciculatum*
Whiteleaf manzanita	*Arctostaphylos viscida*
Wedgeleaf ceanothus	*Ceanothus cuneatus*
Conifer patches	
Foothill pine	*Pinus sabaniana*
Interior live oak	*Quercus wislizenii*
Whiteleaf manzanita	*Arctostaphylos viscida*
Wedgeleaf ceanothus	*Ceanothus cuneatus*
Live oak	
Interior live oak	*Quercus wislizenii*
Canyon live oak	*Quercus chrysolepsis*
Oak woodlands	
Blue oak	*Quercus douglasii*
Valley oak	*Quercus lobata*

Table 3. Dominant species in the lower montane forest zone
Species are organised by the fire-regime types in the zone

Lower montane forest fire-regime type	Scientific name
Dominant species	
Chaparral	
Whiteleaf manzanita	*Arctostaphylos viscida*
Greenleaf manzanita	*Arctostaphylos patula*
Deerbrush	*Ceanothus integerrimus*
Ponderosa pine	
Ponderosa pine	*Pinus ponderosa*
Incense-cedar	*Calocedrus decurrens*
Douglas-fir	*Pseudotsuga menziesii*
Ponderosa pine–shrub	
Ponderosa pine	*Pinus ponderosa*
Incense-cedar	*Calocedrus decurrens*
Whiteleaf manzanita	*Arctostaphylos viscida*
Greenleaf manzanita	*Arctostaphylos patula*
Mountain misery	*Chamaebatia foliolosa*
Black oak	
California black oak	*Quercus kelloggii*
White fir	
White fir	*Abies concolor*
Sugar pine	*Pinus lambertiana*
Douglas-fir	*Pseudotsuga menziesii*
Incense-cedar	*Calocedrus decurrens*
White fir–shrub	
White fir	*Abies concolor*
Mountain whitethorn	*Ceanothus cordulatus*
Giant sequoia	
Giant sequoia	*Sequoiadendron giganteum*
Sugar pine	*Pinus lambertiana*
Riparian	
Black cottonwood	*Populus trichocarpa*
White alder	*Alnus rhombifolia*
Bigleaf maple	*Acer macrophyllum*

Table 4. Dominant species in the upper montane forest zone
Species are organised by the fire-regime types in the zone

Upper montane forest fire-regime type	Scientific name
Dominant species	
Chaparral	
Huckleberry oak	*Quercus vaccinifolia*
Bush chinquapin	*Castanopsis sempervirens*
Mountain whitethorn	*Ceanothus cordulatus*
Red fir	
Red fir	*Abies magnifica*
White fir	*Abies concolor*
Western white pine	*Pinus monticola*
Jeffrey pine–western white pine	
Jeffrey pine	*Pinud jeffreyi*
Western white pine	*Pinus monticola*
Red fir	*Abies concolor*
Jeffrey pine–shrub	
Jeffrey pine	*Pinus jeffreyi*
Huckleberry oak	*Quercus vaccinifolia*
Mountain whitethorn	*Ceanothus cordulatus*
Greenleaf manzanita	*Arctostaphylos patula*
Quaking aspen	
Quaking aspen	*Populus tremuloides*

Table 5. Dominant species in the subalpine forest zone
Species are organised by the fire-regime types in the zone

Subalpine forest fire-regime type	Scientific name
Dominant species	
Whitebark pine–mountain hemlock	
Whitebark pine	*Pinus albicaulis*
Mountain hemlock	*Tsuga mertensiana*
Lodgepole pine	*Pinus contorta*
Lodgepole pine	
Lodgepole pine	*Pinus contorta*

corrections were not performed. Landsat 5 images were converted to reflectance as described by Chander and Markham (2003). Landsat 7 images were converted to reflectance as specified in the Landsat 7 Science Data User's Handbook (NASA 1998). After computing the RdNBR, a 3×3-pixel focal mean was applied. All image processing was performed using *ERDAS Imagine version 8.7*.

Although the severity frequency distributions require continuous data, a standard classification was used to describe and discuss the severity categories. Field data from around the Sierra Nevada and in Yosemite National Park were used to create a standard classification for burn severity. Pixels were classified based on their RdNBR values as follows: unchanged for values less than 42, low for values from 42 to 219, moderate for values from 220 to 565, and high for values over 565. Areas were classified as unchanged if the severity was so low that a change could not be detected in the images 1 year post-fire. This category could contain both unburned and lightly burned pixels.

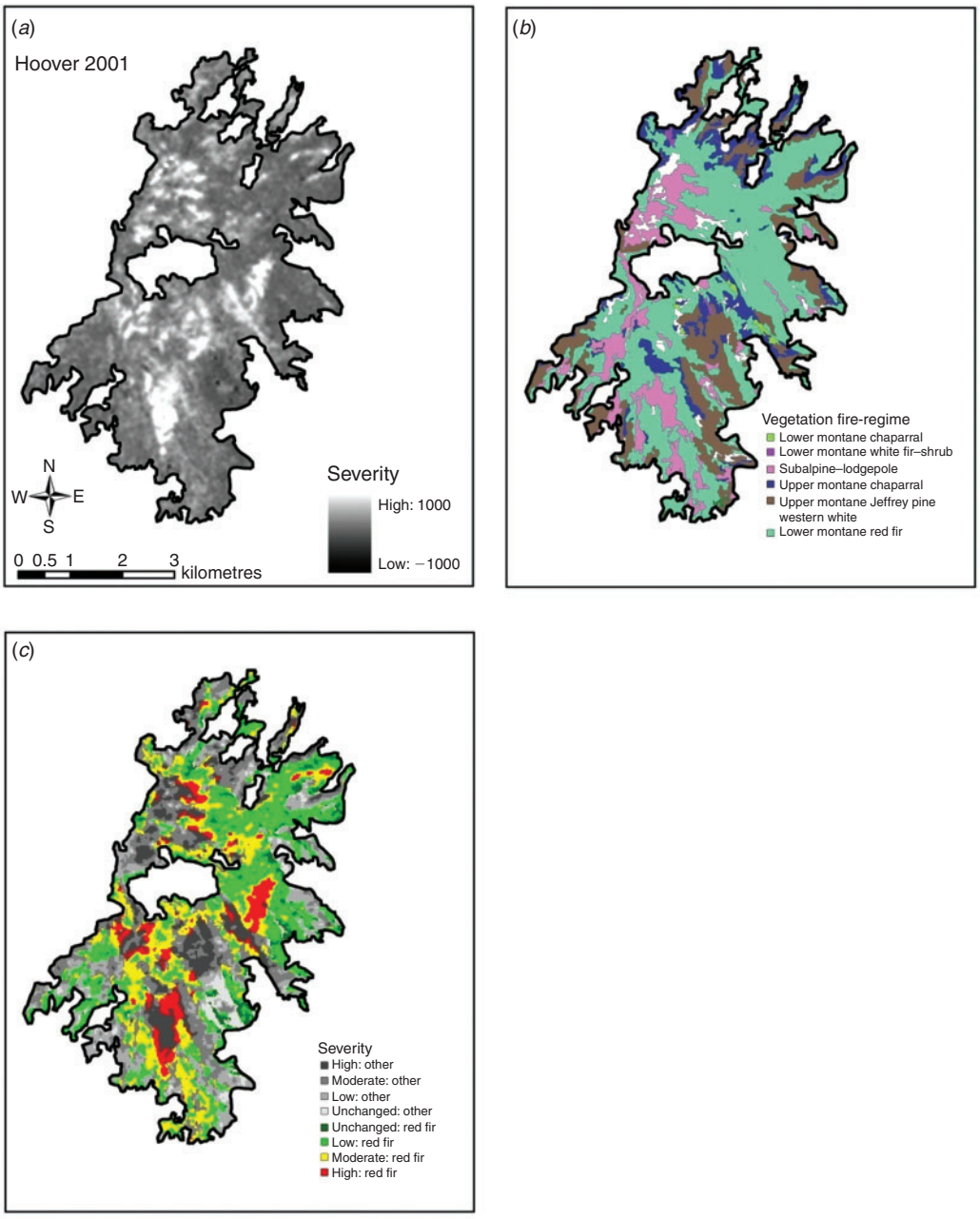

Fig. 4. 2001 Hoover Fire, located in the south-east portion of Yosemite National Park. (*a*) Burn severity map showing the continuous values of severity ranging from –1000 to 1000. (*b*) Map of fire-regime types found in the Hoover fire. Note the upper montane red fir fire regime shown in turquoise. (*c*) Classified burn severity for the upper montane red fir fire-regime type. Colour patches are the red fir type and grey scale patches are the classified burn severity patches for all other fire-regime types. The classification is shown to visually delineate the area used for the red fir fire-regime distribution.

Low-severity stands were generally lightly burned with only the fine fuels removed and some scorching of the understorey trees. Moderate-severity stands retained some fuels on the forest floor, although there was mortality of small trees and scorching of the crowns of medium and large-sized trees. High-severity areas were typified by near-complete combustion of all litter, duff and small logs, close to 100% mortality of small to medium-sized trees, and nearly 100% needle scorch or consumption in large trees. Because most of the fires used in the current study do not have any field data collected for mapping burn severity, the Sierra Nevada classification was used to describe and discuss the severity distributions (below). This classification was created using seven different fires and over 700 field data points for classification and accuracy assessments (Thode 2005).

Table 6. Fire severity distribution characteristics for the foothill shrub and woodland fire-regime types

Fire-regime type	Burned hectares (pixels)	Percentage burned of total hectares	0% min.	25% quartile	Median	75% quartile	100% max.	Current quantitative distribution	Hypothetical distribution
Chaparral	591 (6564)	18.4	–426	567	717	821	1235	High	High
Conifer patches	623 (6923)	21.7	–492	243	382	544	2000	Mod.	High
Live oak	10 250 (113 884)	39.3	–997	160	381	615	1914	Mod.	
Oak woodlands	163 (1811)	15.9	–214	94	205	340	723	Low to mod.	Low

Table 7. Fire severity distribution characteristics for the lower montane forest fire-regime types

Fire-regime type	Burned hectares (pixels)	Percentage burned of total hectares	0% min.	25% quartile	Median	75% quartile	100% max.	Current quantitative distribution	Hypothetical distribution
Chaparral	3334 (37 039)	20.8	–964	475	682	892	1255	High	
Ponderosa pine	13 113 (145 701)	34.2	–948	149	269	409	1629	Low to mod.	Low to mod.
Ponderosa pine–shrub	3893 (43 250)	87.5	–856	87	219	357	1194	Low to mod.	
Black oak	2343 (26 029)	40.4	–996	158	316	577	1374	Mod.	Low to mod.
White fir	9645 (107 162)	33.9	–988	84	168	270	1206	Low	Low to mod.
White fir–shrub	193 (2146)	3.3	–151	60	229	388	992	Bimodal low to mod.	
Giant sequoia	18 (199)	13.5	–82	21	54	85	251	Low	
Riparian	366 (4071)	5.1	–962	291	523	761	1239	Mod. to high	

Table 8. Fire severity distribution characteristics for the upper montane forest fire-regime types

Fire-regime type	Burned hectares (pixels)	Percentage burned of total hectares	0% min.	25% quartile	Median	75% quartile	100% max.	Current quantitative distribution	Hypothetical distribution
Chaparral	2891 (32 123)	73.3	–986	314	557	786	1752	Mod. to high	
Red fir	14 702 (163 352)	23.4	–999	69	158	267	1412	Low	Multiple
Jeffrey pine–shrub	7738 (85 983)	28.0	–995	114	284	457	1642	Low to mod.	
Jeffrey pine–western white pine	6856 (76 177)	13.8	–998	109	232	365	1476	Low to mod.	Low
Aspen	208 (2309)	3.1	–394	118	265	407	904	Low to mod.	

Table 9. Fire severity distribution characteristics for the subalpine forest fire-regime types

Fire-regime type	Burned hectares (pixels)	Percentage burned of total hectares	0% min.	25% quartile	Median	75% quartile	100% max.	Current quantitative distribution	Hypothetical distribution
Whitebark pine–mountain hemlock	210 (2336)	0.4	–799	–48	4	67	546	Low	Low
Lodgepole pine	1698 (18 872)	3.7	–951	54	157	293	1483	Low	Multiple

Table 10. Severity definitions for placing distributions into categories

Low
Mean and median in low
Interquartile range mostly in low or unchanged and none in high
Low-to-moderate
Mean and median in moderate or split between low and moderate
Interquartile range covers low to moderate with none in high
Moderate
Mean and median in moderate
Interquartile range covers low to high OR all within moderate
Moderate-to-high
Mean and median in moderate or split between moderate and high
Interquartile range covers moderate to high
High
Mean and median in high
Interquartile range mostly in high with none in low

Severity frequency distributions

Severity frequency distributions were created for each fire-regime type. The continuous severity maps (Fig. 4*a*) were first partitioned by the fire-regime type map (Fig. 4*b*) to produce a continuous regime-severity map for each fire-regime type. The final classified fire regime severity map for the red-fir fire-regime type is shown in Fig. 4*c*. The classification is shown to help clarify the fire regime severity map, and the threshold values between the different classes are used to describe the resultant fire severity distributions.

The quantiles, median and mean are used to describe the severity distributions because we are interested in the frequency distribution of severity. In addition, the median is less affected by extremely high or low measures and thus is often preferred when dealing with skewed populations (Zar 1999). The severity distributions were created using frequency histograms of pixel values. Every pixel that burned during the 20-year period was used for analysis, and sufficiently large numbers of pixels were available for most of the different fire-regime types (Tables 6–9). Distributions with more available pixels are considered a stronger representation of the severity distributions.

The severity values range between –999 and 2000 for all fire-regime types. The range of values between the 0.5 and 99.5% quantiles is from –471 to 1422; thus the scale for the distributions is set from –500 to 1400. Like all differenced indices based on band ratios, RdNBR values are dimensionless. The distributions are split into unchanged, low, moderate and high based on the standard classification for burn severity described above. The 'unchanged' severity category contains two different types of data. The first type includes pixels within the fire perimeter that showed no change compared with the pre-fire image or the areas outside the fire. These are areas where fire may or may not have burned, but we cannot detect any change from the imagery, possibly because an understorey burn is completely covered by a canopy layer. The second type of data includes pixels where the post-fire response was greater than the pre-fire response values. This occurs when vegetation responds to fire in a vigorous manner, such as meadows or plant communities that have rapid and strong sprouting responses. Both of these types are lumped into the 'unchanged' category because we are interested in quantifying the amount of change due to a loss of vegetation 1 year post-fire, as this is the more common vegetation response in the Sierra Nevada for the fire-regime types addressed in this paper.

The fire regimes were then characterised as having low, low-to-moderate, moderate, moderate-to-high and high fire-severity distributions for the purposes of discussion. The rules established for defining these classifications are found in Table 10.

Fig. 5*b* is an example of a moderate-severity distribution. The RdNBR values are on the *x* axis, and the number and proportion of pixels (*y* axis) are shown in increments of 50 RdNBR along the *x* axis. The normal and smoothed curves give a visual impression of whether the distribution is right-skewed (positive skewness) or left-skewed (negative skewness). In addition, the kurtosis or 'peakedness' can be seen by examining how much higher the smoothed curve is than the normal curve. In Fig. 5*b*, there is a slight positive skewness and a slight kurtosis. Because the theoretical distributions described by Agee (1993) and Sugihara *et al*. (2006) did not include the 'unchanged' category or extremely high values, they look different than those we derived. The main difference is that the theoretical distributions are truncated at the lower and upper ends.

Results

Nineteen fire regime distributions were defined across the four major vegetation zones: five low-severity, seven low-to-moderate severity, three moderate-severity, two moderate-to-high severity and two high-severity. The results are presented by the four major vegetation zones as these fire-regime types will be intertwined spatially on the landscape and fire will frequently move from one fire-regime type to another. Edges of one fire-regime type will certainly be affected by the type of fire coming in from another fire-regime type. Presenting the fire regimes types by the major vegetation zones will help to see how they interact with each other over the landscape.

Foothill shrub and woodland zone

The four fire-regime types in the foothill shrub and woodland zone included high, moderate, and low-to-moderate fire-severity distributions (Table 6, Fig. 5). These areas primarily burned in the 1987 Stanislaus complex, the 1990 A-Rock fire, or the 1996 Ackerson fire. The Stanislaus complex fires started outside the park, whereas the other two began inside. Each of these wildfires was suppressed after burning several thousand hectares both inside and outside of the park.

Within the foothill chaparral fire-regime type, 591 ha burned, comprising 18.4% of the fire-regime type. The foothill chaparral type has a high-severity distribution, with ~75% of the type burned in the high-severity category and ~25% of the area burned in the other three severity categories (Fig. 5*a*). The interquartile range was entirely within the high-severity category, and there was a negative skew.

The distribution for foothill conifer patches fire-regime type had a median within the moderate-severity category and at least 50% of the area under the distribution within the moderate-severity range (Fig. 5*b*). The interquartile range was located completely within the moderate-severity category with a slight positive skew. The foothill conifer patches regime type typically sits within a matrix of foothill chaparral and foothill live oak. However, the 623 ha of the foothill conifer patches type that

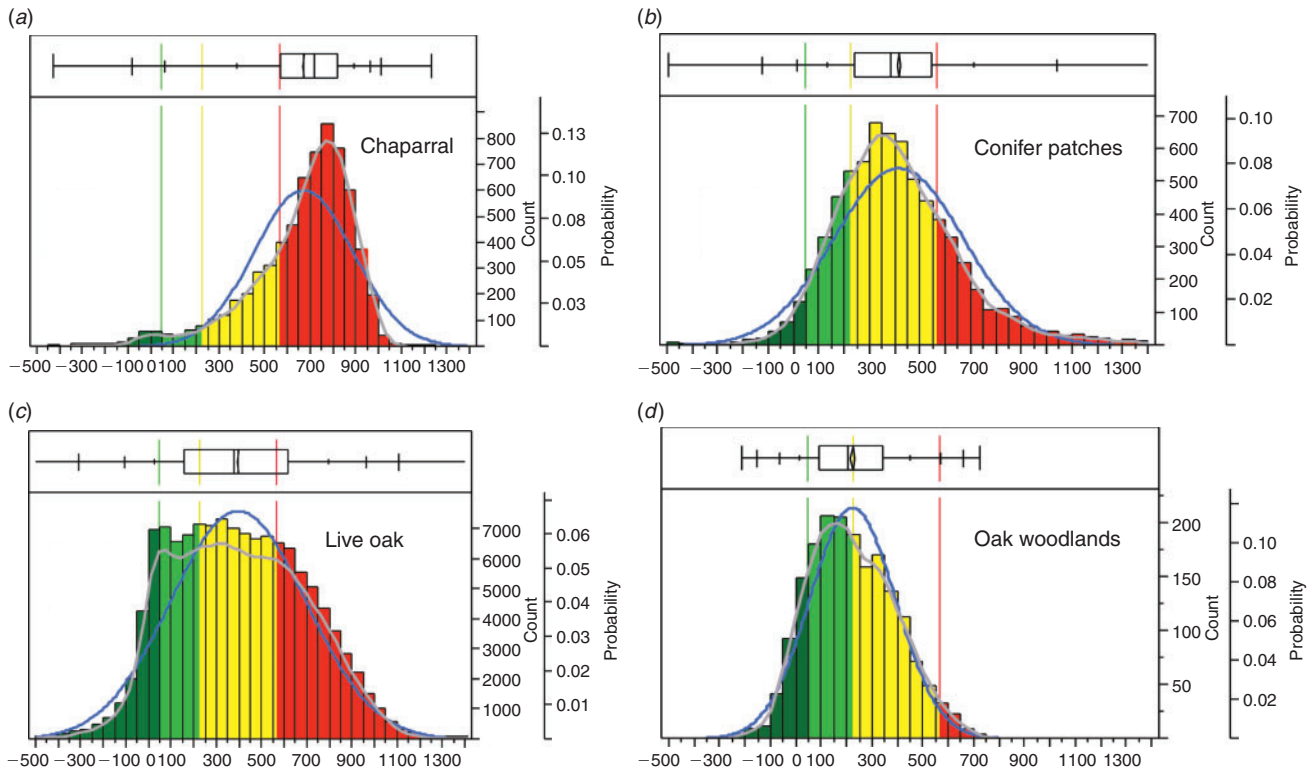

Fig. 5. Fire severity distributions for the foothill shrub and woodland fire-regime types. The probability axis represents probability density. The *x* axis shows the RdNBR value. The left line (42) is the threshold between unchanged and low categories, the middle line (220) is the threshold between the low and moderate categories, and the right line (566) is the threshold between the moderate and high categories. Dark green represents areas classified as unchanged, light green as low, yellow as moderate and red as high severity. The bar at the top indicates the minimum, 0.5, 2.5, 19.0, 90.0, 97.5, 99.0% and maximum values, and the box includes the 25% quartile, median, mean (diamond) and 75% quartile values. The normal (blue) and smoothed curves (grey) are shown.

burned during the 20-year period were almost all within a matrix of the foothill live oak fire-regime type, with very little associated with the foothill chaparral type.

Over 10 000 ha (39.3%) of the foothill live oak fire-regime type burned during the study period. The distribution for this type was slightly bimodal, with maxima in the low- and moderate-severity categories and the median in the moderate category (Fig. 5*c*). The interquartile range spreads across low to high values. The severity distributions for the foothill live oak fire regime and the foothill conifer patches fire regime have virtually identical medians. However, the foothill live oak distribution has a larger range of severity within the interquartile range.

The fire-severity distribution for foothill oak woodlands is low-to-moderate with a very slight positive skew (Fig. 5*d*). The median is just within the low-severity category and the interquartile range covers both low and moderate values. This fire-regime type burned 163 ha, or 15.9% of its land-base during the 20-year period, all of which was within the 1990 A-Rock fire. The type occurs as small patches within or adjacent to larger patches of the foothill conifer patches and foothill live oak regime types.

Lower montane forest zone

The lower montane forest zone regime types had severity distributions that ranged from low to high (Table 7, Fig. 6). This zone had the greatest number of fires during the 20-year period including suppressed wildfires, wilderness fires and prescribed fires.

The lower montane chaparral distribution was slightly bimodal, resulting in a low kurtosis and a slight negative skew (Fig. 6*a*). The mean and median values were nearly identical, and ~75% of the interquartile range was in high severity. This fire-regime type burned 3334 ha, or 20.8% of its land-base during the 20-year period.

The lower montane ponderosa pine fire-regime type had a low-to-moderate severity distribution (Fig. 6*b*). The median was within the moderate-severity category with a slight positive skew and minor kurtosis. This type burned over 13 000 ha, or 34.2% of its land-base, primarily with prescribed fires and wildfires.

The lower montane ponderosa pine–shrub type burned 3893 ha, or 87.5% of its land-base. It had a wide and flat distribution at the top that crossed from the unchanged to moderate-severity categories, indicating that equal proportions of the landscape burned with a wider range of effects (Fig. 6*c*). Although the mode was just within the low category, the median was in the moderate-severity category. This median was slightly lower than the median for the ponderosa pine type that did not have a shrub component.

The lower montane black oak fire-regime type has a moderate severity distribution with a fat tail into the high-severity range that accounted for ~25% of the burned area and almost

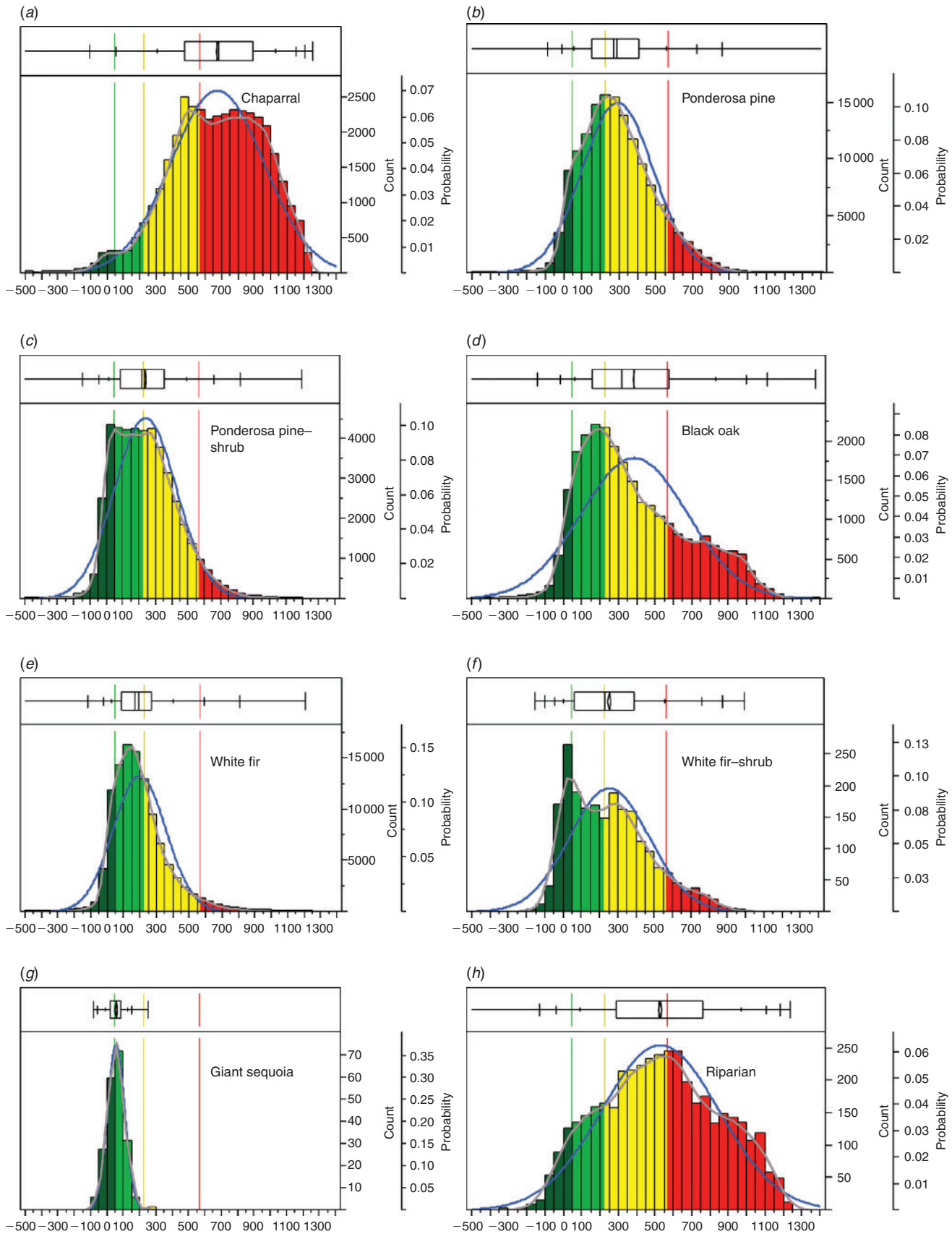

Fig. 6. Fire severity distributions for the lower montane forest fire-regime types. The probability axis represents probability density. The *x* axis shows the RdNBR value. The left line (42) is the threshold between unchanged and low categories, the middle line (220) is the threshold between the low and moderate categories, and the right line (566) is the threshold between the moderate and high categories. Dark green represents areas classified as unchanged, light green as low, yellow as moderate and red as high severity. The bar at the top indicates the minimum, 0.5, 2.5, 19.0, 90.0, 97.5, 99.0% and maximum values, and the box includes the 25% quartile, median, mean (diamond) and 75% quartile values. The normal (blue) and smoothed curves (grey) are shown.

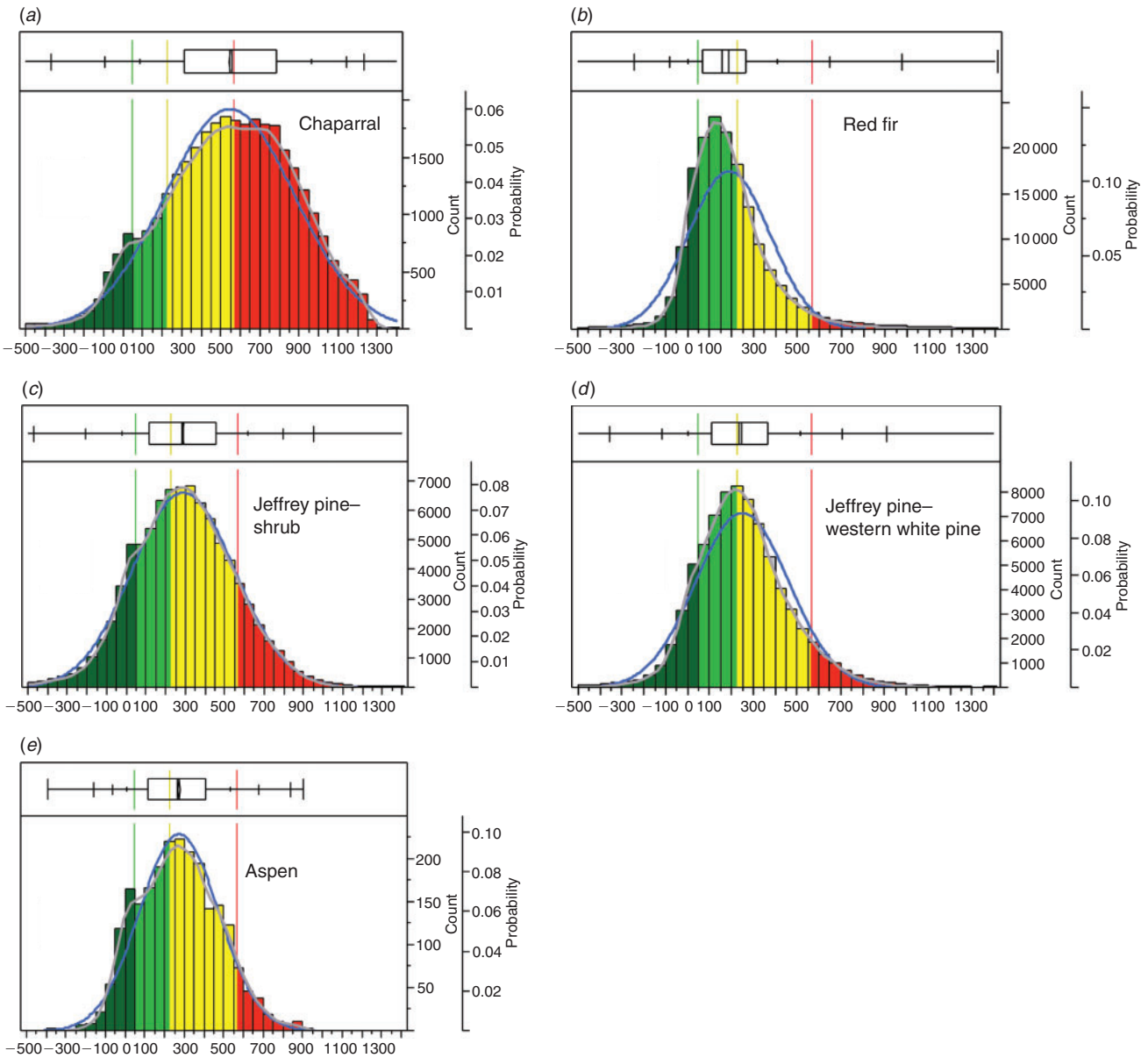

Fig. 7. Fire severity distributions for the upper montane forest fire-regime types. The probability axis represents probability density. The *x* axis shows the RdNBR value. The left line (42) is the threshold between unchanged and low categories, the middle line (220) is the threshold between the low and moderate categories, and the right line (566) is the threshold between the moderate and high categories. Dark green represents areas classified as unchanged, light green as low, yellow as moderate and red as high severity. The bar at the top indicates the minimum, 0.5, 2.5, 19.0, 90.0, 97.5, 99.0% and maximum values, and the box includes the 25% quartile, median, mean (diamond) and 75% quartile values. The normal (blue) and smoothed curves (grey) are shown.

makes this a bimodal distribution (Fig. 6*d*). The mode of the distribution was right on the boundary of the low- and moderate-severity categories, and the median was just in the moderate category.

Nearly 95% of the 9645 ha (33.9% of its land-base) that burned within the lower montane white fir fire-regime type was in the low-severity category (Table 7). Positive skewness and high kurtosis characterise this distribution with the median within the low-severity category (Fig. 6*e*).

The lower montane white fir–shrub fire-regime type had a bimodal distribution with the highest peak (mode) in the low-severity category and the other peak in the moderate category (Fig. 6*f*). The modes bracketed the median for this type, which was higher than the median for the non-shrub white fir type. This type only burned 193 ha, or 3.3% of its land base.

The severity distribution for the lower montane giant sequoia fire-regime type had a narrow range with very limited severity effects. At least 30% of the area burned was in the unchanged category (Fig. 6*g*). The distribution contains virtually no area burned in the moderate-severity category and no area in the high category. Only 18 ha, or 13.5% of its land-base, burned in this type, all by prescribed fires.

Although Sierra riparian zones are thought to be at low risk of burning, 366 ha, or 5.1% of their land-base, have burned;

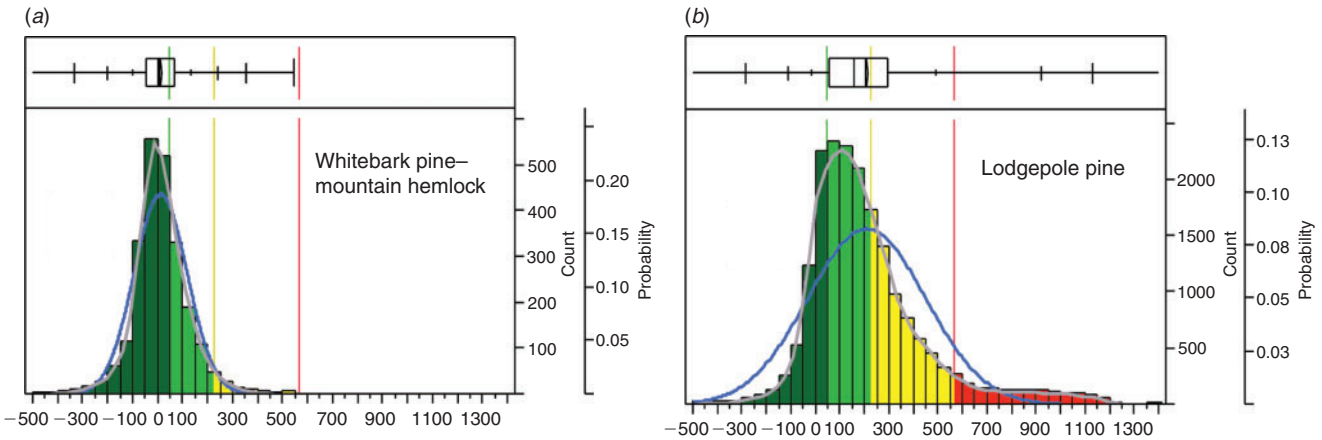

Fig. 8. Fire severity distributions for the subalpine fire-regime types. The probability axis represents probability density. The *x*-axis shows the RdNBR value. The left line (42) is the threshold between unchanged and low categories, the middle line (220) is the threshold between the low and moderate categories, and the right line (566) is the threshold between the moderate and high categories. Dark green represents areas classified as unchanged, light green as low, yellow as moderate and red as high severity. The bar at the top indicates the minimum, 0.5, 2.5, 19.0, 90.0, 97.5, 99.0% and maximum values, and the box includes the 25% quartile, median, mean (diamond) and 75% quartile values. The normal (blue) and smoothed curves (grey) are shown.

sometimes two to three times in the 20-year period. The riparian distribution is a particularly wide distribution, with the median at the high end of the moderate category (Fig. 6*h*). The interquartile range covers both moderate and high severity.

Upper montane forest zone

Fire-severity distributions in the upper montane forest zone tended to be low to moderate, although both higher and lower distributions did occur (Table 8, Fig. 7). Most of this zone was burned by fires that were part of the wilderness fire program.

The upper montane chaparral fire-regime type had a broad moderate-to-high distribution (Fig. 7*a*). The median was just below the boundary between the moderate- and high-severity categories, and the interquartile range was completely within those categories. Nearly 3000 ha and 73.3% of its land-base burned in this type, making this the fire-regime type with the most land-base burned.

The distribution for the red fir fire-regime type was unimodal, right-skewed and had a median within the low-severity category (Fig. 7*b*). The interquartile range was mostly within the low-severity category. More of this fire-regime type (14 702 ha, or 23.4% of its land-base) burned during the 20-year period than any other type.

The distribution for the upper montane Jeffrey pine–shrub fire-regime type was low to moderate (Fig. 7*c*). The median was in the moderate-severity category, and the interquartile range covered both low- and moderate-severity categories. There was hardly any skewness or kurtosis. The type burned 7738 ha, or 28.0% of its land-base, in scattered locations in the wilderness fire zone.

The upper montane Jeffrey pine–western white pine fire-regime type had a low-to-moderate distribution with a median of 232, splitting the interquartile range almost evenly between the low and moderate categories (Fig. 7*d*). There was a slight kurtosis and very slight positive skewness. During the 20 years of the study, 6856 ha, or 13.8% of its land-base, burned, primarily with wilderness fires.

Small stands (208 ha total, or 3.1% of its land-base) of the upper montane quaking aspen fire-regime type were parts of larger fires that burned adjacent fire-regime types in the wildland fire use zone. All the burned aspen type was contained within 74 small patches, with the largest patch being 18.2 ha and 96% of the patches less than 8 ha. The resulting low-to-moderate severity distribution had median value in the moderate category and the interquartile range spanned both low and moderate severities (Fig. 7*e*). Skew and kurtosis were minor.

Subalpine forest zone

Although the subalpine forest zone seldom burns, eight large fires burned portions of the zone. Seven of the fires were part of the wilderness fire program, and one was a suppressed wildfire. The fire-severity distributions were both dominated by low-severity pixels and thus characterised as a low-severity distribution (Table 9, Fig. 8).

The subalpine whitebark pine–mountain hemlock had a low-severity distribution with at least 30% of the area within the fire perimeters in the unchanged category (Fig. 8*a*). The median was in the unchanged category as was most of the interquartile range. Although a small stand of whitebark pine burned, most of the 210 ha that burned was mountain hemlock. Only 0.4% of the land-base of this type burned.

The severity distribution for lodgepole pine was skewed strongly in the low direction, with a relatively long right tail. The median was in the middle of the low category, as was 75% of the interquartile range (Fig. 8*b*). Just under 1700 ha, or 3.7% of its land-base, burned in the lodgepole pine fire-regime type.

Discussion

The ecological significance of the different fire-severity distributions can be seen by examining the interplay between fire severity and vegetation. Vegetation affects fuel characteristics

and fire behaviour, which in turn affect fire severity and subsequent ecological response. As a result, a particular vegetation type is adapted to a specific fire-severity distribution that acts to perpetuate that type.

Fire regimes are assessed over large areas and long time frames to incorporate the range of fire behaviour and effects seen with different weather conditions (Agee 1993; Sugihara *et al*. 2006). Thus, variations in wind, temperature and relative humidity that in turn affect fuel moistures, fire behaviour and effects are 'built' into the distributions. The time frame of this analysis is determined by the available Landsat TM imagery, and thus may be a bit short for some fire regime types that have fire more infrequently, but will be adequate for fire-regime types that have more frequent fire. As we move forward in time with available imagery for these types of analyses, the time frames we can assess will be longer.

Although the fire-regime types are presented individually, they do not necessarily function that way on the landscape. Patches of one fire-regime type will certainly be affected by their neighbour as fire behaviour will not change immediately with a change in vegetation and thus fuels. There will be some distance on the ground that it takes a crown fire to drop to the ground or vice versa with a change in vegetation and fuel type. If you have a high-severity fire regime next to a low- or moderate-severity regime, the edges will be affected. These spatial effects have not been well studied but have been observed when crown fires hit fuel treatments or natural changes in fuels. The size and amount of edge of the patches of fire-regime types will certainly affect how prevalent these effects are. The spatial attributes of fire regime patches are not analysed in this paper but do likely have an effect on the distributions seen.

Hypothesised regimes

Ten out of the 19 severity distributions quantified in this paper had hypothesised historic distributions (van Wagtendonk and Fites-Kaufman 2006). The hypothesised distributions were primarily based on expert opinion, owing to a lack of actual data. Of the 10 theoretical distributions, three of them matched our current distributions. There may be several reasons for this. The first is that the hypothesised distributions were created for historic fire regimes and the distributions in the present paper quantitatively represent 20 years of current fire effects on the landscape. The second is that the current fire regimes may be changing themselves owing to climate change (Westerling *et al*. 2006). To the degree that they have shifted, more quantified current patterns may not match historic regimes, but will still be more relevant to current management and future forecasting.

Third, the current quantitative regimes incorporate current management practices on the ground, which include prescribed fire, wilderness fire and suppression actions. These practices are not considered in historic fire regimes. We do not attempt to filter these practices out within the current distributions even though we acknowledge the effect of these practices on current distributions. van Wagtendonk and Lutz (2007) found that prescribed fire had more unchanged and low severity pixels than wilderness fire and considerably more than suppressed wildfires. In addition, they found that suppressed wildfires had three times as much high-severity fire than wilderness fire and 10 times more than prescribed fire. During the 32-year time frame of van Wagtendonk and Lutz's (2007) study, they found that the different vegetation zones were differentially affected by management actions. Our study gives us a 20-year snapshot of our current fire regimes. Knowledge about management actions and how they affect severity is valuable information that empowers us to better manage our future fire regimes by utilising different types of management fires.

Distribution shapes

Because the theoretical distributions described by Agee (1993) and Sugihara *et al*. (2006) did not include the 'unchanged' category or extremely high values, their distributions are limited at the lower and upper ends. This limitation could be artificially created in the RdNBR data by deciding on a cut-off point and 'stacking' all values above or below that point into one column. However, in nature the spread of these values depends on the reflectance of bands 4 and 7 and is actual information. Thus, the distributions are shown to represent 99% of the variation and are not artificially run up against a 'wall'.

Foothill shrub and woodland zone

The foothill shrub and woodland fire-regime types contained one low-to-moderate, two moderate- and one high-severity distribution. The foothill chaparral type contains species (Table 2) that tend to promote high-severity fire and are well suited to recover after higher-severity fire through scarified seeds and lignotubers (Biswell 1961; Christensen and Muller 1975; Keeley 1987). This could lead to a relatively stable severity distribution through time.

The conifer patches type represents foothill pine as small stands within a matrix of foothill chaparral and live oak. As a result, the severity distributions for the foothill conifer patches fire regime and the foothill live oak fire regime have virtually identical medians. However, the foothill live oak distribution had a larger range of severity.

The area burned in the foothill oak woodlands fire-regime type was all within the 1990 A-Rock fire and occurred in small patches within or adjacent to larger foothill conifer patches and foothill live oak regime types. Both these types have moderate-severity distributions. The association of the small patches of foothill oak woodlands with these other types could explain the tendency in the severity distribution towards moderate.

Lower montane forest zone

Like the foothill chaparral fire-regime type, lower montane chaparral shows a high-severity distribution. The lower montane chaparral type contains several fire-responding species such as mountain misery, white and greenleaf manzanita and deerbrush. These species regenerate well after fire through either resprouting, scarified seeds (Keeley 1987), or both (Hanes 1977), and generally are thought to promote higher-severity fire through their structure, bark shedding or naturally occurring oils and terpenes. This fire-regime type is often adjacent to foothill live oak, lower montane black oak, ponderosa pine and ponderosa pine–shrub. All of these fire-regime types are low to moderate or moderate in severity. Fires burning out of these types into chaparral could account for a part of the low and moderate severity seen in lower montane chaparral and contribute to the large spread of this frequency distribution.

The ponderosa pine and ponderosa pine–shrub distributions both fall into the low-to-moderate category. Ten per cent of the area burned in ponderosa pine was at high severity, with ~35% to 40% of the area in moderate severity. Historically, the ponderosa pine fire-regime type was considered to be a low-severity fire regime. Grazing, fire suppression and other management practices have caused this lower-elevation frequent-fire-regime type to burn more severely than it did historically (Covington and Moore 1994; Skinner and Chang 1996; van Wagtendonk and Lutz 2007). Our data back up these ideas at a landscape scale, as close to half of the area burned at moderate- to high-severity levels. The ponderosa pine–shrub regime type shows a lower overall severity and lower median than the pure ponderosa pine regime type. A shrub component should increase available fuel and create ladder fuels that can more easily carry fire into the crowns of the trees. This would generally cause higher severity. However, the ponderosa pine–shrub type had ~87% of its land-base burned during the 20-year period. During this time, prescribed fires were extensively used, which tended to burn with lower severity (van Wagtendonk and Lutz 2007).

The lower montane black oak fire-regime type showed a moderate severity distribution. Black oak is found at low elevations on xeric sites and is well adapted to light and regular surface fires (Barbour and Major 1995), indicating a pattern of low-severity fires. Black oak–ponderosa pine forests in the Sierra Nevada were intensively managed with fire by the Western Mono, Sierra Miwok and Foothill Yokuts Native American tribes (Anderson 2006). It is possible the distribution is showing a shift to higher severity as a result of frequent fire being removed from the system with the cessation of burning by Native Americans.

The white-fir fire-regime type had a low-severity distribution and was found adjacent to many fire-regime types including ponderosa pine, ponderosa pine–shrub, Jeffrey pine–shrub, Jeffrey pine–western white pine and red fir. All of these types have a low-to-moderate fire regime distribution except for red fir. White fir has short needles that form a relatively compact fuel bed (van Wagtendonk *et al.* 1998). Fires in this type are more difficult to ignite and require dry fuels with wind to reach higher severity levels. van Wagtendonk and Fites-Kaufman (2006) hypothesised this distribution to be low to moderate severity. Ignitions in conjunction with requisite conditions for severe burning in this regime likely did not occur during the 20-year study period in the Yosemite ecosystem, and it remains to be seen whether, with more time, this type might experience rare, large fires that produce larger patches of moderate- and high-severity fire on the landscape.

The lower montane white fir–shrub severity distribution is within the low-to-moderate fire severity categories. This type only burned ~3% of its land-base over the last 20 years. This is the one of the three distributions with the lowest number of pixels, and the overall shape could be a reflection of this. Even with this limitation, the overall median for the white fir–shrub type is higher than the white fir type, which is a logical outcome, as the shrub component would have the effect of raising fire intensity and fire severity.

The lower montane giant sequoia fire-regime type is thought to have frequent low-to-moderate severity fires (Kilgore 1981; Swetnam 1993); however, very little of the area burned within the moderate-severity category (Fig. 6*g*). The prescribed fires that have been used to burn the sequoia groves were purposely of low severity and did not kill any overstorey trees.

The riparian fire-regime type has a moderate-to-high severity distribution that shows a wide spread of fire effects from unchanged to high severity. Riparian areas have been shown to have longer and more variable fire return intervals than upland sites (Skinner 2002). However, dry years occur when these areas will burn, and according to the current distribution, over 75% of the area burned has burned in moderate to high severity. Several areas have burned two to three times in the 20-year period.

Upper montane forest zone

The upper montane chaparral fire-regime type shows a moderate-to-high severity distribution but is very close to being classified as a high-severity distribution, with over 75% of the area burned at moderate and high severities. However, low severity is represented with a thick tail. Of all the chaparral fire-regime types, this is the only one with the mean and median below the high-severity threshold. The proximity of the upper montane chaparral to red fir, Jeffrey pine–shrub and to a lesser extent Jeffrey pine–western white pine may have reduced the severity levels somewhat. All the chaparral types have species that require higher-severity fire to germinate and persist in large numbers across the landscape. It is interesting that the frequency distributions move further into low and moderate severity as you move up in elevation. It is not just an overall shift of the distributions from left to right, but a widening of the distributions that maintains the high-severity areas but adds area in low and moderate severities.

The red fir fire-regime type had a low-fire-severity distribution. Although high-fire-severity patches in red fir can occur, they generally cause a shift in the vegetation type from red fir to upper montane chaparral that will eventually shift back to red fir (Chang 1996; van Wagtendonk and Fites-Kaufman 2006). This conversion to a shrub-field can happen within 5 years, as the primary shrub species are *Ceanothus* spp. that have scarified seeds with a tremendous post-fire response. Because we used a 1997 vegetation map to create the fire-regime types, red fir patches that did burn with high severity before 1997 would appear as upper montane chaparral. This would reduce the amount of high severity shown in the red fir distribution. The red fir fire regime has longer fire return intervals (Pitcher 1987) and crown fires occur only under extremely dry and windy conditions (van Wagtendonk and Fites-Kaufman 2006). Wind-driven crown fires would result in larger patches of high burn severity. However, the probability of many high-severity events occurring between 1984 and 2003 in the red fir fire-regime type was fairly low. Thus, this distribution may need a longer time frame and earlier vegetation maps to get a better representation of the actual severity distribution on the landscape.

The Jeffrey pine–shrub fire-regime type had a distribution with a higher median than its non-shrub equivalent, upper montane Jeffrey pine–western white pine. This is a logical result as the shrub component would increase the intensity and severity of fire. The distribution for the Jeffrey pine–western white pine fire-regime type is low to moderate. Jeffrey pine

generally has less frequent fire with more variable fire return intervals than lower-elevation pine forests but more frequent fire than red fir forests (Skinner and Chang 1996).

The quaking aspen fire-regime type also showed a low-to-moderate severity distribution. Quaking aspen was primarily associated with the upper montane fire-regime types and bare rock. In particular, upper montane red fir, chaparral, Jeffrey pine–shrub and Jeffrey pine–western white pine were co-located with the aspen patches. The red fir and Jeffrey pine–western white pine types both had severity median values ~100 points less than quaking aspen. The Jeffrey pine–brush type had a median approximately equal to the aspen and the chaparral type had a median value almost 300 points more than quaking aspen. Aspen tends to burn only when fires come in from adjacent vegetation. Thus, it makes sense that the small patch sizes of aspen are more easily affected by the surrounding fire-regime types, and the distribution seen here is a mix of those types. In addition, the size and amount of aspen resprouts 1 year post-fire could also help to explain this distribution. The more regrowth and green vegetation on the ground, even if short in stature, the lower the RdNBR number will be.

Subalpine forest zone

Both the fire-regime types in the subalpine zone had low-severity distributions. Virtually all of the area burned in whitebark pine–mountain hemlock burned as low or unchanged severity. Burning conditions in the whitebark pine–mountain hemlock are so poor that even if a fire is ignited, it either goes out or burns with very low intensity owing to a lack of available fuel.

The lodgepole pine distribution peaks within the low-severity range. Fires in lodgepole pine in Yosemite tend to burn as small fires of low severity the majority of the time, and only in extremely dry conditions do crown fires occur. This is due to compact fuel beds and the frequent occurrence of a mesic herbaceous understorey (van Wagtendonk and Fites-Kaufman 2006). During the 20-year time frame of the present study, only 3.7% of the land-base of lodgepole pine burned and over 50% of it burned as low-severity or was in the unburned category. This is different than lodgepole pine found in much of the western United States. Parker (1986) showed that unlike lodgepole pine in the Rocky Mountains, crown fires were not a large factor in creating stand structures in Sierra Nevada lodgepole pine, and found that since the inception of fire records (1930), no crown fires have occurred in the lodgepole pine forests in Yosemite. The severity distribution found in the current study corroborates Parker's work. The amount of area burned during extreme conditions could be expected to be large and possibly wind-driven. Such a situation may not occur frequently, but may burn larger patches than low- or moderate-severity fires. Hence, one or a few very infrequent crown fires could fill in the high side of the severity distribution, creating a bimodal distribution, which is what was hypothesised by van Wagtendonk and Fites-Kaufman (2006). Based on the data in the present study and Parker's (1986) study, this has not happened on the landscape in the last 75+ years. The distribution does have a fat, long tail in the high-severity realm, showing some high-severity events across the landscape, but they have not added up to much land area.

Two factors come into play when assessing the distributions created from this study. The first is the time frame of the assessment. It is likely not long enough for higher-elevation infrequent fire-regime types. The second is the use of a 1997 vegetation map. Some vegetation types convert back to shrub-based systems after high-severity fire. This occurred with red fir but may also be an issue in white fir and ponderosa pine. The distributions for these fire-regime types likely underestimate high severity in fires that were before 1997, as the high-severity areas pre-1997 will be counted as pixels in the chaparral distributions.

Conclusions

This study is a first attempt at quantifying the distribution of effects by fire-regime types for a large landscape over recent decades. The severity distributions described in this study can form a building block from which to discuss current fire regimes across the Sierra Nevada. When current conditions are not significantly different than past conditions, these distributions can give valuable insight into the true severity of historical fire regimes. The distributions can also be used to assess how current conditions are different than our notions of historic severity distributions, and how they differ from our desired future conditions. Although there is a general desire to manage ecosystems to more resemble 'historic' conditions, we have not had good metrics for measuring either the degree to which present conditions differ from past conditions, or, by the same token, our progress towards attaining desired future conditions. The use of imagery allows us the first full-landscape, data-driven assessment of the variability in fire severity on an appropriate scale and establishes a framework for doing so and provides a powerful tool that can be used by land management agencies and fire managers.

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