Research Article

Fire Frequency, Area Burned, and Severity: A Quantitative Approach to Defining a Normal Fire Year

James A. Lutz[1*], Carl H. Key[2], Crystal A. Kolden[3], Jonathan T. Kane[1], and Jan W. van Wagtendonk[4]

[1]College of the Environment,
Box 352100, University of Washington, Seattle, Washington 98195-2100, USA

[2]US Geological Survey, Northern Rocky Mountain Science Center, Glacier Field Station,
P.O. Box 128, West Glacier, Montana 59936, USA

[3]Department of Geography, University of Idaho,
P.O. Box 443021, Moscow, Idaho 83844, USA

[4]US Geological Survey (retired), Western Ecological Research Center, Yosemite Field Station,
P.O. Box 700, El Portal, California 95318-0700, USA

[*]Corresponding author: Tel.: 001-206-616-3827; e-mail: jlutz@uw.edu

ABSTRACT

Fire frequency, area burned, and fire severity are important attributes of a fire regime, but few studies have quantified the interrelationships among them in evaluating a fire year. Although area burned is often used to summarize a fire season, burned area may not be well correlated with either the number or ecological effect of fires. Using the Landsat data archive, we examined all 148 wildland fires (prescribed fires and wildfires) >40 ha from 1984 through 2009 for the portion of the Sierra Nevada centered on Yosemite National Park, California, USA. We calculated mean fire frequency and mean annual area burned from a combination of field- and satellite-derived data. We used the continuous probability distribution of the differenced Normalized Burn Ratio (dNBR) values to describe fire severity. For fires >40 ha, fire frequency, annual area burned, and cumulative severity were consistent in only 13 of 26 years (50 %), but all pair-wise comparisons among these fire regime attributes were significant. Borrowing from long-established practice in climate science, we defined "fire normals" to be the 26 year means of fire frequency, annual area burned, and the area under the cumulative probability distribution of dNBR. Fire severity normals were significantly lower when they were aggregated by year compared to aggregation by area. Cumulative severity distributions for each year were best modeled with Weibull functions (all 26 years, $r^2 \geq 0.99$; $P < 0.001$). Explicit modeling of the cumulative severity distributions may allow more comprehensive modeling of climate-severity and area-severity relationships. Together, the three metrics of number of fires, size of fires, and severity of fires provide land managers with a more comprehensive summary of a given fire year than any single metric.

Keywords: differenced Normalized Burn Ratio, fire severity, fire severity normals, Sierra Nevada, Weibull distribution, Yosemite National Park

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INTRODUCTION

Fire frequency, fire extent, and fire severity are three of the seven fire regime attributes of particular importance to ecologists and land managers (Sugihara *et al*. 2006) who closely monitor changes and trends in natural processes. Changes in fire regimes can alter vegetation type (van Wagtendonk and Fites-Kauffman 2006), species composition (Lutz *et al.* 2009*b*), forest structure (Peterson *et al.* 2005), and regeneration patterns (Swanson *et al.* 2011), which in turn all affect carbon cycling (Hurteau and North 2010), smoke production (Tarnay and Lutz 2011), vertebrate habitat (Roberts *et al.* 2008), and recreation amenity values (Boxall and Englin 2008). Changing fire regimes also impact efforts to manage (Kolden and Brown 2010) and suppress fire. Projections of increased fire activity associated with climate change (e.g., Littell *et al.* 2010, Wotton *et al.* 2010) have increased the need to develop historical fire regime baselines and methods to monitor change. However, few frameworks have been proposed to help land managers quantitatively examine these changes over time or between areas. We propose a set of fire regime metrics—annual fire frequency, annual area burned, and cumulative fire severity distribution—that can be monitored on a purely statistical basis using data available from the Monitoring Trends in Burn Severity (MTBS) database (Eidenshink *et al.* 2007).

The MTBS database provides Landsat-based, 30 m resolution fire severity data and fire perimeters for wildfires in the US from 1984 to present. From the MTBS data, it is possible to quantify the number of large fires (i.e., those above a specified size threshold) for a region of interest, and extract its area burned and severity. The quantity of fires above a certain size threshold (likely to vary based on the specifics of the ecosystem) is important to land managers dealing with logistics and costs of fire and air quality monitoring and, if necessary, suppression. The quantity of fires may also give some indication of the distribution of burned areas within the study region. Area burned is the most commonly monitored wildfire metric and represents that portion of the landscape that has been burned by fire. Area burned is most often quantified by the mapped fire perimeter area rather than the actual area burned within the fire perimeter (e.g., Westerling *et al.* 2006, Morgan *et al.* 2008), which may overestimate the actual burned area (Kolden and Weisberg 2007). Using satellite measurements of burned area and severity is significantly more accurate than using mapped perimeters (Kolden and Weisberg 2007), especially if fire perimeters were approximated by aerial observers. Fire severity approximates the immediate ecological effect of a fire on vegetation and soil. It is distinct from fire intensity, which is a measure of the energy released by the fire (in kW m^{-1}) (van Wagtendonk 2006). Correlations between fire intensity and fire severity vary depending on specifics of vegetation, fuel loading, and fire behavior (Sugihara *et al.* 2006). Fire severity gives an indication of post-fire conditions within the area burned, regardless of whether that area is large or small (Lentile *et al*. 2006). Fire severity, although important ecologically, has been more difficult to quantify and standardize due to varying objectives and perceptions, and most analyses have either ignored it or considered broad severity classifications (i.e., low versus high severity) (see Lentile *et al.* 2006 for examples in different ecosystems).

Area burned can be considered for an individual fire or for an entire fire year (the superimposition of all fires for that year). Within a burned area, some portions burn at comparatively higher and some at comparatively lower severities. Fire severity can be measured through ground observations at localized sites (Key 2006, Key and Benson 2006), but is more commonly measured at broader spatial scales through satellite-derived proxy indices of fire severity, most commonly, the differenced Normalized Burn Ratio, dNBR (Key and Benson 2006). Using data acquired by Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper-plus (ETM+), dNBR is calculated from the near-infrared (Landsat band 4) and the mid-infrared (Landsat band 7), providing 30 m spatial resolution (one pixel = 0.09 ha). The dNBR compares the difference between pre-fire and post-fire Landsat scenes (dNBR = $NBR_{PRE} - NBR_{POST}$); where NBR = $([B_4 - B_7] \div [B_4 + B_7])$, and where B_4 and B_7 represent reflectance values). The dNBR can range between –2.0 and 2.0. Over natural landscapes, however, non-anomalous dNBR values typically have a more limited range of about –0.6 to 1.2., which is usually scaled by a factor of 1000. High values of dNBR represent a combination of a decrease in the reflectance of Landsat B_4, indicating primarily a decrease in photosynthetic materials, and an increase in the reflectance of Landsat B_7, indicating an increase in ash, carbon, and soil, as well as a decrease in surface materials holding water. In most burned areas, the dNBR value of all pixels follows a smooth cumulative probability distribution (Figure 1). Fire severity can also be derived from other satellite indexes such as the relative differenced Normalized Burn Ratio (RdNBR) (Miller and Thode 2007). The RdNBR provides a means of nomalizing satellite-derived fire severity values across vegetation types or between stands of different ages or productivities. The RdNBR value of all pixels also follows a smooth cumulative probability distribution (Thode *et al.* 2011).

Satellite-derived dNBR is most commonly stratified into four burn severity categories (high, moderate, and low severities; and no detected change), with subsequent analysis performed on the four classification levels or upon the simple area burned (Miller and Thode 2007, Miller *et al.* 2008, Lutz *et al.* 2009*a*). Demarcations between severity levels are ideally determined after extensive ground verification of the effect of fire on each vegetation type (e.g., Thode *et al.* 2011). Classifying severity data without detailed ground information has the potential to distort the interpretation of fire severity, particularly in the highest and lowest classifications, or where vegetation types or stand ages are closely intermixed. Furthermore, classification of any continuous variable into discrete bins sacrifices information and, thereby, increases noise in subsequent analyses. Classification is also sensitive to potentially differing interpretations made by remote sensing analysts and field ecologists (Spies *et al.* 2010), suggesting that a statistical

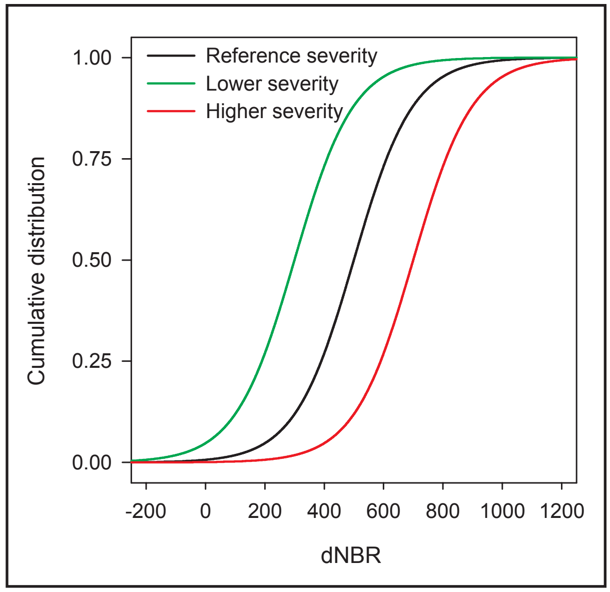

Figure 1. Cumulative distributions of fire severity for a reference area, and for areas that burned with lower and higher severities. Compared to the curve of reference severity (black), the lower severity curve (green) has few high severity pixels. Conversely, the higher severity curve (red) shows an area that burned with more higher severity pixels. These model curves are of the form: $y = \frac{1}{1 + e^{-(dNBR - a)}}$.

approach would be more robust, at least for sufficiently large areas (Hudak *et al*. 2007).

Evaluation of the fire severity distribution itself (Figure 1) can serve as a quantification of the severity of an entire burned area, whether that area represents a single fire or all the fires in a given fire year. The area under the cumulative severity distribution curve decreases as the number of pixels burned at relatively higher severity (i.e., have higher dNBR values) increases (Figure 1). A quantitative metric that both represents the overall severity of the area burned and that increases with severity is one minus the area under the curve, with higher values of this metric indicating a higher cumulative severity distribution. The discrete nature of dNBR values and the variability inherent in real world data suggest that data be aggregated between reasonable possible values of dNBR, limits that will vary between ecoregions.

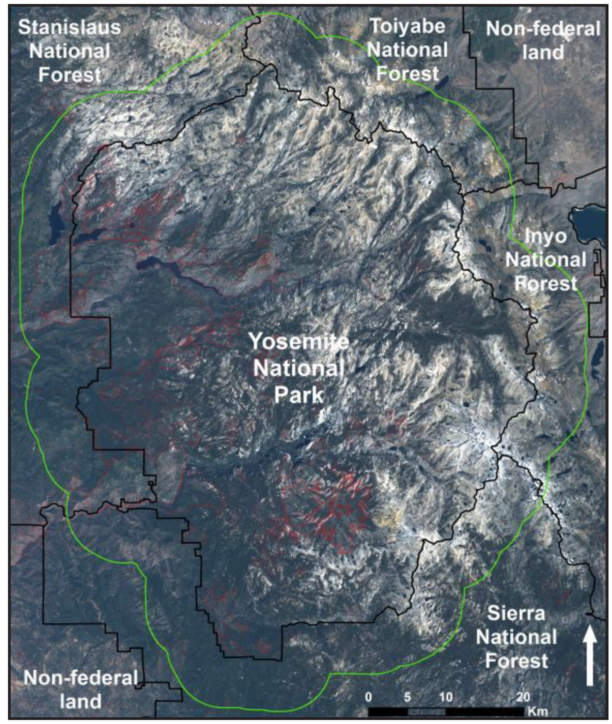

Figure 2. Land management and forest cover within the Yosemite study area. The 4771 km^2 study area (green outline) comprises Yosemite National Park and portions of the Stanislaus, Toiyabe, Inyo, and Sierra national forests—areas with low levels of anthropogenic disturbance. Perimeters for fires >40 ha between 1984 and 2009 are shown in red. Landsat 5 Thematic Mapper scene from 16 August 2010 (bands 3, 2, 1).

METHODS

Study Area

Yosemite National Park is a contiguous management unit of 3027 km^2 located in the central Sierra Nevada, California, USA. Yosemite experiences multiple wildland fires (prescribed fires and wildfires) each year and, since 1972, many naturally ignited fires have been allowed to burn under prescribed conditions (van Wagtendonk 2007). In adjacent lands managed by the Forest Service, most fires are suppressed. Our study area (hereafter referred to as Yosemite) included the area of the park and a buffer radiating 6.5 km from the park boundaries (4771 km^2) (Figure 2). The buffer was selected to maximize the size of the study area while minimizing non-forest cover and developed areas. The study area is in federal ownership (Yosemite National Park, Stanislaus National Forest, Toiyabe National Forest, Inyo National Forest, and Sierra National Forest) with the exception of small inholdings. Yosemite's climate is Mediterranean. July mean minimum and maximum temperatures are 2 °C to 13 °C at higher elevations and 16 °C to 35 °C at lower elevations. Annual precipitation ranges from 800 mm to 1720 mm, with most precipitation falling in the winter as snow (Lutz *et al.* 2010).

The forest vegetation of Yosemite comprises a mosaic of forest types, species, and structural stages (van Wagtendonk and Fites-Kaufman 2006, Fites-Kaufman *et al.* 2007). The lower elevation portions of the park include shrub patches, shrub fields, and woodland as well as forests. The Sierra Nevada fire regime is mixed; fires burn with patches of high, moderate, and low severities at intervals ranging from years to centuries (Agee 1993, van Wagtendonk *et al*. 2002, Sugihara *et al.* 2006*a*, van Wagtendonk and Fites-Kaufman 2006, van Wagtendonk and Lutz 2007). Fire intensity and severity vary by forest type (van Wagtendonk *et al.* 2002, Thode *et al.* 2011). The natural fire return interval for the forested ecosystems of Yosemite National Park ranges from 4 yr to 187 yr (Caprio and Swetnam 1995, Caprio and Lineback 1997, van Wagtendonk *et al.* 2002, Collins and Stephens 2007).

Fire Severity Data

Satellite fire severity data (dNBR) were obtained from MTBS. We first obtained fire perimeters from Yosemite National Park (National Park Service 2010) and from the Forest Service (USDA 2010). Using the area burned from the fire perimeter data, we determined that 84 % of area burned is accounted for by fires ≥400 ha (the standard minimum fire size for MTBS in the western US), while 97 % of the area burned is accounted for by fires ≥40 ha. We therefore set 40 ha as the minimum fire size for analysis. We examined all Landsat scenes with <10 % cloud cover for the Yosemite study area in Landsat Worldwide Reference System (WRS) path 42, row 34, and path 43, row 34, between June and August (inclusive) for the years 1984 through 2010. For each fire, we selected the pre-fire and post-fire scene pair that was best matched for a combination of plant phenology and sun angle after Key (2006). The MTBS project then produced dNBR data for the fires within those scenes. When fires extended beyond the study area boundaries, we clipped the fire perimeters to the study area. The raw dNBR values calculated by MTBS were adjusted by the dNBR offset (a measure of the average difference in dNBR values between unburned portions of the pre-fire and post-fire Landsat scenes). When satellite data indicated that actual area burned exceeded the mapped fire perimeters, as inferred from a dNBR value >150, we extended fire perimeters to include those pixels. We tabulated area burned in multiples of the 0.09 ha Landsat pixels.

Data Reduction and Analysis

We constructed cumulative distributions of burn severity using all the Landsat pixels within the fire perimeters for each year between 1984 and 2009. We then compared each year's cumulative severity distribution with an average severity distribution for all years. We calculated the average severity distributions in two different ways: one that gave more weight to years with greater area burned, and one that gave equal weight to each year in the study period. To determine the overall cumulative severity distribution of all fires, we aggregated all burned pixels for the entire study period (areal averaging). To determine an annual normal distribution, we aggregated all fires >40 ha in each year, and then combined them with equal weight (yearly averaging). Preliminary analysis showed that >99 % of dNBR pixel values fell in a dNBR range of –200 to 1200. Therefore, we constructed severity distributions using only pixels with dNBR values between –200 and 1200, using the actual dNBR values (no binning). We approximated an integration of these cumulative severity distributions by calculating the area under each distribution for each year to generate a single number representative of the shape of the severity distribution. We represented our severity metric (SM) as one minus the area under the curve so that higher numbers reflect higher severity. We calculated:

$$SM = 1 - \sum_{i=-200}^{1200} \frac{Proportion\ of\ pixels\ \leq i}{1401} \quad (1)$$

In addition to the yearly and areal averages, we also used the dNBR range of –200 to 1200 to fit sigmoid (Equation 2), logistic (Equation 3), and Weibull (Equation 4) functions (Weibull 1951) to each year's burned area. Because the Weibull distribution is single-sided (having a zero value at some lower limit [Equation 4]), we hypothesized that it might better model the transition between unburned and burned. Data were fit to the equations with SigmaPlot Version 11.0 (Systat Software, Chicago, Illinois, USA) with x_0, b, and c being the shape parameters of the equations. We bounded the data range to less than the maximum range of dNBR so as to avoid overstating the goodness of fit.

$$y = \frac{1}{1 + e^{-\left(\frac{x - x_0}{b}\right)}} \tag{2}$$

$$y = \frac{1}{1 + \left(\frac{x}{x_0}\right)^b} \tag{3}$$

$$y = 1 - e^{-\left(\frac{x - x_0 + b \ln 2^{\frac{1}{c}}}{b}\right)^c}; \tag{4}$$

$$x > x_0 - b \times \ln (2)^{\frac{1}{c}}$$

For each value of fire frequency, area, and severity, we classified each year into quartiles, considering the first quartile as low, the middle two quartiles as normal, and the upper quartile as high. We compared our purely statistical division of dNBR fire severities with the classified fire atlas based on RdNBR from van Wagtendonk and Lutz (2007). We limited the comparison to fires covered by both studies. The comparison therefore was limited to the years 1984 through 2005, to fires within or crossing the Yosemite National Park boundaries, and to the 6.5 km buffer around the park.

RESULTS

From 1984 through 2009, there were 148 fires >40 ha in the Yosemite study area. The average area burned per year in fires >40 ha was 4144 ha (Table 1). Cumulative distributions of dNBR severity values between –200 and 1200 were best modeled by Weibull func-

Table 1. Annual fire statistics for fires >40 ha in the Yosemite study area, 1984 to 2009, and comparisons among fire regime metrics. Area burned represents the area of Landsat pixels (0.09 ha) either within the reported fire perimeter or outside and adjacent to the reported perimeter with dNBR ≥ 150. The frequency, area burned, and severity of fires are classified by quartile (L = lowest quartile, M = middle 50 %, H = upper quartile). The years with the most extensive annual area burned are associated with high cumulative severity, and the years with low annual area burned are associated with low cumulative fire severity. However, the years with an annual area burned in the middle 50 % are associated with all levels of cumulative burn severity. The three metrics of frequency, area, and severity were consistent in 13 of 26 years (bold).

Year	No. fires >40 ha	Area fires >40 ha (ha)	Severity§	Comparison with middle 50 % of years†		
				No. fires	Area (ha)	Severity (pixel)
1984	6	795	0.20	M	L	L
1985	11	3 395	0.24	H	M	M
1986	4	1 789	0.25	**M**	**M**	**M**
1987	10	12 925	0.35	**H**	**H**	**H**
1988	15	6 550	0.25	H	H	M
1989	1	698	0.17	**L**	**L**	**L**
1990	8	10 909	0.36	**H**	**H**	**H**
1991	4	2 718	0.27	**M**	**M**	**M**
1992	4	538	0.21	M	L	L
1993	1	488	0.20	**L**	**L**	**L**
1994	4	2 412	0.21	M	M	L
1995	3	407	0.25	L	L	M
1996	6	24 812	0.34	M	H	H
1997	3	1 656	0.26	L	M	M
1998	3	1 008	0.21	**L**	**L**	**L**
1999	11	7 257	0.25	H	H	M
2000	1	144	0.16	**L**	**L**	**L**
2001	1	3 018	0.28	L	M	H
2002	5	2 348	0.22	**M**	**M**	**M**
2003	10	5 253	0.31	**H**	**H**	**H**
2004	4	3 846	0.29	M	M	H
2005	10	1 935	0.24	H	M	M
2006	7	3 124	0.25	**M**	**M**	**M**
2007	6	1 228	0.21	**M**	**M**	**M**
2008	6	2 933	0.28	**M**	**M**	**M**
2009	4	5 546	0.29	M	H	H

† L = annual value lower than the middle 50 % of years, M = within the middle 50 % of years, H = annual value higher than the middle 50 % of years.

§ Severity metric (SM) calculated from the cumulative distribution of severity for each year as:

$$SM = 1 - \sum_{i=-200}^{1200} \frac{Proportion\ of\ pixels\ \le i}{1401}$$

tion (Equation 4). All years, as well as areal and yearly aggregations, could be described by this function, with every year and the areal and yearly averages having an $r^2 \geq 0.993$ and $P < 0.001$. The logistic function (Equation 3) was not a good fit when x_0 approached zero (in 1992 and 1994). The sigmoid functions had lower adjusted r^2 than the Weibull function in every year.

Cumulative distribution of fire severity varied among years (Figure 3, Table 2). The average cumulative distribution of severity for all years differed significantly (KS-test, $P < 0.001$) whether the average was calculated on a yearly or areal basis, confirming the potential differences between annual and areal averaging. On an areal basis, the mean dNBR severity in Yosemite was 158, with lower and upper quartiles at 65 and 313 (Figure 4). On a yearly basis, the mean dNBR severity in Yosemite was 102, with lower and upper quartiles at 33 and 214. Calculating SM between dNBR values of –200 and 1200 yielded values of SM from a minimum of 0.16 in 2000 to a maximum of 0.36 in 1990. The areal SM was 0.30 and the yearly SM was 0.25. Years with low severity distributions were characterized by lower area burned, and years with high severity distributions were characterized by greater area burned (Figure 3, Table 1). However,

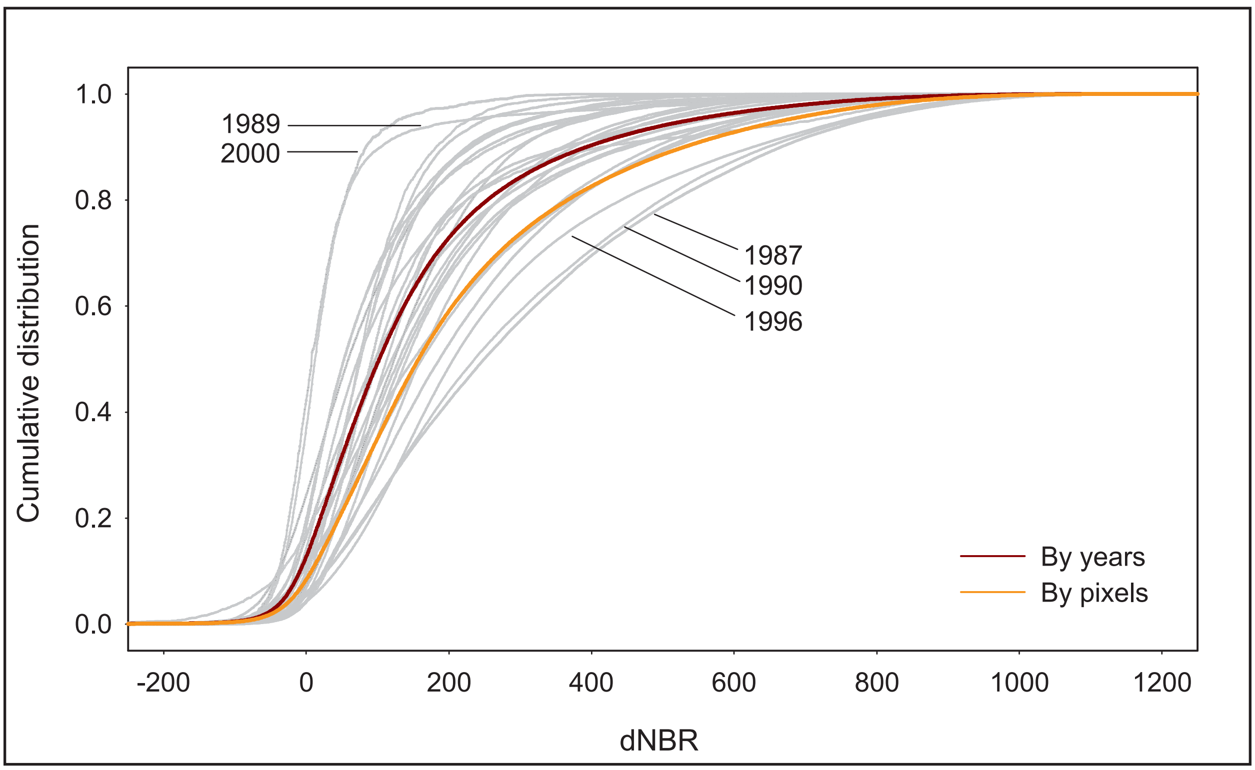

Figure 3. Cumulative fire severity for all fires >40 ha that burned in each year between 1984 and 2009 (gray lines). Each gray line represents the cumulative severity distribution for one fire year. The annual average cumulative severity (each fire year weighted equally) is shown in red. The cumulative severity for the entire area burned by all fires >40 ha in the Yosemite study area between 1984 and 2009 is shown in orange. The two years with the lowest cumulative severity (2000, SM = 0.16; and 1989, SM = 0.17) are at left; the three fire years with the highest cumulative severity (1987, SM = 0.35; 1990, SM = 0.36; and 1996, SM = 0.34) are at right. The year with the least burned area (2000) also had the lowest cumulative severity, but the year with the most area burned (1996) was third in cumulative severity. The years 1987 and 1990 had higher cumulative severities reflecting the lower elevation and more severe fire regimes of the vegetation (mixed forest and shrubs).

Table 2. Weibull parameters for area burned by fires >40 ha in Yosemite between 1984 and 2009. The data illustrated in Figure 3 were fit to a curve of the form:

$$y = 1 - e^{-\left(\frac{x - x_0 + b\ln 2^{\frac{1}{c}}}{b}\right)^c}$$

All P values < 0.001.

Year	b	c	x_0
1984	118.7810	1.0810	54.2297
1985	146.1845	0.8969	75.6685
1986	153.8405	0.9766	92.2235
1987	387.9411	1.4239	243.9727
1988	200.7272	1.0391	97.7872
1989	67.3086	1.0719	9.5990
1990	416.7735	1.4848	253.9185
1991	227.3193	1.1967	135.0312
1992	123.2930	0.9445	52.3423
1993	123.8919	1.6866	74.1267
1994	168.1034	1.2922	59.4338
1995	193.2867	1.0225	94.6221
1996	291.1345	1.1743	212.7715
1997	211.6579	1.3631	131.3029
1998	138.9025	1.6552	75.9263
1999	220.8271	1.3292	121.1346
2000	83.7842	1.5352	1.5352
2001	186.6766	1.0194	140.9227
2002	137.7264	1.4858	90.4649
2003	282.6585	1.3200	187.2860
2004	293.9449	1.2722	153.6713
2005	161.8939	1.3377	111.8003
2006	205.0641	1.6230	123.5403
2007	123.0021	1.2231	75.7596
2008	238.3653	1.5045	160.7112
2009	305.4238	1.4179	165.9796
All pixels†	262.1238	1.1511	160.3395
All years‡	185.5725	1.0499	101.7855

† All burned pixels from all years aggregated.
‡ All burned pixels within one year aggregated, and then years averaged.

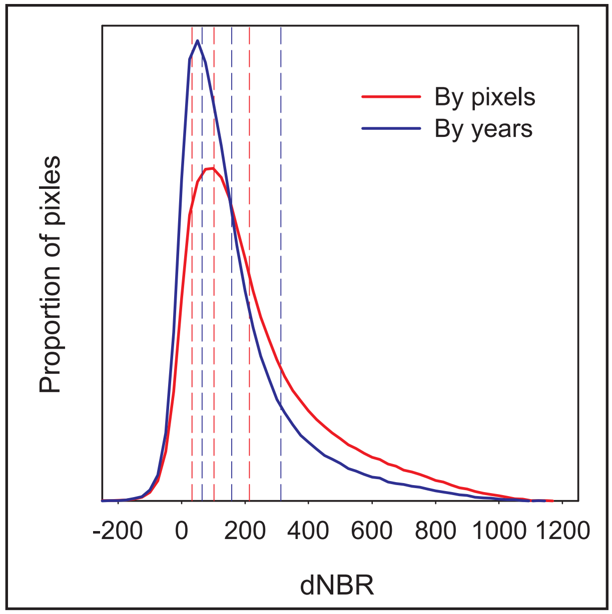

Figure 4. Distribution of fire severity for the Yosemite study area. All dNBR pixels from fires >40 ha from 1984 through 2009 are included. Vertical lines delineate the severity quartiles for all area burned between 1984 and 2009.

those fire regime attributes relating frequency, area, and severity were only consistent in 13 of 26 years (Table 1). Although the three metrics were not consistently related, the individual pair-wise comparisons among variables were significant (Figure 5). Greater numbers of fires were associated with larger annual area burned (r^2 = 0.34, P = 0.001) and with higher

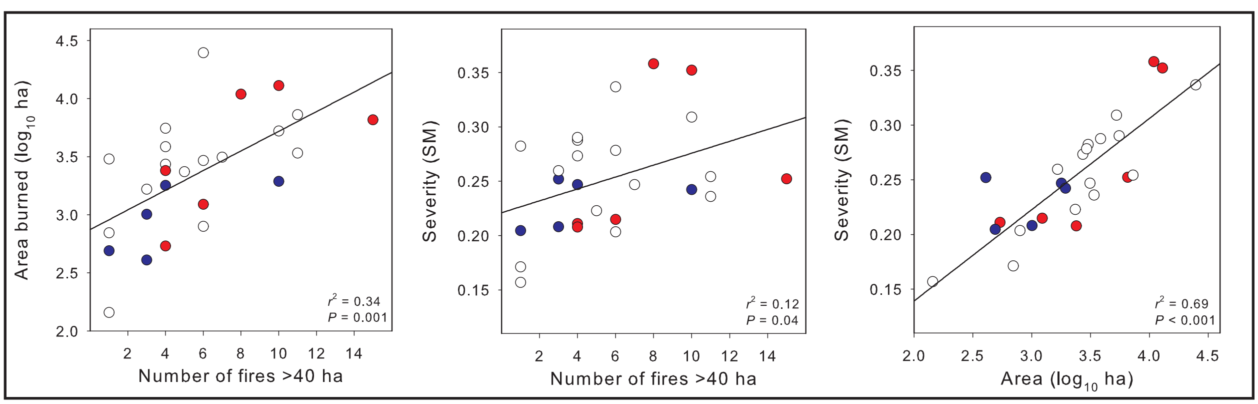

Figure 5. Relationships among number of fires >40 ha, area burned by fires >40 ha, and severity distributions of fires >40 ha in the Yosemite study area for each year between 1984 and 2009. Points shown in red indicate years with low snowpack (*sensu* Lutz *et al.* 2009*a*) and points shown in blue represent years with high snowpack.

annual burn severity as measured by SM (r^2 = 0.12, P = 0.04). The strongest relationship was between annual area burned and SM (r^2 = 0.69, P < 0.001). Between 1984 and 2009, there was no trend in the frequency, area, or severity of fires >40 ha (all r^2 < 0.01, all P > 0.5) in the Yosemite study area (Figure 6).

The purely statistical approach to severity classification (quartiles) was consistent with the classified RdNBR values for the fires in common between the MTBS and previous fire atlas. In comparing the two fire atlases, the MTBS processing of fire severity between 1984 and 2005 yielded 92 374 ha of burned area. The previous Yosemite fire atlas yielded 94 405 ha. The simple quartile numbers understated severity (Table 3). However, the correspondence between classes was high, and the spatial structure of severity patches was consistent between the two approaches (Figure 7).

DISCUSSION

Fire Severity and Annual Area Burned

The years with the most extensive annual area burned are associated with high cumulative severity, and the years with low annual area burned are associated with low cumulative fire severity (Table 1). However, the association often depends on the size of large fires and the vegetation type in which the fire burns. The lower elevation portions of the study area with more shrub cover burn at higher aggregate severity (Thode *et al.* 2011). Fires originating in these lower elevation forests

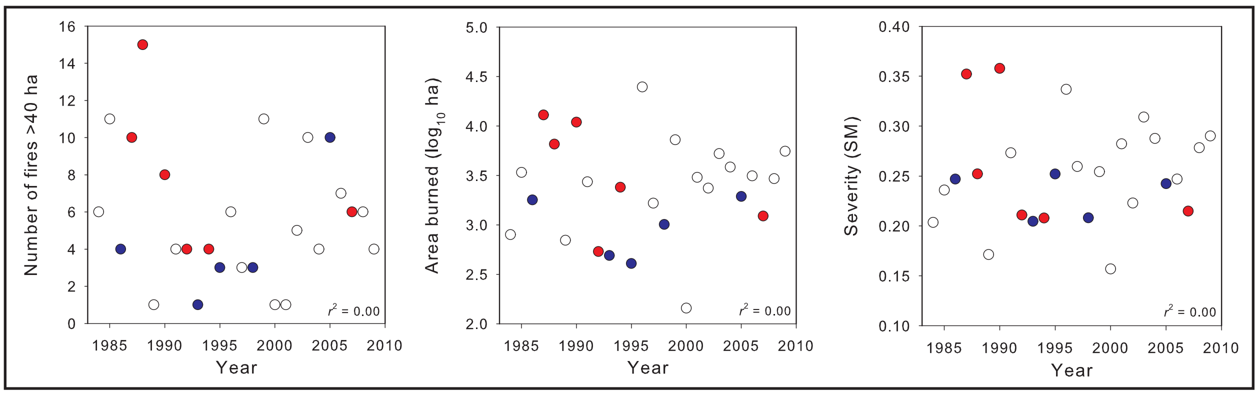

Figure 6. There is no temporal trend in number of fires >40 ha, area burned by fires >40 ha, and severity distributions of fires >40 ha in the Yosemite study area between the years of 1984 and 2009. Points shown in red indicate years with low snowpack (*sensu* Lutz *et al.* 2009*a*) and points shown in blue represent years with high snowpack. The scale of the study area (4771 km^2) is likely too small to discern statistically significant temporal trends.

Table 3. Comparison between severity quartiles and classified severity between 1984 and 2005. The classified severity (from van Wagtendonk and Lutz 2007) uses a fire atlas originally developed by Thode (Miller and Thode 2007, Thode *et al.* 2011). The present study used the MTBS fire atlas. The comparison is for the burned areas of fires covered by both studies.

	Outside perimeter	Lowest quartile	Low-mid quartile	High-mid quartile	Highest quartile
		ha			
Outside perimeter	0.0	225.3	111.2	62.7	24.4
Unchanged	307.5	728.9	287.6	135.7	38.9
Low severity	224.9	887.6	962.9	617.5	25.8
Moderate severity	81.5	388.4	781.0	1195.3	916.0
High severity	12.7	68.9	109.6	279.4	1228.4

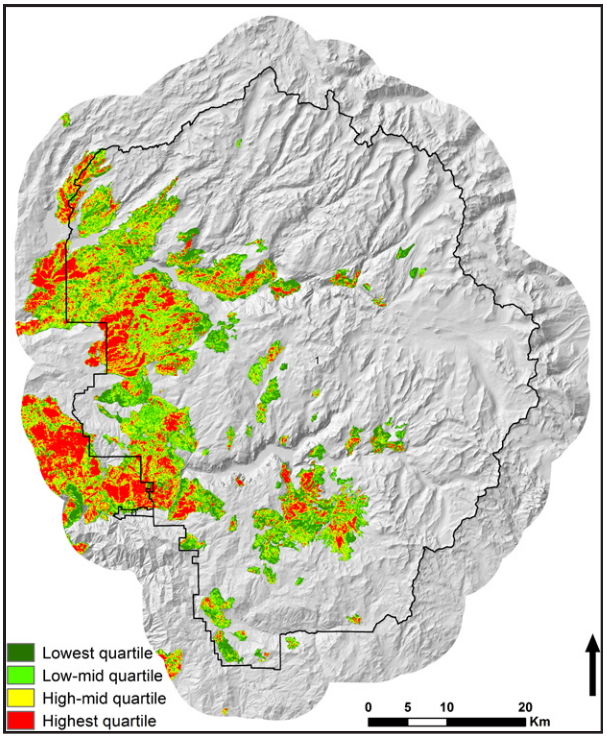

Figure 7. Fires in the Yosemite study area >40 ha between 1984 and 2009 stratified by dNBR quartiles. Quartiles were determined from all burned area over the 26 yr study period. Where areas were reburned, the severity of the most recent fire is shown.

have often been large (1987, 1990, and 1996), and the effect of vegetation type on fire severity distribution seems more important than the effect of fire area (details in Thode *et al.* 2011). The year with the greatest area burned (1996) had SM = 0.35. However, fire years 1987 and 1990, which had approximately half the area burned of 1996, featured equivalent or higher severity (SM = 0.38 and 0.35). These two years had very low levels of spring snowpack. All three of these fires burned in lower mixed conifer forest types, but the 1996 fire year featured higher area burned in closed canopy forest, and the 1987 and 1990 fire years burned in areas vegetated with mixed forest, woodland, and chaparral.

Lower quantities of area burned were more closely associated with lower cumulative burn severity, presumably because conditions not conducive to fire spread are also not conducive to more complete vegetation consumption. The two years with the lowest SM (1989 and 2000) featured only one fire >40 ha (Table 1, Figure 3). Furthermore, these fires were management-ignited prescribed burns, which usually have lower severities (van Wagtendonk and Lutz 2007). Although we did not detect temporal trends in fire frequency, area, or severity, we cannot discount that such trends may exist. Rather, the high interannual variability of fires in the immediate Yosemite area (Table 1, Figures 5 and 6), partially driven by spring snowpack, masks any gradual trend (Lutz *et al.* 2009*a*). Larger spatial scales (e.g., Miller *et al.* 2008) or a longer data record would be necessary to confirm fire regime trends.

Modeling Continuous Fire Severity Distributions

We found the cumulative severity distributions to be very amenable to approximation by continuous functions (Equation 4, Table 2). Although these equations had $r^2 > 0.99$, the residuals were not normally distributed (as would be expected from a cumulative distribution). Therefore, Equation 4 may not model what may be important secondary fire regime attributes, nor may it model ecosystems with multimodal cumulative severity distributions. Our objective in seeking a continuous equation was to represent severity distributions in a way that could be easily manipulated with parameters that could be correlated with climate and vegetation. Although Equation 4 represents severity well, all the Weibull shape parameters (Table 2) are needed to characterize the severity distributions (Figure 3). The single-number approximation from Equation 1 may be as useful, and because it is easier to calculate (see Appendix), may be a convenient and useful tool for land managers.

Local Land Management through Time

We borrowed the "fire normals"—the long-term average values of multiple fire parameters from a geographic area—approach from climatology, where characterizations of climate conditions are most frequently framed as departures from a multidecadal mean, or normal. Our approach in delineating fire severity distributions into quartiles responds to a statistic commonly used in a number of disciplines. Rather than quartiles, it could just as effectively be based on some other percentile if there is ecological justification to do so, but whatever the case, the approach remains well defined and repeatable. There are several important advantages and limitations. The principal advantage is that it can be done automatically, without need to analyze the specific vegetation related correlates of fire severity; the approach is entirely statistical and does not rely on expert judgment. A purely quantitative approach avoids any possibility of bias in the selection of burn severity thresholds. As fire effects information becomes increasingly integrated by third parties into ecological research, resource management, and policy, it will be ever more important to ensure that severity data are not misused by advocates for particular policies. However, this statistical approach is only relevant within a particular study area. Accurate interpretation of satellite-derived fire severity requires calibration with local field data.

The results permit a comparison through time, but there can be little, if any, extrapolation to other geographic areas (Table 3, Figure 7). On the other hand, such aspects of fire regimes in one region can be compared to other regions with some quantifiable and meaningful interpretation of the differences or similarities. A fire normals approach also requires a sufficient period of time so that the fire regime can be adequately represented. The climatological community commonly uses 30 yr periods to describe climate normals for a region. The Landsat-derived dNBR record of 26 yr, used here, approximates that period. A fire normals approach also requires judgment in selecting an area and a set of fires that is sufficiently characteristic of the area for the summary statistics to be of immediate use to land managers. Provided that these conditions are met, land managers tasked with understanding local changes can use these fire normals to compare individual fires and fire years to the historical record. In this study area, the purely statistical approach gives equivalent results to fire-by-fire classification (Table 3, Figure 6).

The lack of this fire-by-fire analysis of fire effects also constitutes the greatest weakness to this approach. Without fire-by-fire analysis of pre-fire vegetation and fire effects, inferences from the raw dNBR values could be incorrect. There is no inherently ecological reason for considering a certain dNBR population percentile to represent a particular level of severity. Inferring ecological effects of satellite-derived severities depends on vegetation type (Thode *et al.* 2011), time since previous fire (Miller and Thode 2007, Thompson *et al.* 2007, Larson *et al.* 2008), and the nature of post-fire regeneration (Key 2006; Kane *et al.* 2008, 2010). In addition, while dNBR is well accepted as a measure of fire severity, in the Sierra Nevada, the relativized version of dNBR (RdNBR) has been shown to be robust (Miller and Thode 2007, but see Soverel *et al.* 2010). This statistical approach could be applied to RdNBR values as well.

Choosing a Severity Metric

The severity metric (Equation 1) and the continuous approximation (Equation 4) provide additional methods for quantifying severity. Severity is most often quantified by classifying into four, or sometimes six, levels of severity. The severity of entire burned areas has previously been quantified by averages (i. e., Roberts *et al*. 2008) or proportions of high severity area (Lutz *et al.* 2009*b*), but SM represents a continuum of severities and distributions. No matter what characteristic severity distribution exists for a particular management unit, questions related to a fire year (i.e., "Was this year an active fire year?") can be examined by comparing the SM for the year in question to the historical average (Figure 3), along with the comparisons of number of fires and annual area burned. The Weibull shape parameters (Table 2), as well as the SM, maintain the continuous distribution of dNBR, and they may also reveal relationships between fire severity and abiotic predictors such as climate conditions, elevation, or vegetation type that are not evident in analyses of classified fire severity. When examining questions related to an area burned, either a single fire or a fire year, (i.e., "Did this fire burn more severely than normal for the area?"), a better comparison is with the severity mean calculated from all pixels over the period of record. An areal metric decreases the influence of those years where there was little burned area.

Programs such as MTBS help managers track the dynamics of the landscapes they are responsible for stewarding by using consistent processing methods. The MTBS methodology (usually limited to fires >400 ha in the western US and >200 ha in the eastern US) can be extended to smaller fires so that essentially all of the burned area (97 % in this work) can be analyzed. Using the Landsat Thematic Mapper period of record, the historical fire severity can be considered in purely statistical terms, allowing comparisons of severity between years. The current no-cost availability of the entire Landsat archive allows many scenes to be examined for the highest quality pre-fire and post-fire scene pair, and the uniform processing procedures of MTBS provide a standardized set of information. The normal fire regime attributes of frequency, area, and severity can all be easily calculated from the data provided by the MTBS program so that land managers can easily calculate the fire normals specific to their location (see Appendix for a calculation example from MTBS data). These fire normals provide a framework for examining how fires or fire years differ from recent means, especially as fire regimes may be affected by future climate change.

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