



Mapped versus actual burned area within wildfire perimeters: Characterizing the unburned

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ABSTRACT

For decades, wildfire studies have utilized fire occurrence as the primary data source for investigating the causes and effects of wildfire on the landscape. Fire occurrence data fall primarily into two categories: ignition points and perimeter polygons which are used to calculate a 'burned area' for a fire. However, understanding the relationships between climate and fire and its ecological effects requires an understanding of the burn heterogeneity across the landscape and the area within fire perimeters that remains unburned. This research characterizes unburned areas within fire perimeters, which provide ecological refugia and seed source for post-fire regeneration. We utilized differenced Normalized Burn Ratio (dNBR) data to examine the frequency, extent, and spatial patterns of unburned area in three national parks across the western US (Glacier, Yosemite, and Yukon-Charley Rivers). We characterized unburned area within fire perimeters by fire size and severity, characterized distance to an unburned area across the burned portion of the fire, and investigated patch dynamics of unburned patches within the fire perimeter. From 1984 through 2009, the total area within the fire perimeters that was classified as unburned from dNBR was 37% for Yosemite, 17% for Glacier, and 14% for Yukon-Charley. Variation in unburned area between fires was highest in Yosemite and lowest in Yukon-Charley. The unburned proportion significantly decreased with increasing fire size and severity across all three parks. Unburned patch size increased with size of fire perimeter, but patches decreased in density. There were no temporal trends in unburned area found. These results raise questions about the validity of relationships found between external forcing agents, such as climate, and 'burned area' values derived solely from polygon fire perimeters.

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1. Introduction

Wildfire is a widespread and often socially polarizing global ecological process, and burned area is projected to increase across North America under most climate change scenarios (IPCC, 2007; Balshi et al., 2009; Bowman et al., 2009; Spracklen et al., 2009). There has been considerable effort to empirically characterize wildfire regimes and model wildfire activity in order to understand both its critical ecological role in community succession processes and identify wildfire hazards to both humans and natural resources-at-risk (Agee, 1998; Dombeck et al., 2004; Chuvieco, 2003; Bowman et al., 2009). In the US, area burned is one of the most widely utilized metrics of wildfire activity, used for understanding and modeling past wildfire regimes (Swetnam and

Betancourt, 1990; Westerling et al., 2003, 2006; Littell et al., 2009), for calculating smoke production and carbon consumption (Hurteau and Brooks, 2011; Tarnay and Lutz, 2011; Liu et al., 2011; Kasischke and Hoy, 2012), and for projecting future wildfire risks and impacts (Flannigan et al., 2005; Littell et al., 2010; Westerling et al., 2011). Area burned, however, is also one of the most inconsistently recorded metrics of wildfire activity and one of the least accurate across data sets and studies (Brown et al., 2002; Silva et al., 2003; Kolden and Weisberg, 2007; NWCG, 2007).

The two primary federal wildfire databases define area burned as the calculated area within a perimeter mapped either by mobile Global Positioning Systems (GPSs) and reported in the federal Fire Occurrence Database (FOD) (NWCG, 2007), or by classification and digitization of a polygon perimeter from satellite data and reported in the Monitoring Trends in Burn Severity (MTBS) database (Kolden and Weisberg, 2007; Eidenshink et al., 2007). Therefore, analyses utilizing these two databases as a source for wildfire activity assume homogeneity in fuel consumption within the wildfire

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perimeter. This assumption ignores both the existence of heterogeneous burn patterns and the significance of unburned islands within a fire perimeter (Eberhart and Woodard, 1987; Turner et al., 1997; Michalek et al., 2000; Kolden and Weisberg, 2007; Lutz et al., 2009; Roman-Cuesta et al., 2009). The importance of unburned islands and their pattern within an individual fire has been widely addressed in localized studies of fire effects on biodiversity and habitat (e.g. DeLong and Tanner, 1996), but their prevalence has not been quantified across time or at landscape scales despite the significant cumulative effects on vegetation patchiness (Larson and Churchill, 2012; Lutz et al., 2012). The size and pattern of unburned islands within fire perimeters constitute critical characteristics of wildfire regimes that, to-date, have not been included in fire regime descriptions.

Methods of mapping wildfire perimeter polygons have evolved over the decades, but whether operators draw perimeters on topographic maps, fly or walk them with a GPS, or digitize them on a computer screen, the operator ultimately ocularly determines the final location of the perimeter polygon with variable precision (Kolden and Weisberg, 2007). That delineation often includes linear topographic features such as unburned riparian drainages intersecting the polygon perimeter and unburned islands wholly contained within the fire interior. These features comprise the primary sources for over-reported area burned (Key, 2006). Spot fires, burnout operations, and fingers where the head of a fire leapt out ahead of the main body can be erroneously omitted by operators, resulting in under-reporting. Kolden and Weisberg (2007) found a mean of only 76% agreement between FOD perimeters and satellite-derived burned area for wildfires in Nevada, primarily associated with over-reporting. The spatial scale of satellite-derived burn severity data can also introduce errors; Fraser et al. (2004) found a 72% rate of overestimation of area burned associated with scaling aggregation coarse-scale data pixels from the Moderate-resolution Imaging Spectroradiometer (MODIS).

Because fire perimeter mapping has traditionally been done for the purposes of monitoring containment during suppression operations, calculating area burned, and requesting post-fire rehabilitation funding (Kolden and Weisberg, 2007; NWCG, 2007), there has been little interest in identifying unburned islands nor the technology to do it easily and consistently. In the last decade, however, the US fire management community has emphasized the utilization of satellite-derived data for post-suppression evaluation based on the 30 m resolution Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper-plus (ETM+) instruments, transformed by one of several spectral indices to identify and map both wildfire perimeters and heterogeneous burn severity patterns within those perimeters (Key and Benson, 2006; Eidenshink et al., 2007). In particular, the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al., 2007), developed as a joint effort between US Geological Survey (USGS), National Park Service (NPS) and Forest Service (USFS), utilizes the differenced Normalized Burn Ratio (dNBR) spectral index to digitally delineate wildfire perimeters with spatiotemporal continuity and consistency.

Quantifying the characteristics of unburned areas within fire regimes at landscape scales is necessary to understand what role unburned islands play in succession processes, ecosystem dynamics, and wildfire risk. The primary objectives of this study were to determine what proportion of area within fire perimeters comprises unburned area, and to characterize and compare unburned area across a 25-year historical period for three dominant forest types found across a broad range of North America. Specifically, we (1) characterize the proportion of unburned area within fire perimeters, (2) assess the variability of that proportion by wildfire severity, (3) characterize distance to an unburned area across the burned portion of the fire, and (4) investigate patch dynamics of unburned patches within the fire perimeter.

1.1. Characterizing unburned pixels

Strahler et al. (1986) describe the utility of identifying scene model components in interpretation of satellite data. Delineating unburned area requires careful consideration of the surface properties that give rise to various dNBR values. The reflectance change of a pixel is dependent upon the flammability (burnable or not burnable) and stand structure (multi-layered canopy or not) of the pre-fire surface, the intensity and nature of the fire, the speed of post-fire vegetative recovery (i.e., speed of resprouting or colonization), the phenological timing of the pre- and post-fire scene selection, and the impacts of different illumination angles on reflectance. Unburned areas are inferred to be those with small changes in reflectance between pre-fire and post-fire satellite images, ideally using unburned areas outside the perimeter as a control on expected variation in unburned values within the perimeter. However, a variety of different surface conditions can give rise to similar pre-fire and post-fire reflectance. Conditions that likely result in a classification of unburned include:

- (1) Unburnable area: continuous areas of rocks, bare soil, water, snow, and ice within the fire perimeter that neither burn nor support vegetation and are correctly classified as unburned.
- (2) Sub-canopy burn (Fig. 1). When fires burn only on the surface beneath continuous canopy cover (cover ~75% or higher) with minimal or no canopy torching, the Landsat TM instrument cannot resolve a spectral change below obstructive canopy. This type of burn primarily consumes surface fuels, kills small trees, and changes the herbaceous and shrub communities as well as playing an important role in nutrient cycling and local soil–water balances. This fire behavior is characteristic of low-severity fire in frequent fire landscapes.
- (3) Very light homogeneous burn: areas that burned, but at a severity too low to differentiate from unburned with the Landsat TM instrument.
- (4) Severe burn in part of a satellite pixel (sub-pixel heterogeneity): when both burned and unburned vegetation exist within the same pixel, the satellite observes a mixed reflectance signal. This can result in a classification of unburned when a small portion of a pixel is actually burned.
- (5) Differences in illumination angle or phenological mismatch. Because dNBR measures the spectral difference between two dates, it is impacted by angles of illumination, shadowing,



Fig. 1. Example of a sub-canopy burn (2010 photo, S. Batiuk, used by permission), that resulted in an unburned classification.

and post-fire regeneration (Key, 2006; Verbyla et al., 2008). The methodology developed by Key and Benson (2006) addresses the issue of post-fire regeneration by calling for both 'Initial' and 'Extended' assessments of the fire's impact. The Initial Assessment post-fire scene is acquired after fire termination to assess consumption and first-order mortality, while Extended Assessment data are acquired the first growing season after the wildfire to quantify delayed mortality and primary regeneration (Key, 2006). Because the Initial Assessment scene is often acquired late in the growing season, it may include areas in shadow that (if paired with scene acquired nearer the solar maximum) appear burned when they are unburned (or vice versa). Well-matched scenes acquired 1 year apart on an anniversary date (to reduce differences associated with solar illumination angles and phenology) minimize misclassification in this category.

- (6) The area burned but regenerated sufficiently prior to post-fire scene acquisition that pre- and post-fire NBR values were nearly equal. This is most common in grasslands and shrublands characterized by fire-adapted, rapidly resprouting vegetation.
- (7) The area was vegetated but did not burn.

There has not, as yet, been any quantitative analysis to identify the proportion of unburned pixels attributed to any one of the above categories. In most forest landscapes and with typical pre-fire and post-fire satellite images, categories 1, 3, 4, and 5 comprise only small proportions of a fire. Categories 2 and 6 may comprise significant portions of burned areas in a specific region (e.g., frequent-fire landscapes with high levels of canopy cover of fire tolerant trees or Mediterranean shrublands). However, many studies of fire and fire effects that use burned area are primarily concerned with fires that kill emergent and canopy trees.

2. Methods

Three national parks (Fig. 2) were selected to represent three predominant forest types found across western North America. Each study area included the national park and additional area outside of the administrative park boundary that represented the ecological extent of the park's forest ecosystem (i.e., the study area boundaries were drawn to exclude fires that burned in grassland, shrubland, or timber harvests). Fires burning across the study area boundaries were only assessed on the portion of the fire occurring within the study area (i.e., they were clipped at the boundary). For Yukon-Charley Rivers National Preserve the US-Canada border also constrained the study boundary.

We created a burn severity atlas for each study area that included all fires occurring from 1984 through 2009 that could be mapped following standard MTBS protocol and best practices (Key and Benson, 2006; Zhu et al., 2006) that exceeded a region-specific size threshold. The former requirement forced the exclusion of some fires from the Yukon-Charley atlas due to the challenges of meeting best practice requirements in Alaska (e.g., anniversary date Landsat imagery) (Kolden, 2010). Region-specific size thresholds were based on a fire size when the summed area of fires exceeding the threshold was at least 95% of the total area burned reported by the FOD for that region. Preliminary analysis identified these thresholds as 40 ha for Yosemite (97% of area burned; Lutz et al., 2009), 20 ha for Glacier (97% of area burned), and 600 ha for Yukon-Charley (99% of area burned). Fires of this size or greater represented 7% (Yosemite), 4% (Glacier), and 51% (Yukon-Charley) of total fires reported from 1984 through 2009 for each study area. Minimum sizes for Yosemite and Glacier were considerably less than the standard MTBS threshold for fires in the

western US at greater than 405 ha, resulting in treatment of many more fires.

2.1. Study area

We carried out this study in the general vicinity of three national parks in the western US: Yosemite National Park in California, Glacier National Park in Montana, and Yukon-Charley Rivers National Preserve in Alaska. Each park represents a forest type and an associated fire regime that is found across a large proportion of North America, but these three parks have also been subjected to less fire suppression over the past century relative to adjacent lands due to both their policies on wilderness fire and inaccessibility. Each park served as the core of a study site and was buffered to a distance determined for that park by its fire history.

Yosemite National Park is located in the central Sierra Nevada of California (Fig. 2) at latitude 37°N. The study area (Yosemite) comprised the entire Park plus a 6.5 km buffer around the park (4771 km²). The vegetation of the study area is predominantly closed canopy forest or woodland, with some shrub patches and shrub fields. Forest cover includes vegetation dominated by (in approximate increasing elevation): foothill pine (*Pinus sabiniana*), ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), red fir (*Abies magnifica*), lodgepole pine (*Pinus contorta*), mountain hemlock (*Tsuga mertensiana*), and whitebark pine (*Pinus albicaulis*). Forest vegetation is interspersed with rocky areas, which provide barriers to fire spread and vegetation. The natural fire return interval for the forested ecosystems of Yosemite ranges between 4 years and 187 years (Caprio and Swetnam, 1995). However, the higher elevation forest types burn infrequently (van Wageningen et al., 2002). From 1984 through 2009, there were 152 fires greater than 40 ha mapped in the Yosemite study area.

Glacier National Park (Glacier) at 48°N latitude represents the sub-boreal and sub-montane coniferous forests characteristic of the northern Rocky Mountains. The study area included all of Glacier National Park and a buffer that extended north into Canada and south along the Continental Divide (29,850 km² total area). Forest associations are dominated by lodgepole pine (*P. contorta*), Engelmann spruce (*Picea engelmannii*) subalpine fir (*Abies lasiocarpa*), Rocky Mountain Douglas fir [*Pseudotsuga menziesii* (Mirb.) var. *glauca* (Beissn.) Franco], and western larch (*Larix occidentalis*) with stands of ponderosa, lodgepole, limber, and whitebark pine (*P. ponderosa*, *P. contorta*, *Pinus flexilis*, and *Pinus monticola*, respectively). Fire season is generally from to late July through September, with most large fires starting by lightning during infrequent, extremely dry years. From 1984 through 2009, 156 fires greater than 20 ha were mapped in the Glacier study area.

Yukon-Charley Rivers National Preserve (Yukon-Charley) at 64°N in Alaska represents the broad range of vegetation diversity found in the North American boreal forest, but is dominated by black spruce (*Picea mariana*) in flats, white spruce (*Picea glauca*) on slopes, and birch (*Betula spp.*) and quaking aspen (*Populus tremuloides*) in more recently burned areas. Fires in Yukon-Charley are 99% lightning-ignited wildfires and are not generally suppressed, as most of Yukon-Charley and the surrounding area falls within the Limited Suppression management designation made by the Alaska Fire Service (Todd and Jewkes, 2006). The study area (Yukon-Charley) included all of Yukon-Charley Rivers National Preserve and a buffer extending 50 km from the preserve boundaries (but not extending into Canada). The study area (30,980 km²) experienced 59 fires greater than 600 ha from 1984 to 2010. However, cloud cover obscured or suitable Landsat data were unavailable for eight fires and these were removed from the Yukon-Charley data set, leaving 51 fires. Of the 51 fires which we analyzed unburned area for, 23 were acquired by Landsat ETM+ after the scan-line corrector failed and patch dynamics could not be



Fig. 2. Locations of Yosemite National Park, Glacier National Park and Yukon-Charley Rivers National Preserve study areas.

investigated for them, leaving 28 fires specifically for the patch dynamics analyses.

2.2. Delineating unburned area

For each fire in the three study-region data sets, a dNBR image (Key and Benson, 2006) was produced using best practices outlined by Key (2006) and consistent with the protocol established by MTBS (Zhu et al., 2006). As MTBS occasionally produces dNBR products with cloud contamination or poorly-matched anniversary dates, we reviewed each fire and, where we found contamination or poorly-matched scenes, we re-selected image pairs and re-mapped dNBR ourselves where possible. Each dNBR image was normalized to an unburned value of zero by adding or subtracting the mean dNBR over a relatively large (approximately 10,000 pixels), relatively homogenous unburned sample delineated outside but near the fire perimeter. In Yukon-Charley, 23 of the 51 fires could only be mapped utilizing Landsat ETM+ data, and subsequently were characterized by missing data lines associated with the ETM+ scan-line corrector problem (Markham et al., 2004).

Because dNBR is a continuous, unit-less metric falling within the range of -2000 to 2000 , (typical values between -200 and 1200), there has been a considerable effort to define classification thresholds for unburned areas and differing classes of burn severity through field validation (Key, 2006; Thode, 2005; French et al., 2008). For this study we objectively defined unburned area as the dNBR range from -100 to 100 (Fig. 3). The range encompassed over 90% of unburned area in previous studies using calibrated dNBR (Key, 2006; Thode et al., 2011). Recognizing that some burned area may be included within this range, and that some unburned area could be excluded, we assumed this range encompassed the vast majority of unburned area. Thus, it represented one way to differentiate fire landscape effects and provided a comparative metric between cases, regardless of the label (i.e. unburned) assigned to it. It was “unburned” because the range was most representative of that condition.

The dNBR raster for each fire was aggregated using a 3×3 mean value filter to produce two spatial scales of fire data: 30 m (0.09 ha; unfiltered) and 90 m (0.81 ha; filtered) resolution, where the value of each 90 m pixel was the mean dNBR of the nine 30 m

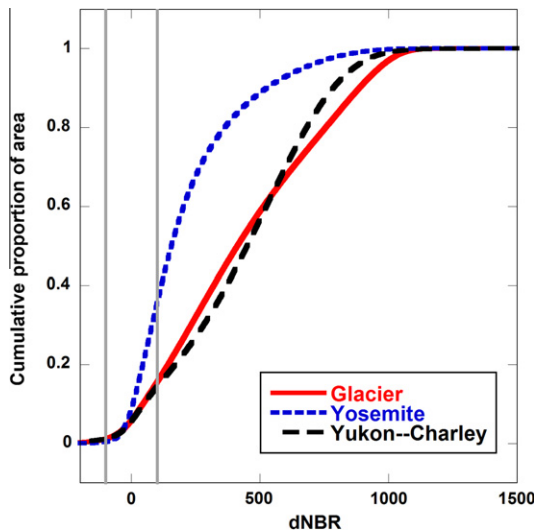


Fig. 3. Cumulative distribution of dNBR for each of the three study areas indicating the proportion of the fire atlas pixels classified as unburned using the -100 to 100 dNBR range.

pixels comprising it. Each fire was then classified for both resolutions into burned or unburned areas using the $-100 \leq \text{dNBR} \leq 100$ range. We defined an unburned patch as any contiguous set of unburned cells. We classified as 'small' unburned patches using the 30 m data and 'large' unburned patches in the 90 m data. We used two spatial resolutions to address the dilemma posed between ecological relevance and statistical significance. While 30 m (0.09 ha) pixels are autocorrelated (Thompson et al., 2007) and problematically can produce false positives or negatives, they could represent small (sub-0.09 ha) but important ecological refugia such as wet meadows in Yosemite and narrow stream features in Yukon-Charley. The larger 90 m \times 90 m unburned patches are less likely to represent noisy data, but this scale may not include all relevant unburned patches.

For each of the three study regions, we calculated the proportion of unburned area on a per fire basis and then summarized annually and by size of the area within the fire perimeter (i.e., the "fire size"). We also compared the proportion of unburned overall fire severity as determined by the Severity Metric (SM) (Lutz et al., 2011). The SM is a measure of the cumulative distribution of dNBR for a fire, and is calculated as: one minus the sum from $i = -200$ to 1200 of the proportion of pixels less than or equal to i divided by 1401 .

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

Four measures of burn heterogeneity were calculated for each fire: (1) distance of a given burned pixel to the nearest unburned pixel for both small (one Landsat TM pixel; 0.09 ha) and large (nine Landsat TM pixels; 0.81 ha) patch sizes, and the distance to the fire perimeter; (2) mean patch size (ha); (3) patch density (number of patches per 100 ha); and (4) square Pixel value (SqP; a measure of patch shape complexity that is scale-invariant and specifically for raster data; Frohn, 1998). In Yukon-Charley, analyses of patch sizes, density, Square Pixel, and distance to an unburned patch were conducted only on those fires with complete spatial coverage (28 out of 51 fires). Each of the metrics was assessed as a function of fire size and compared across study regions. Significance was assessed at $p = 0.01$.

3. Results

3.1. Proportion of unburned area

The proportion of fire area that was unburned varied considerably by region, fire size, and interannually. The total proportion of unburned area within fire perimeters was 35% for Yosemite ($n = 154$), 14% for Glacier ($n = 156$), and 13% for Yukon-Charley ($n = 51$). The mean unburned proportion per-fire was 52% for Yosemite (range 8–97%), 24% for Glacier (range 3–96%), and 17% for Yukon-Charley (range 4–71%) (Fig. 4). Yosemite had the greatest range of interannual variability (22–92%); while Glacier (range 7–41%) and Yukon-Charley (range 7–17%) varied comparatively less interannually (Fig. 5).

The proportion of unburned area had a significant negative correlation (using the exponential model $y = ab^x$) to overall severity of the fire, as described by the SM, for Yosemite ($R^2 = 0.90$), Glacier ($R^2 = 0.82$), and Yukon-Charley ($R^2 = 0.86$) individually (Fig. 6). Considering the three regions together, SM also exhibited a significant negative correlation to unburned area ($R^2 = 0.88$), where the proportion of unburned area decreased with increasing severity (as defined by the SM) for all three of the study areas. The proportion of unburned area also exhibited a slight decrease with increasing fire size (\log_{area}) over all three regions (Fig. 7). The weak negative trend was significant at $p < 0.01$ for Yosemite ($R^2 = 0.13$), Glacier ($R^2 = 0.13$), Yukon-Charley ($R^2 = 0.08$), and all three parks combined ($R^2 = 0.17$).

3.2. Patterns of unburned area

Patterns of unburned area within fire perimeters varied across regions and by pixel resolution representing the size of unburned patches (Fig. 8). Yosemite burned areas were the closest to any kind of unburned area (0.09 ha patch, 0.81 ha patch, or fire perimeter), Glacier burned areas were generally the furthest from an unburned patch within the fire perimeter, and Yukon-Charley burned areas were generally the furthest from the fire perimeter. For example, in Yosemite only 6% of burned pixels were more than 300 m away from a 0.09 ha unburned patch, compared to 21% in Glacier and 17% in Yukon-Charley (Table 1). For a 0.81 ha (i.e.,

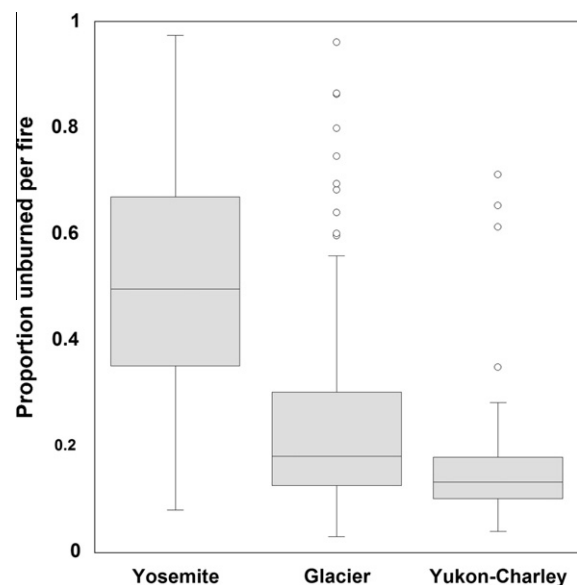


Fig. 4. Box plots showing inter-quartile range and mean % unburned for individual fires in each of the three study regions: Yosemite, Glacier, and Yukon-Charley.

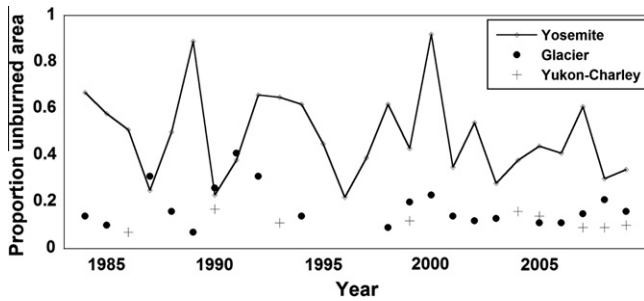


Fig. 5. Interannual variability of proportion of unburned area within fire perimeters for Yosemite, Glacier, and Yukon-Charley. Only Yosemite had enough fire years to develop a trend line; Glacier and Yukon-Charley fire years are too infrequent.

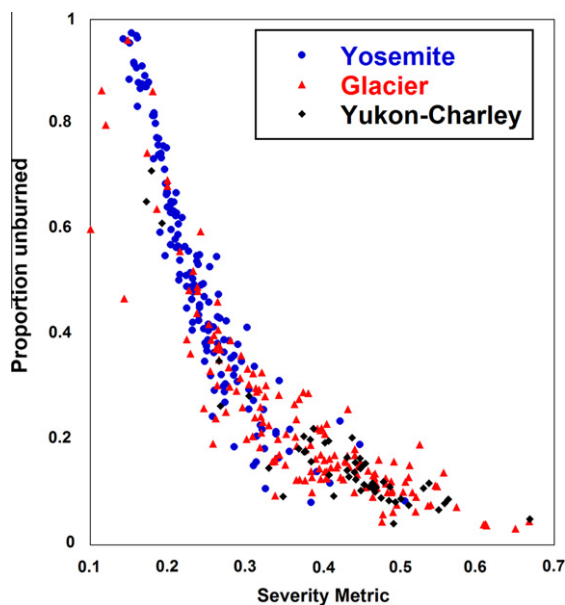


Fig. 6. Scatterplot of % area of unburned per fire by the Severity Metric (SM) of the fire.

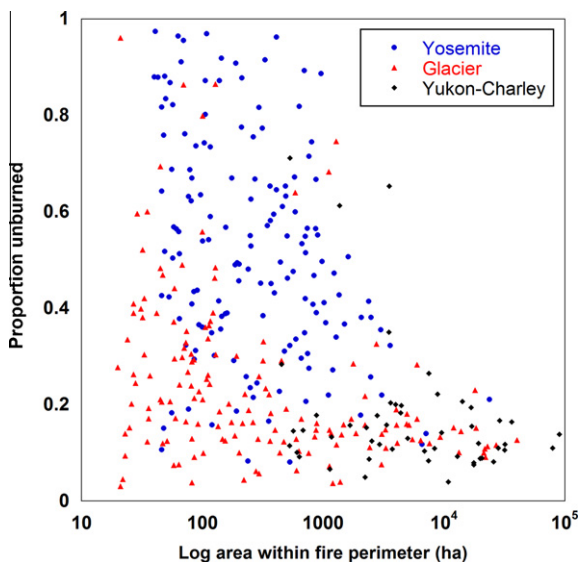


Fig. 7. Scatterplot of % area unburned per fire as a function of area within fire perimeter for each of the three study regions: Yosemite, Glacier and Yukon-Charley.

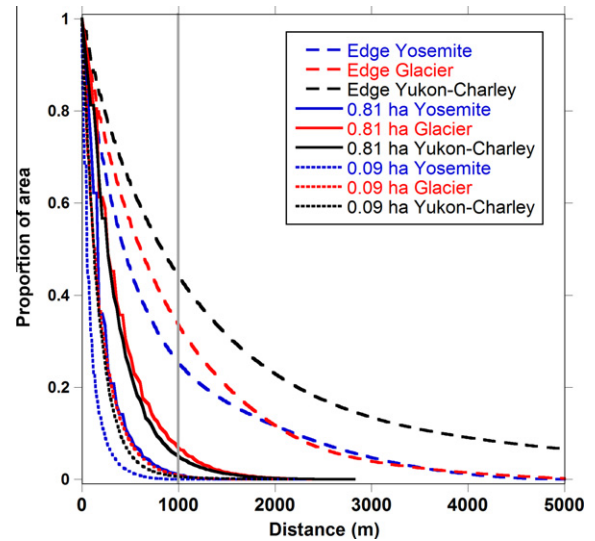


Fig. 8. Proportion of burned area greater than a given distance (m) from the fire perimeter edge (large-dash line), the nearest 0.81 ha unburned patch (solid line) and the nearest 0.09 ha unburned patch for each of the three study regions: Yosemite (blue), Glacier (red), and Yukon-Charley (black). For example, the % of burned area that is greater than 1000 m (vertical gray line) from the fire's edge is 25%, 33%, and 44% for Yosemite, Glacier, and Yukon-Charley, respectively, while the respective % of burned area greater than 1000 m from a 0.81 ha unburned patch is 1, 7, and 5, and the respective % greater than 1000 m from a 0.09 ha unburned patch is 0.003, 0.9, and 0.6.

90 m²) unburned patch size, a lower proportion Yosemite burned pixels (21%) was greater than 300 m away as compared to Glacier (45%) and Yukon Charley (44%). For Yukon-Charley, 76% of burned pixels were greater than 300 m from the fire perimeter, compared to 69% for Glacier and 61% for Yosemite.

Mean unburned patch size (calculated using 0.09 ha pixels) per fire was 19.5 ha in Yosemite, 2.3 ha in Glacier, and 1.2 ha in Yukon-Charley (Fig. 9a). Mean unburned patch density was 12 patches per 100 ha for Yosemite, 22 patches per 100 ha for Glacier, and 13 patches per 100 ha for Yukon-Charley (Fig. 9b). Square Pixel values (patch shape complexity) had a significant logarithmic correlation to size of fire for each of the three parks (Fig. 10), with the strongest relationships found at Glacier ($R^2 = 0.86$) and Yukon-Charley ($R^2 = 0.71$), and a weaker but still significant positive relationship found for Yosemite ($R^2 = 0.53$).

4. Discussion

It is widely acknowledged that not all of the area within a wild-fire perimeter burns, but this acknowledgement has not previously been accompanied by quantification of unburned area and its patterns in order to more accurately characterize fire regimes, fire emissions (but see Kasischke and Hoy, 2012), and fire-climate studies. We found that while 81% of the area within mapped wild-fire perimeters actually burned over the 25-year study period, this proportion varied considerably by study region, year, and fire size and severity. While size of fire was only weakly correlated to proportion of unburned area, severity of the fire was strongly negatively correlated to unburned proportion for all three regions. Yosemite had fewer, larger, less complex unburned patches compared to the smaller, more numerous, more complex unburned patches of Glacier and Yukon-Charley, but a greater proportion of Yosemite burned area was closer to unburned area.

Of additional importance is the lack of any apparent temporal trend in the proportion of unburned area in either Yosemite or Glacier (Yukon-Charley does not have enough fire years

Table 1

The proportion of the fire area within the perimeter that is greater than the distance given from an unburned area for 0.09 ha and 0.81 ha unburned patches and the fire perimeter.

		Proportion of fire greater than the given distance (m) from unburned area		
		Yosemite	Glacier	Yukon-Charlie
<i>0.09 ha Patches (m)</i>				
30	0.69		0.85	0.86
60	0.45		0.71	0.74
150	0.18		0.44	0.42
300	0.06		0.21	0.17
<i>0.81 ha Patches</i>				
90	0.74		0.87	0.81
180	0.36		0.61	0.65
300	0.21		0.45	0.44
600	0.06		0.21	0.17
<i>Edge of fire</i>				
300	0.61		0.69	0.76
600	0.40		0.50	0.60
900	0.28		0.37	0.47
1200	0.14		0.15	0.26

represented to assess temporal trend) (Fig. 5). This suggests that over the last 25 years, while some studies have found a significant increase in the proportion of high severity fire for larger extents (i.e., Miller et al., 2008), there is no evidence supporting a corresponding change in the proportion of unburned area at the scale of the three representative study regions. The spatial distribution of unburned patches throughout even large fires indicates that burned forests of the three study regions are not “devastated” or the “moonscapes” at times described by the media or those researchers seeking to characterize “catastrophic fire”. For Yukon-Charley and Glacier, over 50% of the burned area is within 135 m of a small (0.09 ha) and 270 m of a large (0.81 ha) unburned remnant, while over 50% of Yosemite is within 60 m of a small and 180 m of a large unburned remnant. Such proximity to an unburned patch (compared to the considerably greater distance to the edge of the fire perimeter) and the relatively high patch densities found for all three parks indicate that refugia for at least some animal and plant taxa remain present in all three ecosystems, and that seed sources may exist within even large, severe burns (Roberts et al., 2008; Lutz et al., 2009; Fig. 11).

Also telling is the significant difference between the proportions of unburned area in the low-to-moderate severity fire regime of Yosemite versus the predominantly stand-replacing fire regimes of Glacier and Yukon-Charley. As the majority of federal land in

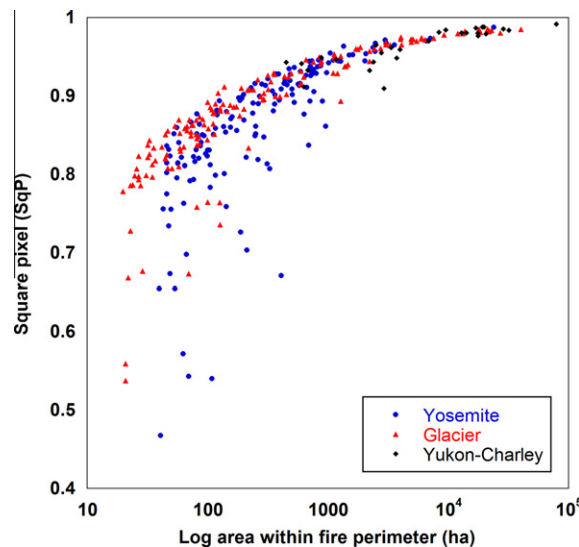


Fig. 10. Square Pixel (SqP) plotted by size of fire perimeter area. A SqP value close to zero indicates non-complex shapes, while a SqP value close to 1 indicates the greatest departure from a perfect square, and the greatest shape complexity.

the contiguous US is associated with low or moderate severity fire regimes (Schmidt et al., 2002), and over a third of the area falling within fire perimeters in Yosemite was classified as unburned, there could be considerable potential for misinterpretation of fire effects using only fire perimeters. In some years, the proportion of unburned pixels in Yosemite can be attributed to management-ignited prescribed fires to reduce surface fuels (van Wageningen and Lutz, 2007). In 2000, there was a single management-ignited fire in Yosemite, and in 1984, 45% of area burned was management ignited. These management-ignited fires featured spatially contiguous fuel consumption beneath the canopy in lower mixed-conifer forest. However, even during years without many management fires, the proportion of unburned area was still larger than for the other two parks. This proportion of unburned area also considerably exceeded that found by previous studies that focused on a single or limited number of fires (Eberhart and Woodard, 1987; DeLong and Tanner, 1996) as opposed to all fires in a study region over multiple decades as assessed here. Our findings are comparable to the mean 20% unburned area found by Kasischke and Hoy (2012) for 4 years of wildfires in interior Alaska, the only other study to the best of our knowledge that has quantified regional-scale, multi-year unburned area.

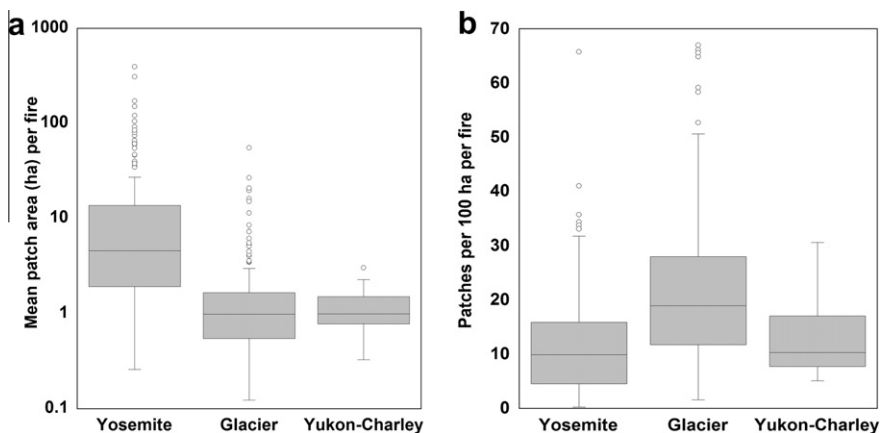


Fig. 9. Mean unburned patch size in ha (left) and patch density per 100 ha (right) for each of the three study regions: Yosemite, Glacier, and Yukon-Charley.



Fig. 11. An unburned Ponderosa pine refugia that will reseed the burned area in the surrounding area in Yosemite National Park (2012 photo, J. van Wagtenonk).

Numerous ecological studies focused on population dynamics after a single wildfire highlight the importance of remnant patches of habitat within wildfire perimeters and the role of unburned remnants in determining landscape heterogeneity and macroscale patch dynamics (Eberhart and Woodard, 1987; Turner et al., 1994; Ratz, 1995; DeLong and Kessler, 2000). Unburned patches are often referred to as biological legacies or residuals (Turner et al., 1998), and function as refugia for a wide variety of fauna and flora both during and after a wildfire (Gassaway and DuBois, 1985; DeLong and Kessler, 2000), providing habitat from which residual species can repopulate the burned area (Turner et al., 1997). These refugia are particularly important for some avian species (Kotliar et al., 2002) as well as insects and small-to-large mammals incapable of outrunning the fire or taking refuge in subsurface spaces (Swengel and Swengel, 2007; Roberts et al., 2008; Garvey et al., 2010). In some particularly large wildfires, and depending on the range of the fauna, these unburned islands will provide the primary habitat and/or source of food for species for days to decades following the wildfire (Cunningham et al., 2003; McKenzie et al., 2004). For some forested ecosystems, and particularly in mixed-severity wildfire regimes, unburned islands provide a refuge for obligates and the primary seed source for forest regeneration (Turner et al., 1997; Clarke, 2002; Ooi et al., 2006). Unburned remnants also play an important role in riparian zones, where plants and soil typically harbor higher moisture levels, decreasing their susceptibility to wildfire (Dwire and Kauffman, 2003; but see Olsen and Agee, 2005), and can function to minimize soil transport and protect fisheries by serving as runoff barriers (Vose et al., 1999). Studies ignoring these unburned sites assume a uniform, denuded burn scar; our results indicate this is an oversimplified, unjustified, and erroneous assumption.

In comparing the three parks, we begin to characterize unburned area as it relates to burned area within fire perimeters. Yosemite is characterized by a low-to-moderate severity fire regime, and these lower severity fires translate to a higher proportion of unburned area that is interannually variable. Unburned patches were nearly six times larger in Yosemite than in the other two parks, although the largest unburned patches resulted from management-ignited surface fires under dense canopies of white fir. These characteristics are both consistent with the fire regime and with the highly heterogeneous fuels in Yosemite compared to the more homogenous fuels burned in Glacier and Yukon-Charley. The latter two parks exhibit larger portions of stand-replacement fire behavior, which translates into lower portions

and smaller patches of unburned. The latter two parks also do not have large prescribed fire programs, whereas Yosemite has been conducting landscape-scale prescribed burns for over 40 years. All three parks show increased unburned patch shape complexity with size of fire (as represented by the Square Pixel value), nearing maximum shape complexity ($SqP = 1$) well below the maximum burned area for each park (Fig. 10). This runs counterintuitive to the representation of the largest wildfires as homogenous moonscapes, as all three parks have historically retained unburned islands that are both numerous and complex in shape with high amounts of edge; maximizing the interface with burned areas and facilitating post-fire repopulation.

4.1. Implications and limitations

As several recent studies project larger wildfires under climate change (Balshi et al., 2009; Bowman et al., 2009; Spracklen et al., 2009), some limited studies have found a significant relationship between fire size and severity (Duffy et al., 2007), and we found a significant negative relationship between severity and unburned proportion, this would initially seem to suggest that the projected larger fires would leave lower unburned proportions. However, we found only a weak relationship between fire size and unburned proportion for all three of our study areas. This contrast in results is potentially due to the limited number of fires (24) analyzed by Duffy et al. (2007) and their use of mean NBR as a severity metric, but the proportion of burned area is at least partly fuel-limited, and changing fuel arrangements across study areas and over time can have a considerable influence on the outcome of these analyses. Both studies, however, suggest that as future fires burn more severely, the proportion of unburned area is likely to decrease. While there is not currently a long enough temporal data set to robustly assess temporal trend, continued acquisitions from space-borne sensors will soon allow for such analyses. Decreased proportion of unburned area would likely provoke significant changes in ecosystem function and resilience after wildfire.

Due to the ambiguity of inferring ecological consequences from fire perimeters alone, land managers may want to use fire severity data for assessing trends in burned area as well as fire severity. While these data have historically been difficult to acquire, the MTBS program now provides severity data for all US wildfires greater than 400 ha (>200 ha in the Eastern and Southern geographic regions). This is particularly critical for units managing ecotypes characterized by historically low-to-moderate or mixed-severity fire regimes, since our results indicate that these ecotypes are more likely to have a greater proportion of unburned remnants and a greater range of variability in the resulting habitat patterns. Although the MTBS methodology is uniform, the interpretation of satellite-derived burn severity values depends on the vegetation type and calibration with ground data (French et al., 2008; Thode et al., 2011; Cansler and McKenzie, 2012).

Fire severity data produced by MTBS are not without limitations, which we would be remiss not to acknowledge here. As discussed in the methods section and by French et al. (2008), historically there are gaps in the Landsat record in Alaska and elsewhere. As of mid-2012, only the Landsat ETM+ sensor is still acquiring data, and the failure of the scan-line corrector reduced the actual data collection of each sweep (resulting in “lines” on the scene). Cloud cover is a significant problem during the growing season in many parts of the US, and both cloud cover and interannually-variable phenology challenge the best practices use of anniversary date scenes (Key, 2006). Finally, the dNBR thresholds for burn severity classes, including the delineation of unburned, remain unvalidated for the majority of US ecotypes where too few ground observations have been made, leading to uncertainty in the accuracy of fire severity classifications.

Our findings will impact the science utilized to manage natural resources at landscape scale. As we have noted, the amount of scientific literature that utilizes area burned from fire perimeters is prolific; much of that literature has found its way into fire and resource management plans and tactics over the years through the science application and technology transfer channels. However, we question how many of those studies would maintain their findings if relationships were reanalyzed with corrected area burned data that excluded unburned areas within the fire perimeter. Furthermore, we suggest that overlooking the large and numerous unburned patches within wildfires is a critical error, because those patches are of such ecological significance (Turner et al., 1997, 1998).

5. Conclusion

Previous studies have identified the relative proportion, the complexity, the patterns, and the importance of unburned islands within a single or a few wildfires (e.g., Eberhart and Woodard, 1987; DeLong and Tanner, 1996); however, many recent large-scale studies of wildfire drivers discount the significance of unburned areas by utilizing fire perimeters to quantify area burned as an input variable. The present study indicates that in three dominant forest ecotypes of North America, unburned island remnants comprise a significant portion of the area within the fire perimeter. Unburned zones occur in proportions and patterns unique to the wildfire regime of each ecotype, with the highest proportion of unburned area (35%) occurring in the low-to-moderate severity fire regime in our study (Yosemite), while the moderate-to-high severity fire regimes, Glacier and Yukon-Charley, were characterized by considerably less unburned proportion at 14% and 13%, respectively. Glacier had more, smaller fires than the other study areas and was characterized by smaller unburned patches occurring at a higher density, while the largest fires, largest patches and lowest density of those patches were found in Yukon-Charley.

Perhaps the similarities were more important, however, than the differences between the three regions. For all three regions, we found patterns of decreasing unburned proportion with increasing fire severity, in association with fewer and larger unburned islands. Given the short temporal period spanned by this study and the limited number of fire years in the two higher severity fire regimes for that period, we did not pursue an examination of climate impacts on unburned area proportions and patterns. However, as many studies have found trends of increasing size and severity over the last century and predicted these trends to continue under climate change scenarios, we hypothesize that if larger fires occur, more complete burns that harbor fewer unburned islands would result. This has considerable negative implications for habitat conservation and efforts aimed at assisted migration of species, but requires much further study to fully explore.

Finally, given the growing interest in quantifying relationships between climate, vegetation, human activity, and emissions to wildfire extent in the scientific and management communities, we suggest that development of a database that excludes unburned islands from wildfire area burned will produce more accurate results in these studies. Furthermore, we suggest that both the proportion of unburned area and the shape, frequency, size, and complexity of unburned patches constitute critical fire regime characteristics that should be assessed in future studies. These steps are particularly important for those developing models used for management and regulation, such as wildlife habitat modeling, conservation prioritization assessments, and carbon, smoke, and particulate matter emissions. Since current area burned data uniformly overestimate the true area burned by wildfire by failing

to exclude unburned areas (i.e., include errors of commission), we suggest that national and global estimates also significantly overestimate emissions from wildfires, with implications to those agencies and units that exceed regulatory emissions caps. Correcting the base area burned data utilized to parameterize this and other process models can more accurately approximate terrestrial system dynamics.

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