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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 or between 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.

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 $\sim$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.