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Is proportion burned severely related to daily area burned?

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Abstract

The ecological effects of forest fires burning with high severity are long-lived and have the greatest impact on vegetation successional trajectories, as compared to low-to-moderate severity fires. The primary drivers of high severity fire are unclear, but it has been hypothesized that wind-driven, large fire-growth days play a significant role, particularly on large fires in forested ecosystems. Here, we examined the relative proportion of classified burn severity for individual daily areas burned that occurred during 42 large forest fires in central Idaho and western Montana from 2005 to 2007 and 2011. Using infrared perimeter data for wildfires with five or more consecutive days of mapped perimeters, we delineated 2697 individual daily areas burned from which we calculated the proportions of each of three burn severity classes (high, moderate, and low) using the differenced normalized burn ratio as mapped for large fires by the Monitoring Trends in Burn Severity project. We found that the proportion of high burn severity was weakly correlated (Kendall $\tau = 0.299$) with size of daily area burned (DAB). Burn severity was highly variable, even for the largest (95th percentile) in DAB, suggesting that other variables than fire extent influence the ecological effects of fires. We suggest that these results do not support the prioritization of large runs during fire rehabilitation efforts, since the underlying assumption in this prioritization is a positive relationship between severity and area burned in a day.

Keywords: burn severity, daily area burned, dNBR, fire progression, forest fires, infrared perimeter mapping, northern Rockies

1. Introduction

Extreme wildfires are often so defined because they are of record size, produce numerous fatalities, significantly alter ecological trajectories of succession, and initiate new or revised fire management policies (Pyne 2004, Kolden and Brown 2010, Lannom *et al* 2014). Globally, several extremely large fires have occurred over the last century, notably the Great Fire of 1910 in Idaho and Montana, USA (Pyne *et al* 1996), the 1988 Yellowstone Fires (Turner *et al* 1994), the 1997 Indonesian Forest Fires, and the Australian Black Saturday Fire in 2009.

The number of large wildland fires in the western United States has increased four-fold in recent decades (Westerling *et al* 2006), producing increases in fire extent (Littell *et al* 2009), costs of management (Butry 2001), and threats to people and property (Theobald and Romme 2007). The proportion of area burned with high burn severity has also increased in some areas (Dillon *et al* 2011, Miller and Safford 2012, Mallek *et al* 2013), where burn severity is commonly defined as the degree of ecosystem change following a fire (Ryan and Noste 1985, Morgan *et al* 2001, Lentile *et al* 2006). Individual large fires consume significant amounts of biomass (Hicke *et al* 2013) and can have long-term ecological effects on vegetation structure and

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composition (Kashian *et al* 2006, Goetz *et al* 2007, Romme *et al* 2011), but less is known about the degree of overall ecological change caused by the largest fires (Turner *et al* 1997, Keane *et al* 2008) or in areas of rapid fire growth (Turner *et al* 1994) when fires make large advances, or 'runs'. When large fire runs result in a large area burned in a day, it is commonly described as an extreme fire behavior event, but high tree mortality does not always result (Hudak *et al* 2007, Lentile *et al* 2007).

High intensity fires can result in high tree mortality. Using daily area burned (DAB) maps from the 1988 Greater Yellowstone Fires, Turner *et al* (1994) found that when DAB exceeded 1250 ha, about half of that area burned with crown fire,. Heward *et al* (2013) found that high burn severity and high fire intensity generally occur concurrently across the western US. Fires that burn under weather conditions that significantly deviate from statistical norms have a higher proportion of crown fires (Turner *et al* 1994) and higher severity (Bigler *et al* 2005) in Rocky Mountain forested ecosystems. Extreme weather and high severity fire often occur together, with wind playing a large part in fire intensity and fire extent (Beer 1991, Bessie and Johnson 1995), and it is under those conditions we expect high tree mortality (Stephens and Moghaddas 2005).

We set out to test whether larger daily areas burned in forests were characterized by a greater proportion of high burn severity or if they simply burned more area. We focused on fires that occurred in the Northern Rockies, USA, due to its preponderance of fire monitoring data. Using infrared (IR) perimeter mapping data and maps of burn severity, we compared individual daily areas burned from 42 wildfires and the proportion of high burn severity within those areas to test if the proportion of high burn severity was strongly correlated to area burned. Additionally, we wanted to determine if the largest daily fire runs (95th percentile, DAB greater than 108 ha) resulted in a higher proportion of high burn severity.

2. Methods

2.1. Study area

The US northern Rocky Mountains (hereafter referred to as the Northern Rockies) have experienced large fires throughout the 20th century (Morgan *et al* 2008), a trend expected to continue through the 21st century (Littell *et al* 2009, Littell 2011, Spracklen *et al* 2009). The Northern Rockies are characterized by a distribution of dry, cold, and mesic forest types (Morgan *et al* 2008) of mixed conifer and pine forests that are generally stratified by elevation and aspect gradients (Arno 1980). We selected 42 fires from this region (figure 1, table 1) during the years 1984–2011, based on the availability of both differenced normalized burn ratio (dNBR) indices and IR perimeter maps for a given fire.

2.2. IR perimeter mapping

Fire managers commonly use IR perimeter maps to establish areas of fire growth and calculate overall fire size on wildfire incidents. Airborne IR flights are usually conducted at night or in early morning, both to maximize thermal contrast and to provide wildland fire managers with perimeter maps for decision making associated with upcoming daily operations (Quayle *et al* 2012). We obtained IR perimeter mapping data from the National Interagency Fire Center (2013) File Transfer Protocol (FTP) site (http://ftpinfo.nifc.gov), which is used to store and transfer wildland fire incident data and documents (including remotely sensed and other geographic information data). We required a minimum of five consecutive days of IR perimeter maps per fire in order to exclude areas of inconsistent perimeter mapping. Many of these inconsistencies can be attributed to 'blooming' of the IR image, which can occur when fire columns or convective currents include hot gases at a temperature sufficient to be detected as a heat source (Quayle *et al* 2012). Another possible source of inconsistency is interpreter error. Deviations in accuracy of perimeter mapping from IR images due to error by interpreter personnel is generally within a range of plus or minus 10 m (T Zajkowski, Forest Service, personal communication).

Spatial maps of DAB (see figure 2 for example) for each of the 42 fires were constructed by subtracting the perimeter of the last mapped day from the perimeter of the previous day, and so on to the start of the mapped sequence. We used fire area from the first mapped day to calculate area burned for the next day, but did not include it in the area analyzed. In this way, the minimum number of five consecutive days of mapped IR perimeter per fire resulted in at least four days of DAB per fire. If the previous day's IR perimeter extended spatially beyond the current day perimeter, we excluded that overlap from analysis. To address the inaccuracies of IR mapping associated with blooming and geospatial location, we buffered IR perimeter maps by 30 m. Areas that were not classified as high, moderate or low burn severity were excluded from calculations of proportion burned and DAB size.

2.3. Burn severity inferred from dNBR

Wildfire burn severity has been defined several ways (e.g. Ryan and Noste 1985, Lentile *et al* 2006, Keeley 2009, Kolden and Rogan 2013). We define it here as the degree of ecosystem change following a fire (Morgan *et al* 2001, Lentile *et al* 2006). We use the dNBR (Key and Benson 2006), a spectral index calculated from multispectral remotely sensed data, to infer severity. While we acknowledge that dNBR is a unitless ratio of optical reflectance and itself not a measure of severity, this spectral index has shown reasonable correlations with aboveground vegetation mortality (Lentile *et al* 2009) and other surface changes (Smith *et al* 2007). We thus considered the dNBR severity classifications of low, moderate, and high as proxies for those surface changes. A detailed overview of severity methods and

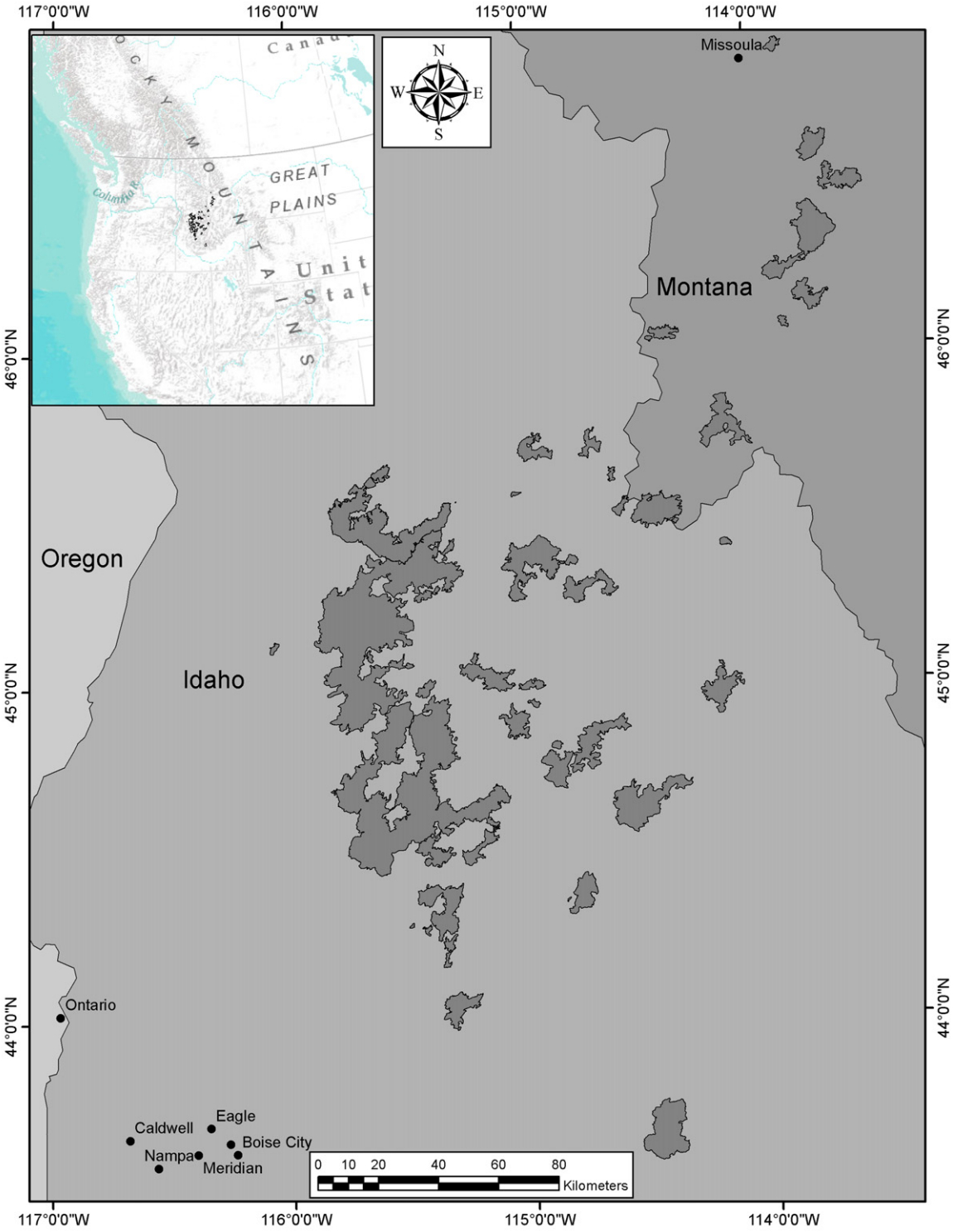

Figure 1. Study area of central Idaho and western Montana illustrating 42 wildland forest fires used in this analysis.

terminology can be found in recent reviews (Lentile *et al* 2006, Keeley 2009).

We retrieved classified dNBR data compiled by the Monitoring Trends in Burn Severity project (MTBS, www.mtbs.gov, Eidenshink *et al* 2007), which has mapped and classified dNBR for all western US fires greater than 4 km^2 since 1984 from multispectral data acquired by the Thematic Mapper (TM) sensor on Landsats 4 and 5, the Enhanced Thematic Mapper-plus (ETM+) sensor on Landsat 7, and the Operational Land Imager (OLI) sensor on Landsat 8. The dNBR raster for each fire is calculated using the near-IR band short-wave IR bands from near-anniversary dates, cloud-free pre- and post-fire scenes (Key and Benson 2006). We selected those MTBS fires with scene acquisition dates within a

Table 1. Daily areas burned (DAB) for 42 fires from central Idaho and western Montana. DABs were delineated using five or more consecutive daily infrared perimeter maps.

Year	Fire	Area analyzed (ha)	Number of DABs	Largest DAB (ha)
2005	Beaver Jack	479	25	327
2005	Burnt Strip Mountain	1991	57	459
2005	Center	51	8	17
2005	Reynolds Lake	162	24	27
2005	Rockin	104	11	63
2005	Signal Rock	917	59	147
2006	Boundary	109	13	43
2006	Meadow	410	29	91
2006	North Elk	216	19	57
2006	Potato	566	9	456
2006	Red Mountain	948	17	488
2007[a]	Cascade Complex[b]	2690	212	238
2007	Castle Rock	5238	104	1065
2007[a]	Cottonwood	943	38	159
2007	Fisher Point	2404	126	563
2007[a]	Goat	2245	41	1556
2007[a]	Lolo	1282	97	228
2007[a]	LoonZena	1151	127	301
2007[a]	Monumental	2245	58	604
2007[a]	Monumental-North Fork[c]	3438	176	353
2007[a]	Monumental-Yellow[d]	9758	118	1831
2007[a]	North Fork	5576	63	2849
2007	Papoose	146	28	54
2007[a]	Raines	989	74	302
2007[a]	Rattlesnake	9308	196	2664
2007[a]	Red Bluff	1983	44	538
2007[a]	Riordan	3975	107	861
2007	Rombo Mountain	441	37	110
2007[a]	Sandy	2794	25	971
2007[a]	Shower Bath	73	12	22
2007	Tag	4249	169	885
2007[a]	Trapper Ridge	370	18	86
2007	Wyman #2	4152	132	388
2007[a]	Yellow	669	27	126
2011	Castro	465	43	68
2011	Coyote Meadows	64	11	28
2011	Hells Half	121	12	37
2011	Indian	97	7	47
2011	Saddle	7219	125	5209
2011	Salt	52	132	3
2011	Up Top	1442	105	200
2011	West River Side	354	18	251
	Totals	84 801	2697	5209

[a] Fires that were sampled using two-year pre-fire satellite scene.
[b] Cascade Complex includes North Fork, Monumental, Yellow, Sandy, and Riordan fires of 2007 after they were mapped as one IR perimeter.
[c] Monumental-North Fork includes the Monumental and North Fork fires after they were mapped as one IR perimeter.
[d] Monumental-Yellow includes Monumental, North Fork, Sandy, and Yellow fires after they were mapped as one IR perimeter.

maximum separation of less than 30 days (to limit the impacts of changing sun angles) and three years between pre- and post-fire scenes (to limit impacts of vegetation growth and succession) according to best practices described by Key (2006). All dNBR calculations used approximately one-year post-fire satellite scenes. Three-year separation between pre- and post-fire scenes was required in order to accommodate burn severity mapping of several large wildfires of the 2007 fire season: the Rattlesnake Complex fires and the Cascade Complex fires (LoonZena and Raines). This three-year pre-fire satellite scene selection included 15 fires total, all of which occurred during the 2007 fire season (table 1). These fires accounted for 49 489 (58%) ha of area analyzed. The final size of each DAB was calculated as the area classified as having burned at low, moderate, or high severity by the MTBS project, and excluded the areas mapped by IR perimeters but not mapped by MTBS, scan-line corrector errors of Landsat 7, non-processed masked areas, and the 'unburned to low' and 'increased greenness' categories of MTBS.

2.4. Burn severity proportions

We calculated proportions of low, moderate, and high burn severity classes for every DAB equal to or greater than 0.81 ha. The threshold of 0.81 ha was selected as a minimum size because it corresponds to a 3×3 Landsat pixel area (90 m × 90 m). This also allowed us to stipulate that the area was actual fire growth and not subpixel-scale differences in interpretation of IR perimeter data. Loss of area due to removal of DABs of less than 0.81 ha totaled 655 ha (<0.008% of area). We mapped 2697 DABs for analysis, totaling 84 801 ha.

2.5. Statistical analysis

We calculated Kendall's Tau (τ, Kendall 1976) for correlations between proportion high burn severity and the size of DABs for both all DABs and only DABs larger than 108 ha, the 95th percentile size threshold of all DAB sizes. We did this to specifically test if large DABs (large fire runs) functioned differently than the dataset as a whole and correlated to significantly greater area classified as high severity. We considered alternative approaches, such as the Bayesian-based approaches used by Mallek *et al* (2013), including generalized linear mixed effects models. With the very high variability in the proportion burned severely, especially with small to moderately sized DABs, we opted for the simpler, albeit less powerful approach because there was no presumption of underlying probability distribution. To determine if there was a significant difference between smaller (<108 ha) and the largest (>108 ha) DABs above the 95th percentile, we conduct a Kolmogorov–Smirnov test (Conover 1971) of significant difference between proportion distributions, stratified by severity class.

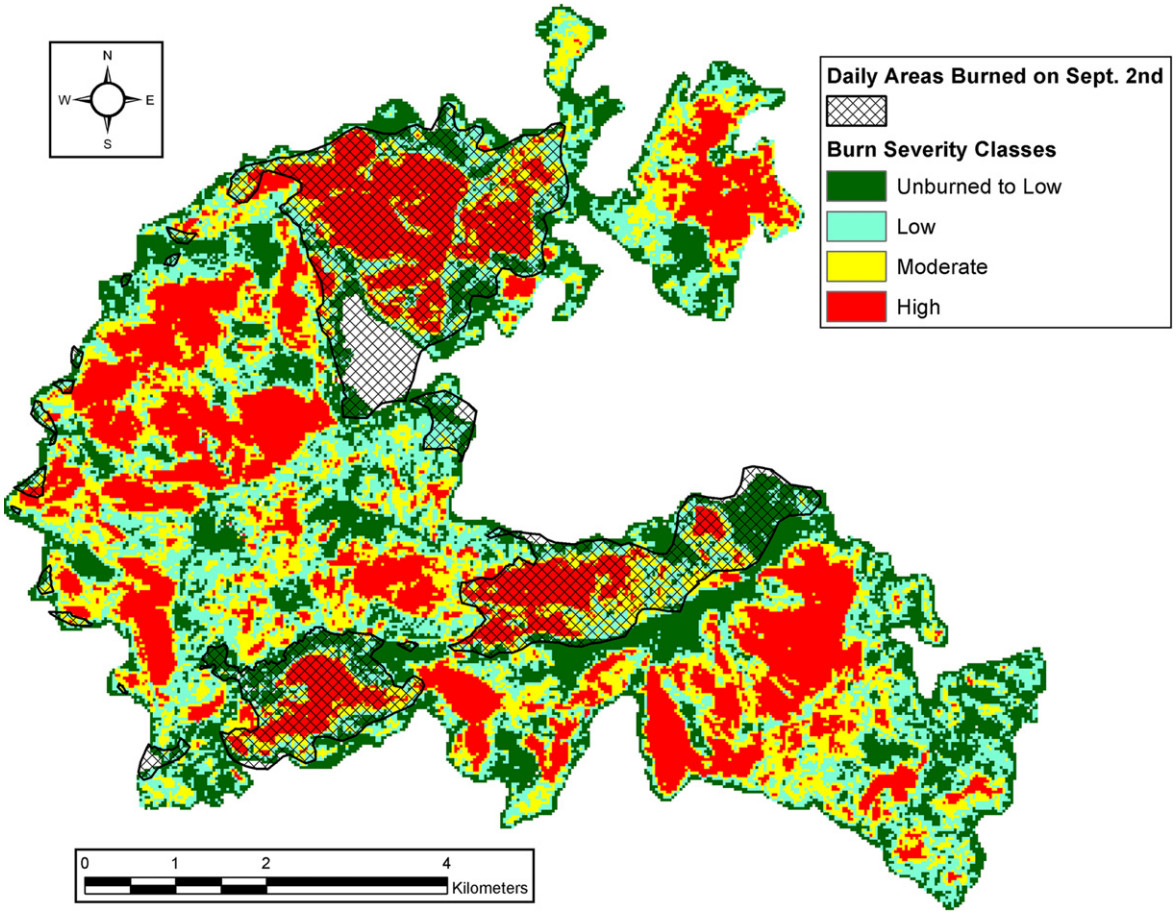

Figure 2. Example of daily areas burned (DAB) that occurred on the Burnt Strip Mountain Fire in central Idaho on 2 September 2005, and the associated burn severity. Areas within DABs other than low, moderate or high burn severity (i.e., white areas outside infrared perimeter, or unburned to low) were removed from analysis.

3. Results

DABs varied in size from 0.81 ha to 5209 ha (figure 3). We found that the proportion burned with high severity was significantly, but weakly, positively correlated with DAB size ($\tau = 0.299$, $P < 0.001$) when all DAB sizes were analyzed (figure 4). Proportion low severity ($\tau = -0.169$, $P < 0.001$) and proportion moderate severity ($\tau = -0.043$, $P < 0.001$) were both significantly but weakly and negatively correlated with DAB size. The 135 DABs that exceeded the 95th percentile (>108 ha) comprised 64% (54 195 ha) of the total burned area analyzed. When analyzing only these largest DABs, the proportion burned with high severity was also weakly, but positively correlated to area burned ($\tau = 0.118$, $P = 0.043$).

Median proportions of burn severity classes within the smaller (⩽108 ha) DABs below the 95th percentile were 43% low severity, 33% moderate severity, and 13% high severity; with median proportions within the largest DABs: 23% low severity, 26% moderate severity, and 49% high severity. (figure 5). Smaller DABs (⩽108 ha) were characterized by significantly greater proportions of low ($D = 0.332$, $P < 0.001$) and moderate ($D = 0.320$, $P < 0.001$) severity fire, while DABs exceeding the 95th percentile (>108 ha) were characterized by a significantly greater proportion of high severity fire effects ($D = 0.480$, $P < 0.001$).

4. Discussion

It is somewhat counter-intuitive and yet ecologically important that proportion burned at high severity was only weakly correlated with both large and small sizes of daily areas burned in the 42 large wildland fires we analyzed. Although large DABs may burn at significantly greater proportion of high severity at times, variation is high. When burned areas occurred below 95th percentile thresholds, in this study 108 ha, DAB had little or no influence on severity. Larger, more severely burned areas are slower to regenerate to trees (Lentile *et al* 2005), experience delayed vegetation recovery (White *et al* 1996), and may pose more risk for erosion (Robichaud *et al* 2000), and have a greater influence on wildlife habitat (Romme and Knight 1981). Because of these increased risks, and often due to the perceptions and media portrayals of large runs as being 'catastrophic,' these areas are often prioritized during post-fire rehabilitation efforts. Our results suggest this prioritization may be unnecessary—large fires and large fire runs are not all burned with high severity.

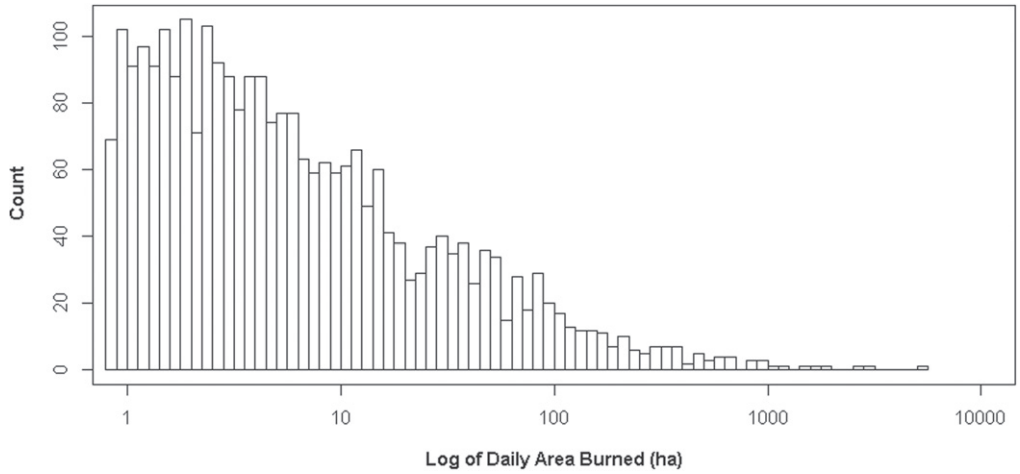

Figure 3. Histogram of 2697 individual daily areas burned used for this analysis. Note use of log scale. Number of Bins = 70.

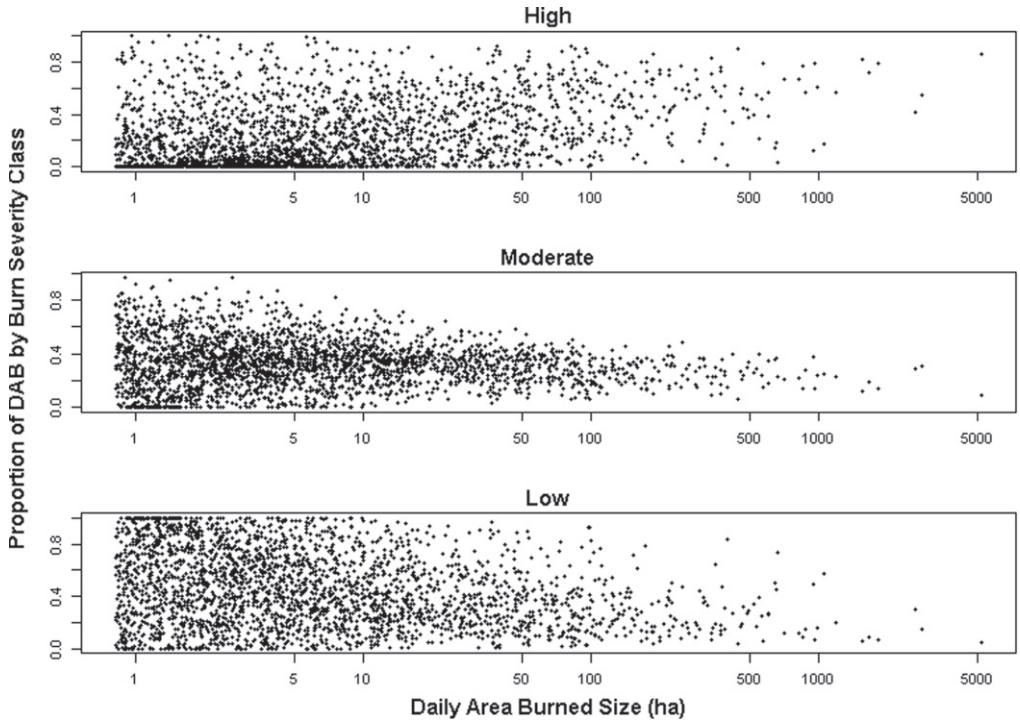

Figure 4. Scatterplots of proportions of low, moderate, and high burn severities for 2697 daily areas burned (DABs) relative to size of DAB.

Burn severity can be related to environmental conditions, including topography, weather, climate and vegetation (Kushla and Ripple 1997, Holden *et al* 2009, Dillon *et al* 2011). Available fuel can play a predominant role in determining fire severity, particularly in the wildland urban interface (Hudak *et al* 2011). The fires we analyzed burned through many different forest vegetation types and conditions that surely influenced the fire behavior and effects. Birch (2013) analyzed the environmental controls on burn severity at 10 819 randomly located points in these fires. He found that percent existing vegetation cover was most important, with other topography and vegetation variables more important than climate and weather. One of the variables that is difficult to test in these studies is the role of wind events in determining burn severity, even though wind is well established as being critical to driving fire behavior (Bessie and Johnson 1995). Since wind events are a primary driver of large fire runs in a single day (Westerling *et al* 2004), the lack of a strong correlation between high burn severity and DAB size for both groups (i.e., all DABs and only large DABs) found here suggests that wind is not necessarily a primary driver of burn severity in forests of the Northern Rockies, but this warrants further study to understand the causes of burn severity. Both Dillon *et al* (2011) and Birch (2013) found wind to be less of a contributor to burn severity than topography, vegetation, and climate factors.

The dNBR is imperfect in observing all aspects of burn severity (Lentile *et al* 2009, Smith *et al* 2010), though it has

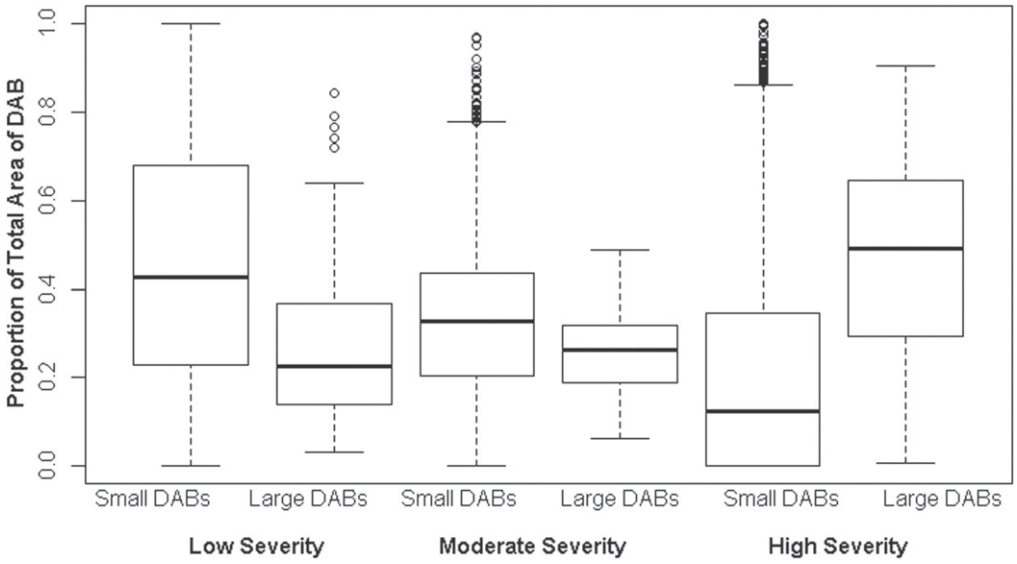

Figure 5. Boxplots of proportion distributions for large and small daily areas burned (DAB) for three burn severity classes. Large DABS $n = 135$ (95th percentile) small DABS $n = 2562$ (the remainder).

been found to be correlated with percent tree mortality and less strongly with other fire effects on the understory or the ground surface (Hudak *et al* 2007, Smith *et al* 2007). For areas of low biomass prior to fire, the relativized dNBR (Miller and Thode 2007) or the RBR (Parks *et al* 2014) are useful, but 81% of the area we analyzed was forested, so we chose to use dNBR. Additionally, values of both ground observed and remotely sensed burn severity represent similar conditions at higher burn severity values (Cocke *et al* 2005). We used data from MTBS, but classification thresholds and perimeter delineation are subjectively determined by analysts and may be inconsistently applied (Eidenshink *et al* 2007, Kolden and Weisberg 2007). Additionally, the area analyzed from across the four years may not be a full representation of the variability in conditions under which fires occur in the Northern Rockies. The effects of wildland firefighting suppression tactics, such as burnout operations, which have the ability to alter fire activity, are not considered here although they may modify the naturally occurring area burned and burn severity, as might prior fire and vegetation (fuel) management.

Understanding the behavior and evolution of large fires, as well as their ecological effects, is critical for fire and land managers. Large fires account for the majority of area burned (Calkin *et al* 2005), and the trend towards increasing size and frequency of large fires is expected to continue through the 21st century (Running 2006, Littell *et al* 2009, Littell 2011, Spracklen *et al* 2009). Large DABs are of particular concern, since their spread rates often present challenges for evacuating civilians and safely and effectively managing and suppressing wildfires (Rothermel 1993, Governor's Blue Ribbon Fire Commission 2004). Rapidly burning fires and related large fire growth have contributed to the death of many wildland firefighters in Mann Gulch (Rothermel 1993), South Canyon (Rosenkrance *et al* 1994), Cramer (Office of Inspector General 2004), and most recently the Yarnell Fire, which claimed the lives of 19 fire fighters (Arizona State Forestry Division 2013). Further research can potentially help identify both landscape characteristics conducive to large DABs and management actions (such as vegetation treatments or suppression approaches) that will minimize their negative impacts. The use of IR perimeter mapping to characterize DAB rates from multiple explanatory environmental variables will contribute to improved understanding of fire effects and fire behavior.

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