BURN SEVERITY AND AREAS OF DAILY FIRE GROWTH

FOR 42 FOREST FIRES IN IDAHO AND MONTANA, 2005 – 2011

A Thesis

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Abstract

This work consisted of two studies of burn severity using infrared perimeter maps and satellite-inferred burn severity data, differenced Normalized Burn Ratio, from 42 wildland fires from central Idaho and western Montana from 2005 to 2007, and 2011.

Study 1 examined the proportion of burn severity categories for individual daily areas burned. We defined 2,697 areas, from which we calculated the proportion of three burn severity classes. The proportion of high severity was weakly correlated with size of area burned. Large areas burned do not consistently produced larger proportions of high severity.

Study 2 analyzed burn severity relative to 20 environmental variables using the Random Forest machine learning algorithm. We used ten daily weather observations, eight 34-yr climate percentiles, seven topographical index measurements, and four vegetation characteristics from 10,819 randomly located points. We found that higher percentage existing vegetation cover had larger influences on changes in burn severity.

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Is Proportion Burned Severely Related to Daily Area Burned?

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Abstract

We examined the relative proportion of burn severity categories 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 2,697 individual daily areas burned (0.81 - 5209 ha, median 4.5 ha), 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 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 individually mapped burned areas covering 84,801 ha and 358 fire days. This is important as high severity areas have a large influence on successional processes and our results indicate that large proportions of high severity are not a result of large fire growth.

Keywords: *area burned, burn severity, daily areas of growth, dNBR, fire progression, forest fires, infrared perimeter mapping*

Introduction

Several historic fires have occurred in the U.S. northern Rockies over the last century, notably the Great Fires in 1910 (Pyne et al. 1996), the 1967 Sundance Fire, which burned more than 20,000 ha in just nine hours (Anderson 1968), and the 1988 Yellowstone Fires (Turner et al. 1994). The number of wildland fires in the western United States has increased in recent decades (Westerling et al. 2006), with similar increases in fire extent (Littell et al. 2009; NWCG 2009), costs of management (Butry 2001), and threats to people and property. The proportion of area burned with high severity has also increased in some areas (Dillon et al. 2011), where severity is commonly defined as the degree of ecosystem change following a fire (Ryan and Noste, 1985; Morgan et al. 2001). Individual large fires consume significant amounts of biomass (Hicke et al. 2013) and can have long-term ecological effects on vegetation structure and composition (Kashian et al. 2006; Romme et al. 2011), but little is known about the degree of overall ecological change caused by larger fires (Turner et al. 1997; Keane et al. 2008) or in areas of rapid fire growth (Turner et al. 1994). When large fire “runs” result in large area burned in a day, high tree mortality does not always result (Hudak et al. 2007; Lentile et al. 2007).

Fires that burn under severe fire weather conditions have a higher proportion of crown fires (Turner et al. 1994) and higher severity (Bigler 2005). Extreme weather and high severity fire many times occur together (Bessie and Johnson 1995), with wind playing a large part in fire intensity and fire extent (Beer 1991; Rothermel 1991). Using daily area burned maps from the 1988 Greater Yellowstone Fires, Turner et al. (1994) found that when daily area burned exceeded 1250 ha, about 50% of the area burned with crown fire. Heward et al. (2013) found that high burn severity and fire intensity generally occur concurrently in remotely sensed data for 16 wildfires across the western U.S

We set out to test if large daily areas burned produced a greater proportion of high burn severity or if they simply burn more area. 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 large fire runs (which we define as daily area burned greater than 105 ha), usually caused by extreme fire weather, resulted in a higher proportion of high burn severity.

Methods

Study Area

The U.S. northern Rockies have been identified as having changes in seasonal warming and earlier spring snowmelt that have led to increases in the number of large wildfires (Westerling et al. 2006). The region has experienced large fires throughout the 20th century (Morgan et al. 2008), a trend expected to continue through the 21st century (Littell et al. 2009; Spracklen et al. 2009). We selected 42 fires from this region (Figure 1:1 and Table 1:1) during the years 1984-2011, based on the availability of both dNBR indices and IR perimeter maps for a given fire.

Infrared 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 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 (Zajkowski 2012, *personal communication*).

Spatial maps of Daily Area Burned (DAB) (see Figure 1:2 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. Fire area from the first mapped day was used to calculate area burned for the next day, but was not included 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 IR perimeter extended spatially beyond the current day perimeter, we excluded that overlap from analysis. With the unknown accuracy of IR mapping, we buffered IR perimeter maps by 30 m. We were able to map 136,634 ha of daily fire progression using IR perimeters. We mapped 84,456 ha of DABs for analysis. Size of DABs was calculated as the area that was mapped as having a burn severity category of Low, Moderate, and/or High.

Burn Severity Inferred From Differenced Normalized Burn Ratio

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). We use the differenced Normalized Burn Ratio (dNBR) (Key and Benson 2006), a spectral index calculated from multispectral remotely sensed data, to infer severity. We acknowledge that dNBR [unitless] is in itself not a measure of severity, but given this spectral index has shown reasonable correlations with aboveground vegetation mortality (e.g., Lentile et al. 2009) and other surface changes (Smith et al. 2007); the dNBR severity classifications of low, moderate, and high can be effectively considered as proxies for those surface changes. A detailed overview of severity methods and terminology can be found in recent reviews (Lentile et al. 2006; Keeley 2009).

We retrieved classified differenced Normalized Burn Ratio (dNBR) data compiled by the Monitoring Trends in Burn Severity (MTBS) program (www.mtbs.gov) (Eidenshink et al. 2007). MTBS has mapped burn severity for all western U.S. fires greater than 4 km^2

(1000 acres) 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-infrared and short-wave infrared 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 maximum separation of less than 30 calendar 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). Three-year separation between pre- and post-fire scenes was required in order to accommodate burn severity mapping of significant large wildfires of the 2007 fire season: Rattlesnake Complex, Cascade Complex and its corresponding individual fires, LoonZena, and Raines Fires. This three-year pre-fire satellite scene selection included 15 fires total, all of which occurred during the 2007 fire season (Table 1:1). These fires accounted for 77,456 (57%) ha of IR mapped fire progression. All dNBR calculations used approximately one-year post-fire satellite scenes. Areas that were not classified as high, moderate or low burn severity were excluded from calculations of proportion burned and daily area burned. Thus, we excluded areas mapped by IR perimeters but not mapped by MTBS, line-scan corrector errors of Landsat 7, non-processed masked areas, and the Unburned to Low and Increased Greenness categories of MTBS.

Burn Severity Proportions

We calculated proportions of Low, Moderate, and High burn severity classes for every DAB larger than 0.81 ha (Figure 1:3), resulting in 84,801 ha analyzed. The threshold of 0.81 ha was selected as a minimum size because it corresponds to a 3 X 3 Landsat pixel area (90 m x 90 m). This also allowed us to stipulate that the area was actual 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 654.8 ha (<0.008% of area) and resulted in 2,697 DABs used for analysis (46% of all possible DABs).

Statistical Analysis

We calculated Kendall Tau (Kendall 1976) correlations between proportion burned with high burn severity and the size of DABs. The median proportion of each burn severity class was also calculated. We then repeated the median proportion and Kendall Tau correlation calculations for DABs larger than 105 ha, the 95th percentile of all DAB sizes. We did this to specifically test if large DABs (large fire runs) correlated to increases in area burned severely.

Results

We analyzed a total of 358 days of IR-defined fire progression with 84,801 ha burned in 42 fires and 2,697 DABs (Table 1:1). DABs varied in size from 0.81 ha to 5209 ha (Figure 1:4). Median proportions across all DABs were: 41% 'Low', 32% 'Moderate', and 14% 'High'. We found that the proportion burned with high severity was poorly correlated with DAB (Tau= 0.299, P-value=<0.0001) for all DAB sizes. Only 136 DABs were large (> 105 ha) but these comprised nearly 64 % (54,299 ha) of the total burned area analyzed. Large DABs covered 95 days of fire growth. The largest DAB (5,209 ha) included in our analysis occurred August 22, 2011 on the Saddle Creek Fire (Figure 1:5) near North Fork, ID. The proportion burned with high severity was also poorly correlated with area burned for large DABs (Tau= 0.109, P = 0.0599). Median proportions for burn severity within large DABs were: 22% 'Low', 26% 'Moderate', and 49% 'High'.

Discussion

It is somewhat counter-intuitive and yet ecologically important that proportion burned at high severity was poorly correlated with area burned in the 42 large wildland fires we analyzed. The median proportion of high severity is much higher for our 136 large DABs (49%) than across all DABs (14%). Thus, although large DABs may produce a larger proportion of high severity at times, this increase is not consistent across all areas burned. Larger, more severely burned areas are slower in terms of tree regeneration (Lentile et al. 2005), vegetation recovery (White et al. 1996), 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.

Burn severity can be related to environmental conditions, including topography, weather, climate and vegetation (Kushla and Ripple 1997; Holden 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). One of the variables that is difficult to test in these studies is the role of wind events in determining fire 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 DAB size and high burn severity 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 et al. (in review) found wind to be less of a contributor to burn severity than topography, vegetation, and climate factors.

Our analysis has limitations. The dNBR is imperfect in observing all aspects of burn severity (Lentile et al. 2009; Smith et al. 2010), though it has 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). 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. Wildland firefighting suppression tactics, such as burnout operations, which have the ability to alter larger areas of fire activity are not considered here but 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; 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, South Canyon, Cramer, and most recently the Yarnell Fire, which claimed the lives of 19. 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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Table 1:1. 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. "+" Indicates fires that were sampled using three-year pre-fire satellite scene.

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^{+}	Cascade Complex*	2690	212	238
2007	Castle Rock	5238	104	1065
2007^{+}	Cottonwood	943	38	159
2007	Fisher Point	2404	126	563
2007^{+}	Goat	2245	41	1556
2007^{+}	Lolo	1282	97	228
2007^{+}	LoonZena	1151	127	301
2007^{+}	Monumental	2245	58	604
2007^{+}	Monumental-North Fork**	3438	176	353
2007^{+}	Monumental-Yellow***	9758	118	1831
2007^{+}	North Fork	5576	63	2849
2007	Papoose	146	28	54
2007^{+}	Raines	989	74	302
2007^{+}	Rattlesnake	9308	196	2664
2007^{+}	Red Bluff	1983	44	538
2007^{+}	Riordan	3975	107	861
2007	Rombo Mountain	441	37	110
2007^{+}	Sandy	2794	25	971
2007^{+}	Shower Bath	73	12	22
2007	Tag	4249	169	885
2007^{+}	Trapper Ridge	370	18	86
2007	Wyman #2	4152	132	388
2007^{+}	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	2,697	5,209

* Cascade Complex includes North Fork, Monumental, Yellow, Sandy, and Riordan fires of 2007 after they were mapped as one IR perimeter.

** Monumental-North Fork includes the Monumental and North Fork fires after they were mapped as one IR perimeter.

*** Monumental-Yellow includes Monumental, North Fork, Sandy, and Yellow fires after they were mapped as one IR perimeter.

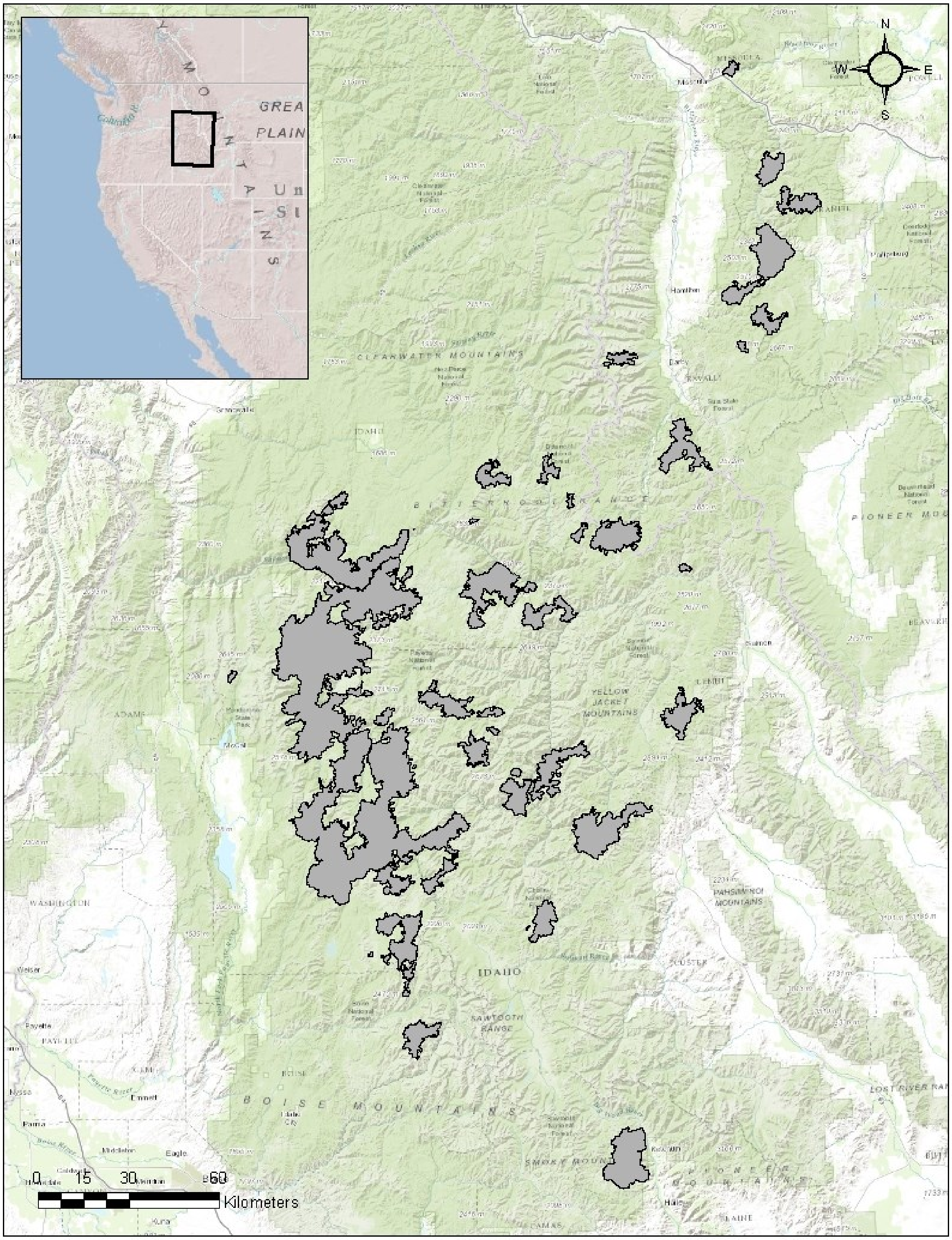

Figure 1:1. Study area of central Idaho and western Montana illustrating 42 wildland forest fires used in this analysis.

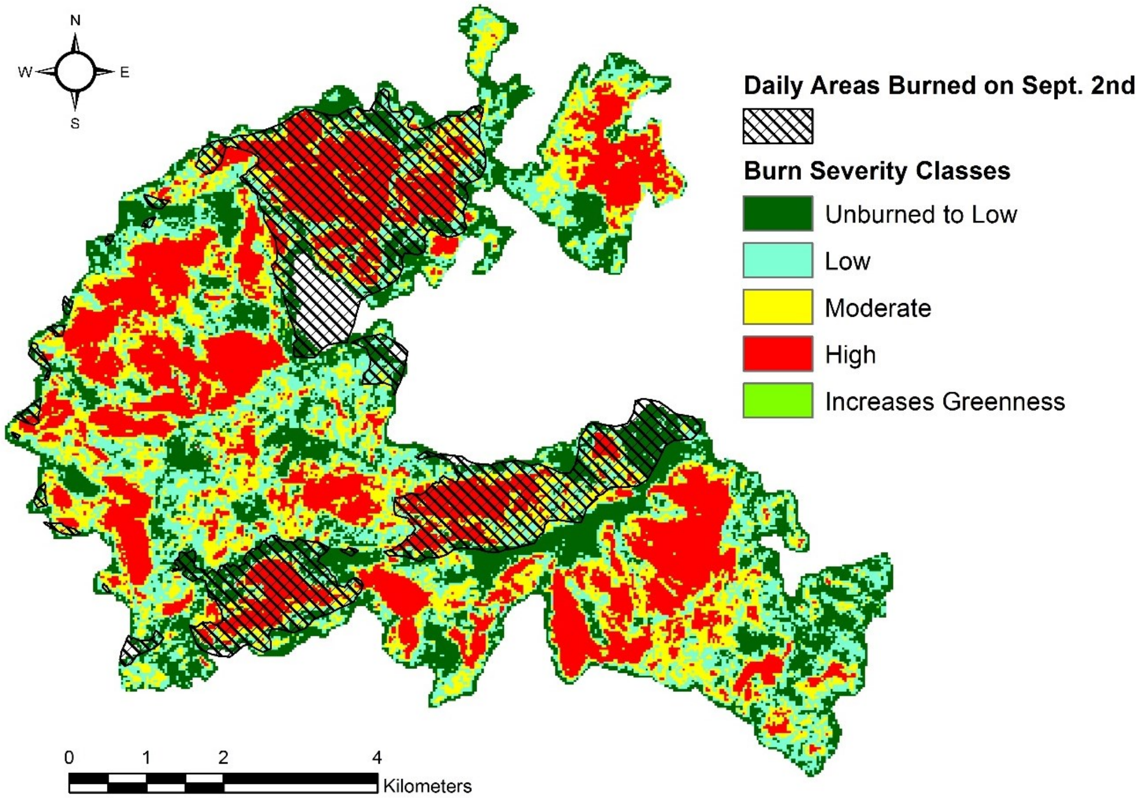

Figure 1:2. Example of Daily Areas Burned (DAB) that occurred on the Burnt Strip Mountain Fire in central Idaho on September 2, 2005, and the associated burn severity. Areas within DABs other than low, moderate or high burn severity (i.e., white areas outside the burn severity perimeter, or unburned to low or increased greenness) were removed from analysis.

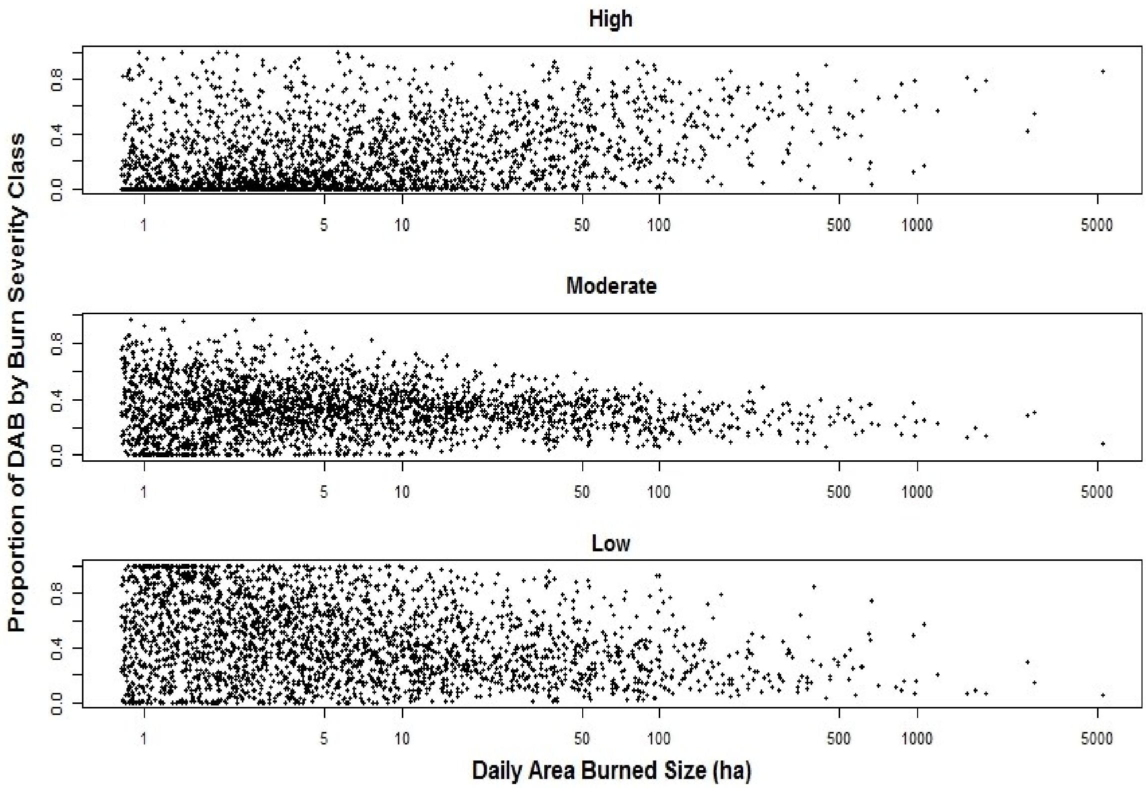

Figure 1:3. Scatterplots of proportions of low, moderate, and high burn severities for 2,697 Daily Areas Burned (DAB) relative to size of DAB.

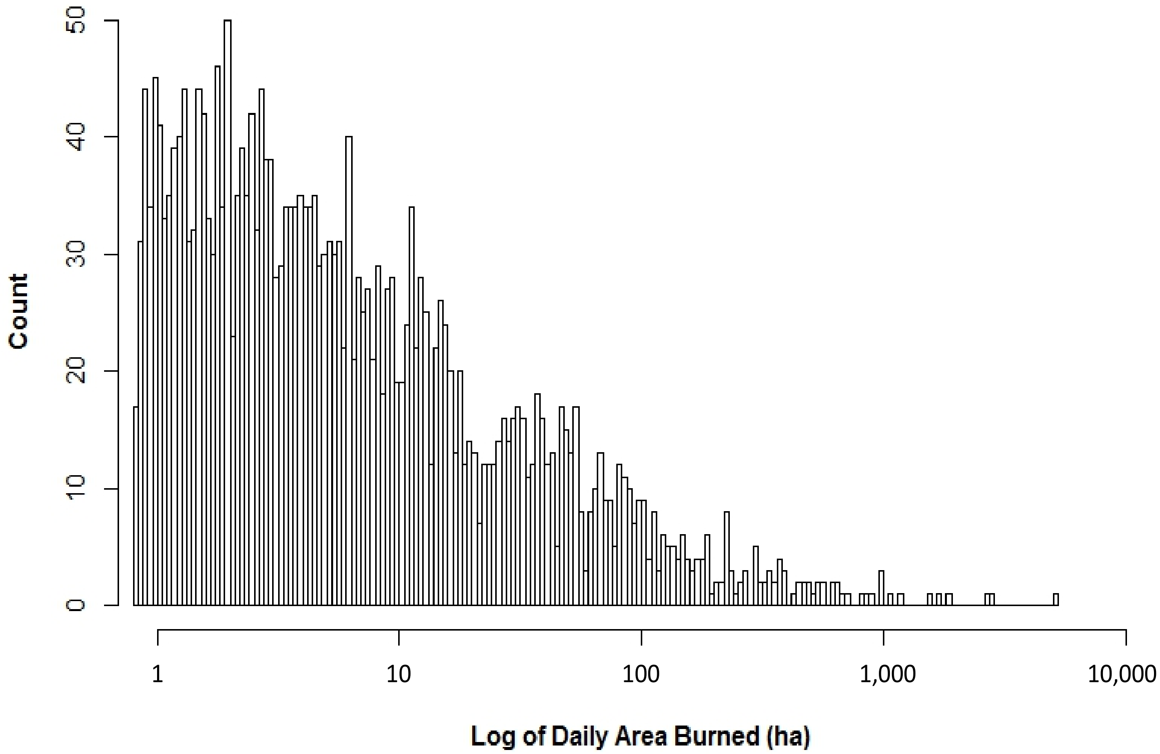

Figure 1:4. Histogram of the 2,697 individual Daily Areas Burned used for this analysis. Note use of log scale. Bin size = 150.

Figure 1:5. Convective smoke column from the 2011 Saddle Complex near North Fork, ID. On this day, 22nd of August 2011, 5,209 ha burned with 86% high severity. This is the largest individual Daily Area Burned we analyzed as recorded by IR perimeter mapping. (Photo by Bob Tincher)

Daily Fire Weather And Environmental Factors Influencing Burn Severity Of 42 Forest Fires In Central Idaho And Western Montana, 2005-2007 And 2011

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Abstract

Burn severity as inferred from satellite-derived differenced Normalized Burn Ratio (dNBR) has been used in many large-scale studies evaluating fire impacts on ecosystems but the environmental controls on burn severity across large forest fires are poorly understood. We used infrared perimeter maps on forty-two large forest fires in central Idaho and western Montana to locate areas that burned in a known 24-hour period. We then used Random Forest to analyze dNBR within those daily areas burned relative to five daily weather observations, seven 34-yr climate percentiles, five topographical measurements, and three vegetation characteristics at 10,819 randomly located points within the daily areas burned. We were able to sample 353 fire days with daily areas burned totaling 111,200 ha. We found that percent existing vegetation cover had the largest influence on changes in burn severity.

Although this could be due to scale, given many topography and vegetation variables (30 m) accounted for more of the variability than many climate and weather (4 km) variables, we posit that this reflects the influence of local "bottom-up" fuel and topography variables on burn severity and that vegetation conditions due to prior disturbance and management affect vegetation response even when fires burn severely.

Keywords: *area burned, burn severity, dNBR, infrared perimeter mapping, Random Forest, wildland fire*

Introduction

The size and number of wildland fires in the western United States has increased in recent decades (Westerling et al. 2006; Littell et al. 2009) and the northern Rocky Mountains have accounted for the majority of area burned in the western US for the last several decades (Westerling 2008). Longer fire seasons with more and larger fires in recent decades in this region are correlated with warmer springs (Westerling et al. 2006). North America and specifically, the western US is considered to be vulnerable to future climate-driven increases in the frequency of large and high intensity fires (Westerling et al. 2006; Spracklen et al. 2009; Moritz et al. 2012). Fires impact vegetation, subsequent disturbance effects, and ecosystem functions (Bowman et al. 2009), so understanding the relative importance of climate, weather, vegetation and topography to burn severity will inform both science and management.

Area burned severely has increased in some locations since 1984. Miller et al. (2009) found increases in extent of stand replacing high severity fires in the Sierra Nevada and southern Cascade Mountains, but Hanson and Odion (2013) did not. Burn severity increased in the Gila National Forest of the southwestern US (Holden et al. 2009). High severity fires may have long-term effects on ecosystem structure and composition (Kashian et al. 2006; Goetz et al. 2007; Romme et al. 2011). Burn severity has been defined many ways (Lentile et al. 2006; Keeley 2009). We define it as the degree of ecosystem change following a fire (Ryan and Noste, 1985; Morgan et al. 2001).

Fire causes substantial changes in the reflective properties of the fire landscape (Jakubauskas et al. 1990; Landmann 2003). Surface reflectance changes from days to weeks following fires (Trigg and Flasse 2000) and fire intensity affects the subsequent surface reflectance in a wide variety of ecosystems (Cocke et al. 2005; Smith et al. 2005; French et al. 2008). This change makes possible the interpretation of burn severity using spectral data. Satellite-derived time series have been used to evaluate ecosystem recovery from fire for many science and management applications (Morgan et al. 2001; Diaz-Delgado et al. 2003; Kotliar et al. 2003). A common definition, used to capitalize on the availability of remotely-sensed data for studying fire, is the degree of change pre-fire to one year post-fire as indicated by the differenced Normalized Burn Ratio (dNBR) (Key and Benson 2006). The dNBR spectral index has been correlated with field-based assessments of burn severity (Van Wagtendonk et al. 2004; Cocke et al. 2005; De Santis and Chuvieco 2009; Jones et al. 2009). The Monitoring Trends in Burn Severity program (MTBS http://www.mtbs.gov) maps dNBR for all large fires (>405 ha) from 30-m Landsat satellite data (Eidenshink et al. 2007).

Environmental conditions influence fire growth, occurrence, and extent, but the degree to which they influence burn severity is unclear. Extreme fire weather conditions and stand-replacing crown fire many times occur together (Bessie and Johnson 1995) with wind influencing both fire behavior and fire growth (Beer 1991; Rothermel 1991). Littell et al. (2009) related area burned from 1916 to 2003 to summer drought across forested ecosystems of the western US. Abatzoglou and Kolden (2011) found similarities in conditions for fire growth for fires in interior Alaska from 1980 to 2007. Both Morgan et al. (2008) and Heyerdahl et al. (2008) found that years of widespread fires in forests of the northern Rockies had warm, dry summers following warm springs. The environmental factors influencing burn severity may be distinctly different than those influencing fire occurrence and extent (Romme and Knight 1981; Christensen et al. 1989; Heyerdahl et al. 2002; Dillon et al. 2011). Burn severity can be highly variable, even when large areas burn in a single 24-hr period (Birch et al. 2013 Chapter 1).

Many studies that have considered burn severity have specifically focused on the amount and proportion of areas burned with high severity, especially areas with stand-replacing fires (e.g., Holden et al. 2009; Thompson and Spies 2009; Dillon et al. 2011; Hanson and Odion 2013). Turner et al. (1994) examined the 1998 Greater Yellowstone Fires using daily fire growth maps (Rothermel 1994) and found that total daily area burned was mainly explained by 100-hr and 1000-hr fuel moisture. Jones et al. (2009) found that above average summer highs and low precipitation were important in growth and severity of the largest fire of the North Slope of Alaska. Dillon et al. (2011) found that topography had the largest influence on the probability of high severity fire, and that climate was more important in years of widespread fires.

Objective

Our objective was to understand how burn severity varies with topography, climate, vegetation, and daily weather. We build on the study of Dillon et al. (2011) to test their hypothesis that topography, fuels and localized weather conditions were more important than climatology in influencing burn severity. We focused on daily area burned because we could link weather to the day fires occurred. We expect fine-scale weather, especially wind, to influence burn severity. We add vegetation characteristics and daily weather observations in order to further understand the multiple factors that might influence burn severity. We used Random Forest to examine how 20 different topography, vegetation, daily weather, and climate factors influenced variations in continuous dNBR and compared results for all and for the largest daily areas burned. We hypothesized that climate and weather would be relatively more important influences on burn severity when large forest fires burned large areas, usually during extreme fire weather.

Methods

Study Area

We examined 42 forest fires in central Idaho and western Montana from 2005 - 2007 and 2011 (Figure 1:1 and Appendix A). Central Idaho and western Montana include diverse forest types, topography, weather and climate. This area has had many fires in recent decades (Westerling et al. 2006, Morgan et al. 2008) with varying burn severity (Dillon et al. 2011). The US northern Rockies have been predicted as having the highest risk of climate-affected change in area burned (Spracklen et al. 2009). This area has a continental climate with cold winters and warm summers. The 42 fires of this study lie within the US climate divisions of ‘Central Mountains’ of Idaho and ‘Western’ of Montana (http://www.esrl.noaa.gov/psd/data/usclimdivs/data/map.html).

Burn Severity Data

Continuous differenced Normalized Burn Ratio (dNBR) data were obtained from the Monitoring Trends in Burn Severity project (MTBS) (Eidenshink et al. 2007). Fires were selected based on the same requirements as described in Chapter 1 (see Chapter 1*, Burn Severity Inferred From Differenced Normalized Burn Ratio*) and thus included all fires with both MTBS data and daily infrared (IR) fire progression maps for at least 5 days. We adjusted the raw dNBR values obtained from the MTBS project by the dNBR offset. The dNBR offset is a value representing the average difference in NBR values between unburned areas of pre- and post-fire satellite scenes. This value accounts for spectral changes that occurred not as a result of the fire.

Random Sample Point Selection

Using IR perimeter maps (see Chapter 1, *Infrared Perimeter Mapping*) from the 42 selected fires we chose random points (Figure 2:1) for which we obtained daily weather observations, topographical measurements, vegetation characteristics, and climate data. For the 42 fires we were able to establish 394 days of area burned larger than 0.09 ha, the area of a single Landsat pixel, which totaled 171,375 ha. Loss of areas less than 0.09 ha totaled 13 ha (<0.0001%). We removed a 30-m IR perimeter buffer resulting in a total of 136,634 ha (79.7% of total IR area) and 7,216 daily areas burned. We further constrained our sampling to 111,397 ha (64.9% of total IR area) of forests using the Landfire Existing Vegetation Type Forest geospatial layers (NatureServe 2011) (Appendix B). We used Existing Vegetation Type as it represents the vegetation composition. Landfire Version LF2001 was used for all Landfire data layers for fires from 2005 to 2007, with Landfire version LF2008 used for 2011 fires. We randomly selected sampling points across all 42 fires with a minimum distance of 127.5 m between points. We established the minimum distance of 127.5 m as it is the rounded minimum distance required such that no two points were sampled from adjacent Landsat pixels. Setting this minimum sampling distance precluded the confounding factor of spectral mixing between pixels that are adjacent to one another, known as the adjacency effect (Otterman and Fraser 1979; Jianwen et al. 2006). This minimum distance eliminated the ability to sample from every one of 394 possible IR progression days, missing 41 days and 126 ha (<0.002 % of total area). Of these 41 days, only five days were not sampled on another fire. Ultimately, we sampled 10,819 points in 353 fire days with total daily area burned of 111,397 ha.

Topographical, Vegetation, Weather, And Climate Data

For each of the randomly located points, we obtained data for 20 topography, vegetation, weather, and climate predictors. We initially identified 47 predictors as potentially influential to burn severity based on the literature (See Appendix F for full list of 47 predictors). We removed 12 predictor variables that were highly correlated (Spearman's Rho > 0.75) with another variable. We used Random Forest analysis of dNBR at our random points (see next section), which resulted in an optimum model of 20 predictors. We identified the optimum model (i.e., fewest predictors that could best predict changes in dNBR) by running a model selection routine that tested the performance of models with successively fewer predictor predictors. The 20 optimum predictors are described below.

Topographical- We examined five topography measurements from a 30-m Digital Elevation Model (DEM). We used two types of topographic information: slope and aspect and slope position and curvature. Indices of slope and aspect were: Slope (%), Heat Load Index (McCune and Keon 2002), Topographic Solar Radiation Aspect Index (Roberts and Cooper 1989), and Slope-Cosine-Aspect Index (Stage 1976). The measurement of slope position and curvature was a Topographic Position Index (Weiss 2001) calculated in an annular neighborhood with a 2,000 m outer radius and 300 m inner radius. See Appendix C for descriptions of each topographical predictor.

Vegetation- Three representations of pre-fire vegetation characteristics were obtained from Landfire (www.landfire.gov): Fuel Characteristics Classification System, Environmental Site Potential, and Existing Vegetation Cover. Landfire geospatial layers provide 30 m pixel representations of vegetation characteristics (Landfire 2013). Surface fuels layers were sampled from the Fuel Characteristics Classification System fuelbeds. Fuel Characteristics Classification System layers represent fire environment fuelbeds that contribute to fire behavior and effects (Riccardi et al. 2007). Environmental Site Potential represents the vegetation characteristics that could be at a given location and conditions that would become established (late or climax stages) without disturbance (http://www.landfire.gov/National ProductDescriptions19.php). Existing Vegetation Cover as expressed by Landfire data layers in forested areas is percent tree canopy cover from 10% to 100%, by 10% intervals. Areas with less than 10% tree canopy are not considered forested areas by Landfire classifications. See Appendix D for descriptions of vegetation layer obtained from Landfire.gov.

Weather- We selected five daily weather variables based on the known daily areas burned. These five predictors were retrieved from a 4-km gridded modeled dataset. The spatially gridded climate data were combined with temporal attributes of regional-scale reanalysis and daily gauge-based precipitation (Abatzoglou 2011; Abatzoglou and Brown 2011) (http://nimbus.cos.uidaho.edu/METDATA/). Weather predictors included Maximum and Minimum Relative Humidity, Duff Moisture Code, Burning Index, and Energy Release Component. See Appendix E for descriptions of weather predictors. Additionally, we calculated values of wind-aspect alignment as the absolute value of aspect direction minus wind direction with values from 0 and 360 having perfect up-slope wind, to 180 having down-slope wind (Examples: absolute value of (180 aspect direction - 359 wind direction) = 179, down-slope wind; absolute value of (225 aspect direction - 270 wind direction) = 45, partial up-slope wind). Slopes less than 10 percent were calculated as having a wind-aspect alignment of 0, or perfect alignment. We calculated this predictor to test if fires pushed with changing degrees of up-slope winds burned with varying severity.

Climate- Seven climate predictor variables were calculated from 34 years of daily weather measurements at the observation points. Percentiles were calculated from the daily weather measurement compared to all daily weather measurements from July 1 to September 30 (92 days) from 1979 to 2013. We considered this time period as it corresponds to summer fire months for which IR perimeter data were collected. The seven climate predictors included: Fine Fuel Moisture Code, Maximum Temperature, Burning Index, Weed Speed, Maximum Relative Humidity, Minimum Temperature, and Downward Shortwave Radiation.

Statistical Analyses Using Random Forest

We used Random Forest (Breiman 2001), a machine learning regression tree analysis method, to study how topography, fuels, weather, and climate predictors interacted to explain changes in continuous dNBR values, first for 47 predictors and then for the 20 predictors selected for the optimum model. We followed the methods of Dillon et al. (2011) in the use of cross-validation, ten predictor importance groupings, an optimum model selection, and partial dependence plots. Unlike Dillon et al. (2011), we used five replicate Random Forest runs, each with 1500 regression trees, and continuous burn severity data instead of focusing on high burn severity only. Random Forest produces a pseudo R^2 calculated as 1 minus the Mean-Square-Error (MSE) divided by the variance that occurs within the response variable, dNBR (i.e., $R^2 = 1\text{-MSE/Variance (dNBR)}$). MSE is the sum of the squared residuals divided by the sample size (n=10,819) and was calculated as the median MSE across all five replicates. Importance rankings of predictor variables were based on the percent increase of total MSE for each predictor.

We repeated the analysis, including removal of correlated predictors and then initial and optimum Random Forest runs, for observation points that were only located within daily areas burned greater than 600 ha. We refer to this analysis as “large fire growth”. The threshold of 600 ha was selected as it corresponds to the 99.5th percentile of the size of the daily areas burned and included 4,113 observation points.

Results

Burn severity as indicated by dNBR at the 10,819 randomly located points ranged from 1218 to -431 in the 42 fires (Figure 2:2). The optimum model contained the model with the fewest number of predictor groups that resulted in model error within one standard error of the minimum from the initial analysis. The optimum analysis resulted in a pseudo R^2 of 0.42. The optimum model included 20 predictors related to topography, vegetation, weather, and climate (Figure 2:3). The top predictor for the Random Forest optimum analysis was Existing Vegetation Cover; with Slope-Cosine-Aspect Index second. The Environmental Site Potential characteristics (see Table 2:1 for descriptions), Fine Fuel Code Percentile, and Maximum Relative Humidity completed the third predictor importance group. The partial dependence plots of the optimum analysis show that higher percentages of Existing Vegetation Cover and greater values of Slope-Cosine-Aspect Index (i.e. steeper or more northern facing slopes) had a greater influence on changes of dNBR values (Figure 2:4). Environmental Site Potential of cold/wet forests had the largest influences on changes in dNBR, with 90 percentile or greater Fine Fuel Moisture Code, and Maximum Relative Humidity below 60%.

For the "large fire growth" reflecting 99.5th percentile of daily areas burned, the optimum model had a pseudo R^2 of 0.49. We removed two additional variables that were highly correlated (Spearman's > 0.75) with other predictor variables for 14 of 47 total removed (Appendix F). Daily areas burned greater than 600 ha still accounted for 4,113 observation points (38% of total) and 52,155 ha (47%) of daily areas burned as determined from IR perimeter mapping. Of all 7,216 daily areas burned, 37 (0.005%) were larger than 600 ha. The Random Forest optimum model indicated just eleven predictors that could best describe changes in dNBR (Figure 2:5). Similar to the analysis containing all points, Existing Vegetation Cover and Slope-Cosine-Aspect Index provided the largest influence on changes of dNBR. The third and fourth predictors were different: climate variable Wind Speed and vegetation variable Fuels Characteristics Classification System. We produced and compare partial dependence plots for the top two predictor variables, Existing Vegetation

Cover and Slope-Cosine-Aspect Index, as they are the same for both the “all points” analysis and “large fire growth” analysis.

Discussion

The environmental controls on burn severity include interactions of topography, climate, vegetation and weather, and all individual partial dependence plots were non-linear with thresholds. As dNBR is a spectral index that responds primarily to vegetation change (Hudak et al. 2007), it is not surprising that pre-fire Existing Vegetation Cover would have the largest influence, and likely this reflects potential tree mortality. Post-fire changes in vegetation cover could produce significant changes in spectral reflectance of the post-fire environment. Smith et al. (2007) found correlations between remotely sensed burn severity (dNBR and char fraction) and percent post-fire tree cover. Topography also influenced burn severity. Slope-Cosine-Aspect index (Stage 1976), our second predictor, a measure of the combination of slope and aspect, likely reflects effective moisture and biomass available to burn, as well as probability of burning. Dillon et al. (2011) found that topography had the largest influence on high severity fire. All of our topographic predictor variables in our optimum model had been included in their models.

All of the polygons representing large daily areas burned within known 24-hour periods included multiple topographic facets as they burned across complex montane topography. All were part of large fires that burned for multiple days, and therefore were burning under relatively extreme conditions, which might suggest that climate and weather would be more important than topography within large areas burned. While the top two predictors, Existing Vegetation Cover and Slope-Cosine-Aspect Index, did not change in importance when we analyzed only those points in the largest daily areas burned, the climate predictor variable of Wind Speed did become more important, moving into third. Partial dependence plots for Slope-Cosine-Aspect Index indicate that areas of large fire growth may be more influenced by steeper or more northern aspects then smaller fire growth. This may be because during large fire growth conditions (i.e. extreme fire weather), northern aspects may be able to burn. Within our predictor variable of Environmental Site Potential cold/wet forest types influenced burn severity the most. Holden et al. (2009) found that cool northern-aspects of the Gila Wilderness of the southwestern US were more likely to burn with high severity fires. Barrett et al. (2010) also found that aspect influenced burn severity as indicated by the relative reduction of organic soil layers of black spruce stands in Alaskan boreal forest.

Dillon et al. (2011) found that while climate was important, local, bottom-up controls reflecting topography and fuels more strongly influenced the probability of high severity fires across six ecoregions. In contrast to Dillon et al. (2011), we included wind and day of fire weather at a resolution of 4 km instead of 32 km, and the full range of burn severities as indicated by a continuous dNBR gradient (not just high severity), but focused on fewer fires within a region. Their findings and ours support the hypothesis that the environmental controls on burn severity differ from those on fire extent. We were surprised that wind did not highly influence burn severity because sustained crown fires that can result in tree mortality usually require wind (Van Wagner 1977). Wind is a common factor in both fire extent and fire behavior (Beer 1991; Rothermel 1991; Bessie and Johnson 1995) especially in dry fuels (Cruz and Alexander 2010). Neither wind direction nor velocity were found to be highly contributing factors to burn severity in our analysis. (See Appendix G for analysis using 30 m scale wind data using WindNinja). Both increase fire intensity (Rothermel 1972). For the 99.5th percentile of daily areas burned, wind was more important. The lack of wind as a significant contributing factor to burn severity is consistent with what Dillon et al. (2011) found. It is possible that the spatial and temporal resolution of our wind data is still too coarse, so that we don't know the wind conditions when the particular points burned. More likely, this confirms that burn severity is influenced by different environmental factors, or the same ones but at different relative importance than fire intensity (Agee 1996).

Higuera et al. (in review) found that duff and 1000-hr fuel moisture greatly influenced area burned in this region. We might expect these predictors to be important to burn severity, for they reflect long-term drying which could result in large areas with a majority of biomass dry enough to be consumed (Meyn et al. 2007; Krawchuk and Moritz 2011). Four of our top eight predictor variables are a measure of moisture content, whether air (RH) or fuel (Duff or Fine Fuel Code). These many different forms of moisture content may account for changes in burn severity. Higher moisture content, especially Maximum Relative Humidity, which we interpret as night-time RH recovery, may limit smoldering combustion (Ferguson et al. 2002) which influences burn severity (Wade 1993; Sackett et al. 1996).

Environmental variables, especially wind, interact to influence fire behavior (Bessie and Johnson 1995). Within our analysis there were a large number of predictors and many potential interactions. Perhaps the lack of dominance by a single group of predictors (topography, vegetation, climate, or weather) in influencing severity reflects the different potential causes of severity among the many different types of vegetation that the fires burned across and the number of IR progression days that we were able to use for weather and climate observations.

Understanding the relative importance of the drivers of burn severity will require further research. While dNBR is certainly more often correlated with overstory tree mortality (Cocke 2005; Hudak et al. 2007), it also reflects soil effects (Lewis 2006). Possibly, these different aspects of burn severity are influenced by different environmental characteristics and thus may explain we see the intermixing of predictor variable types. Soil burn severity (Parson et al. 2010) may be more influenced by duff consumption and soil heating (Ice et al. 2004) while overstory tree scorch and crown consumption might be tied more to flame length and intensity (Rothermel 1972).

Burn severity may also be controlled by pre-fire and post-fire conditions such as winter snow fall and conditions of the next growing season, which may have greater influence on severity then do conditions that occurred on the day the area was burned. Drying and warming trends days before an area burned may also influence burn severity. Hudak et al. (2011) found that weather up to 5 days before was significant in predicting daily area burned. Further, our fires were all larger than 405 ha and had escaped initial suppression actions or were managed with limited suppression. Fires that were contained or areas of fires that were initially suppressed may have different factors that contributed to burn severity. We did not account for the effects of fire suppression tactics such as burnouts or larger scale backfiring, which may use aerial ignition systems. These could significantly alter patterns and intensities of fire activity (Backer et al. 2004), but detailed data on locations of tactics applied is difficult to obtain. While these tactics may be needed for public and firefighter safety and to limit future fire growth, they may influence both burn severity and direction of fire spread.

Limitations

We constrained our sampling to forested areas within the northern Rockies. Areas of non-forest and those forested areas outside the northern Rockies may likely have different interactions between the factors contributing to burn severity that would be specific to that area, due to weather or climate, and for that type of ecosystem, due to vegetation characteristics. Our data was sampled at both 30 m and 4 km spatial scales which could have influenced our findings. The coarse scale of our weather and climate predictor variables (4 km) may not represent the microclimate gradients that might drive burn severity. Additionally, Landfire vegetation characteristics may not capture finer-scale fuel heterogeneity (< 30m) that may also drive burn severity. Our topographic predictor variables match the spatial scale of dNBR (30 m) observations which may account for them being placed higher in importance rankings. Random Forest analysis is more selective of predictors with more categories and continuous data (Strobl et al. 2007; Strobl et al. 2009). Our dataset contains both types of data, with our analysis showing intermixing of predictors within the importance rankings.

Implications

Over a third of the predictors that influence forest burn severity are climate variables. This suggests that burn severity will be sensitive to climate change (Meehl et al. 2007). Many of these climate drivers we identified are likely to change in the future (Mote et al. 2005; Knowles et al. 2006) and to the degree that they change, burn severity may change as well (Miller et al. 2009). While climate may be less influential on burn severity than topography and vegetation, and fire extent is affected by climate and weather, the ecological effects of fire may be less sensitive to climate change than area burned. Additionally, modern day fire suppression actions have increased amounts of both dead and living vegetation (Barrett et al. 1991; Arno et al. 1997) and changed forest composition (Arno et al. 1993, 1995; Keane et al. 1996). Such changes in vegetation conditions can lead to uncharacteristic burn severity (Quigley et al. 1996; Barbouletos et al. 1998; Morgan et al. 1998).

Conclusion

We used IR perimeter maps to locate specific areas of fire growth and progression. Others have used progression but on a limited basis, mostly on an individual fire (Turner et al. 1994) or at a much larger spatial scale (Jones et al. 2009). IR perimeter maps are regularly obtained for wildland fire suppression actions, but use for research has been limited. Accuracy of IR perimeter maps has yet to be established, including that of comparing dual-sensor perimeter measurements for different intensity fires. We used a 30 m buffer of the IR perimeters in an effort to stipulate that the fire growth occurred on a specific day. However, they offer great potential for linking climate and weather observations during a particular day to the area burned on that day to better understand the individual and combined effects of climate, topography, vegetation, and human action on fire behavior and effects.

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Table 2:1. Environmental Site Potential (ESP) descriptions of the NatureServe terrestrial ecological systems used in this analysis (NatureServe 2011). ESP represents the possible ecological system at a given site not actual. Highlighted items indicate the top two ESP factors influencing dNBR. Count is how many times ESP was sampled.

ESP Code	Description	Forest Type	Count	Partial Dependence Value
1056	R Mt. Subalpine Mesic-Wet Spruce-Fir Forest	Cold	2080	420
1055	R Mt. Subalpine Dry-Mesic Spruce-Fir Forest	Cold	3709	412
1167	R Mt. Poor-Site Lodgepole Pine Forest	Cold	110	392
1046	N R Mt. Subalpine Woodland and Parkland	Cold	69	372
1161	N R Mt Conifer Swamp	Cold	132	360
1045	N R Mt Dry-Mesic Mixed Conifer Forest	Dry	2358	362
1053	N R Mt Ponderosa Pine Woodland	Dry	65	341
1159	R Mt. Montane Riparian Systems	Mesic	271	384
1166	Middle R Mt. Montane Douglas-fir Forest	Mesic	1572	382
1160	R Mt. Subalpine/Upper Montane Riparian	Mesic	221	360
1047	N R Mt Mesic Montane Mixed Conifer Forest	Mesic	25	335
1154	Inter-Mountain Basins Montane Riparian Systems	Mesic	9	333
1062	Inter-Mt. Basins Mahogany Woodland	Mesic	9	332
1011	R Mt. Aspen Forest and Woodland	Mesic	7	330
1106	N R Mt Montane-Foothill Deciduous Shrubland	Other	1	346
1139	N R Mt Lower Montane-Foothill-Valley Grassland	Other	2	344
1145	R Mt. Subalpine-Montane Mesic Meadow	Other	1	342
31	Barren-Rock/Sand/Clay	Other	178	333

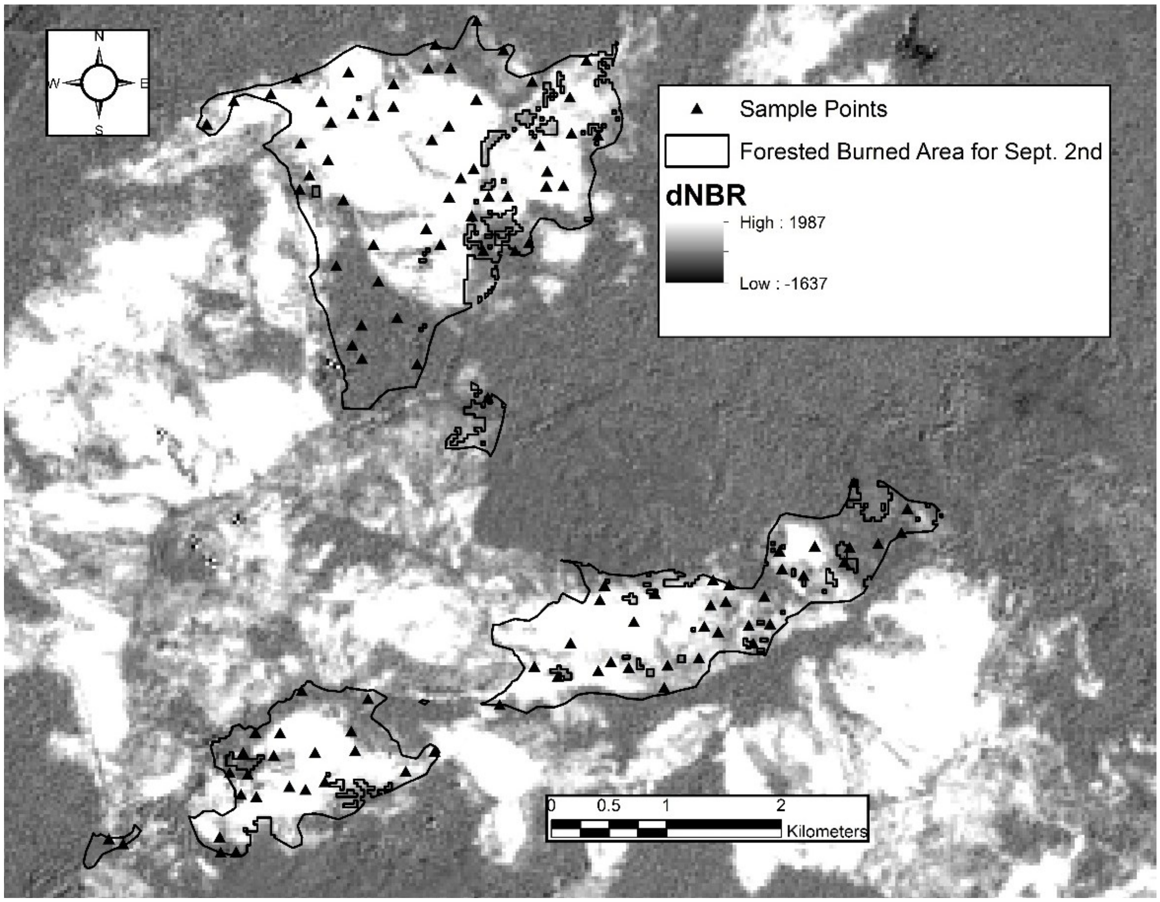

Figure 2:1. Example of forested daily areas of growth and randomly sampled points that occurred on the Burnt Strip Mountain Fire in central Idaho on September 2, 2005. Areas were delineated by use of daily IR perimeter maps.

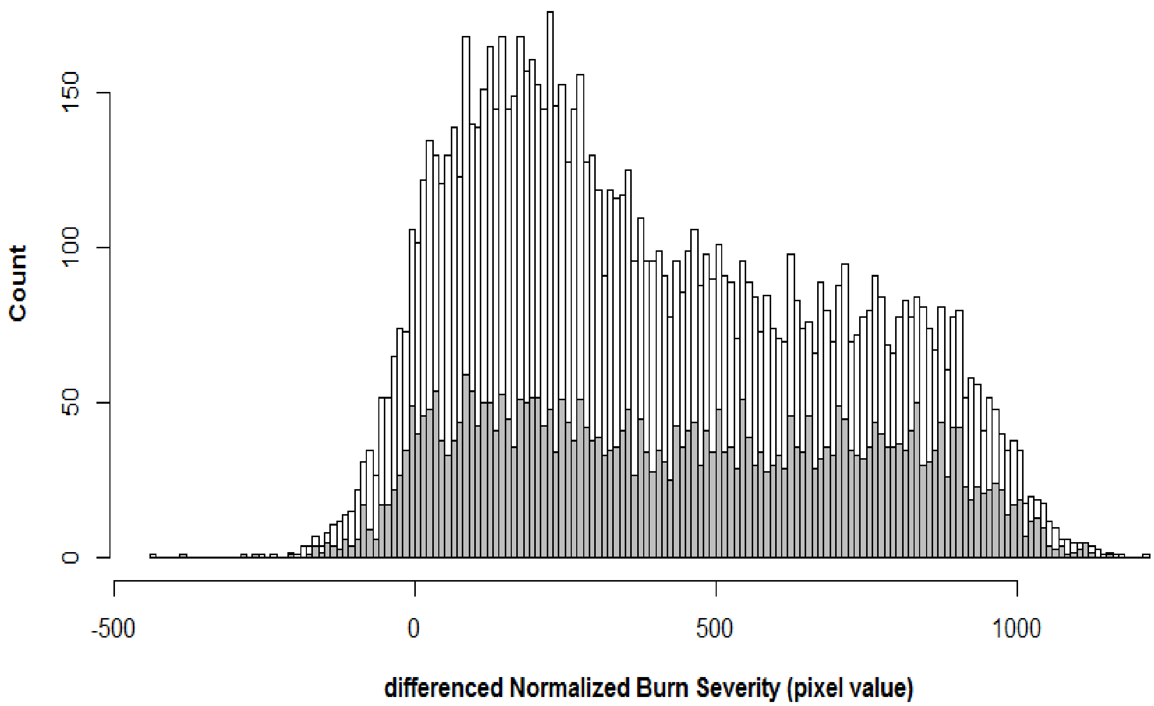

Figure 2:2. Differenced Normalized Burn Severity pixel values for all 10,819 randomly selected points (white bars) and 4,113 points within large areas of fire growth (gray bars). Bin size = 200.

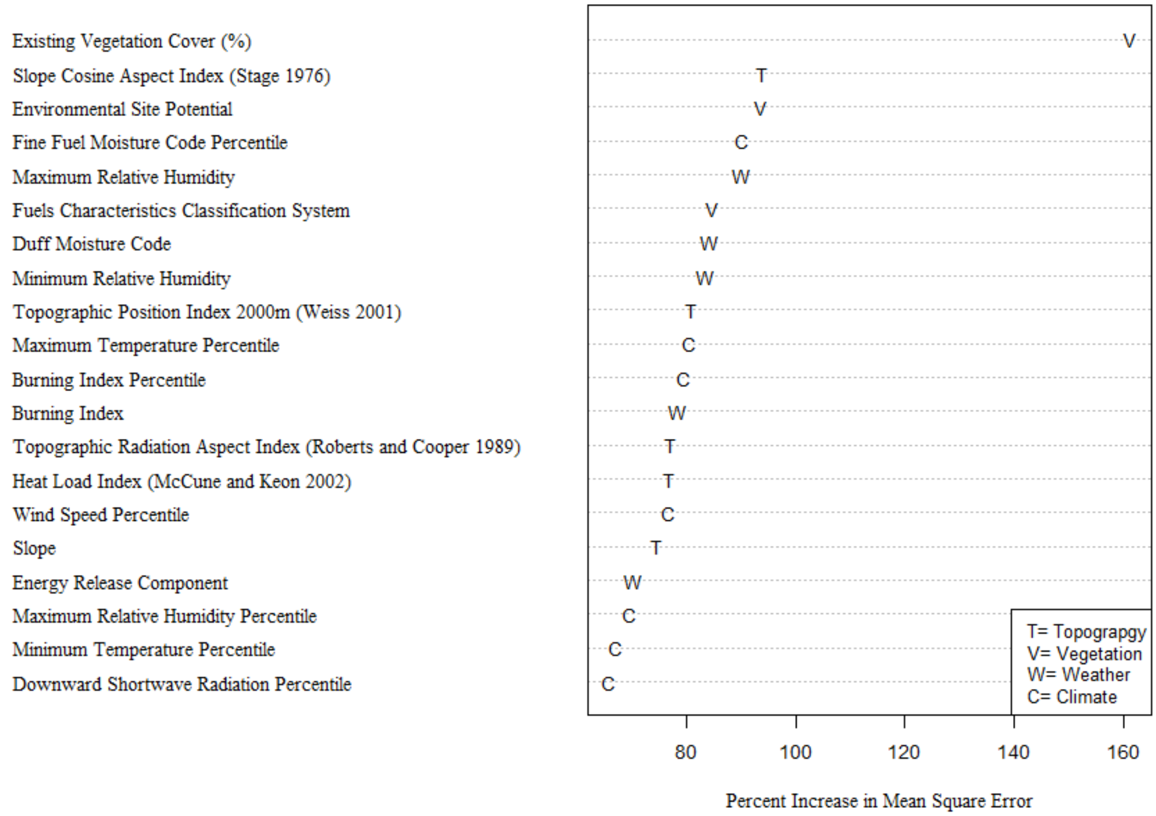

Figure 2:3. Importance rankings of 20 predictors of dNBR as explained in an optimum model provided by Random Forest regression trees for 10,817 observation points. Predictor importance is measured as the percent increase of each predictor variable on the total MSE.

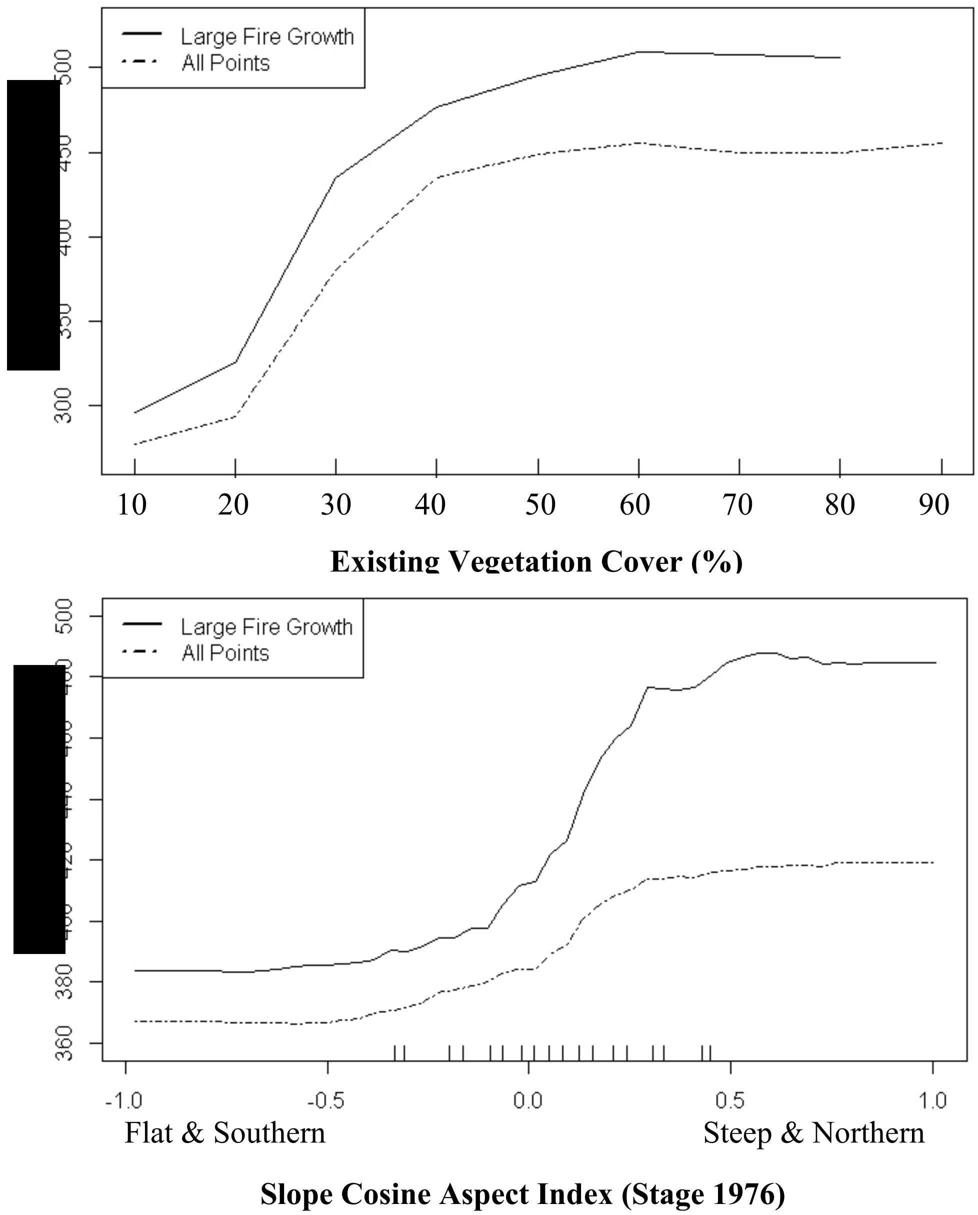

Figure 2:4. Random Forest partial dependence plots of Existing Vegetation Cover and Slope-Cosine-Aspect Index for All Points (dotted line) and points within Large Fire Growth (solid line). Partial dependence plots show the dependence of the regression function ($F_j(X_j)$) on the predictor while holding all others at their mean. Use relative range of y-axis values to compare between All Points and Large Fire Growth lines. Existing Vegetation Cover has about the same influence on burn severity between large fire growth and other areas, while steeper or more northern aspects have more influence during large fire growth.

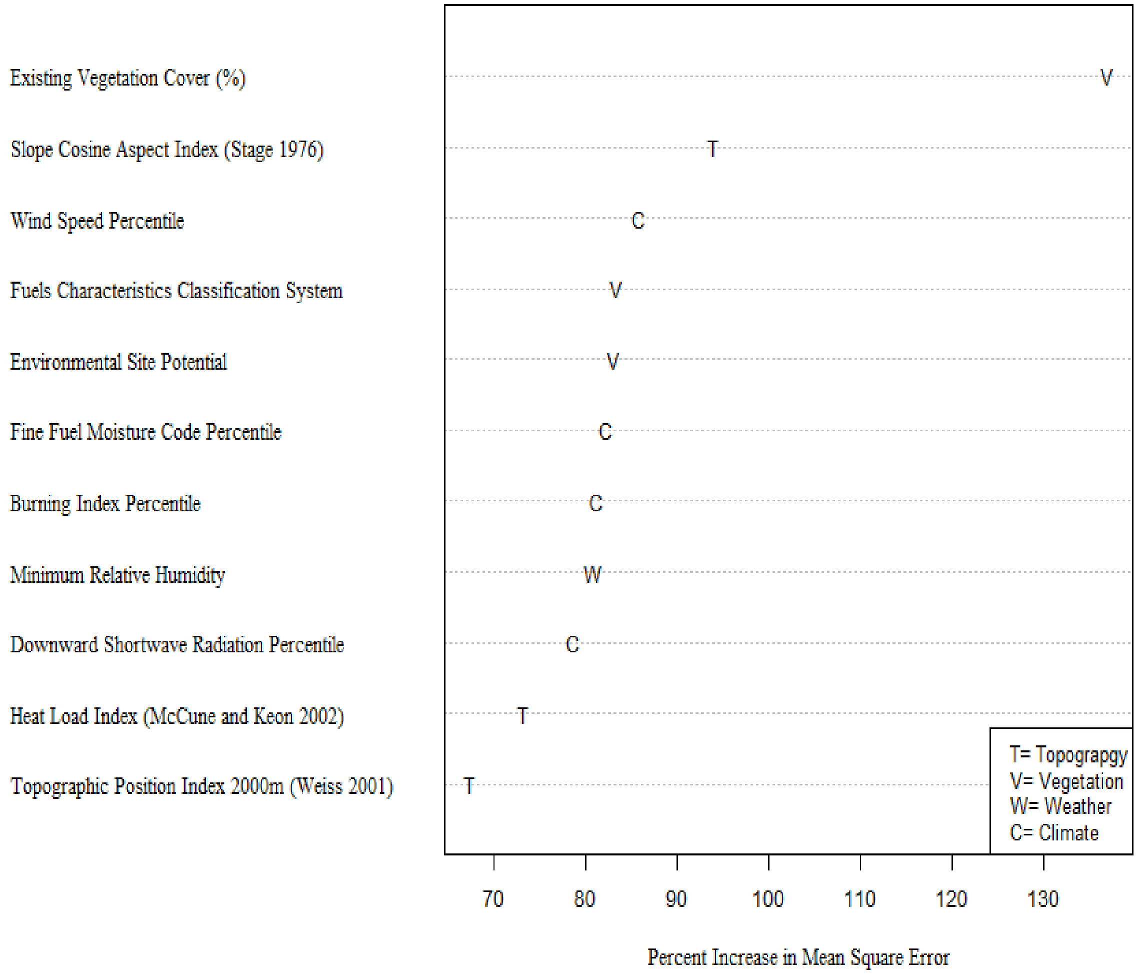

Figure 2:5. Predictor importance of 11 factors of dNBR, for 4,113 observations in daily areas of fire growth larger than 600 ha, as explained in an optimum model provided by Random Forest regression trees. "Percentile" predictors are considered climate and calculated as the percentile from the 34 year mean for day of observation for summer fire months: July, August, and September.

Appendix A: 42 selected fires

We analyzed 42 forest fires in a six year period. Fires were selected based on availability of both dNBR burn severity indexes obtained from the Monitoring Trend in Burn Severity Project and infrared perimeter data.

Fire	**Year**	**Number of Progression Dates**	**Progression Dates Analyzed**	**Forested Area Analyzed (ha)**
Beaverjack	2005	5	9/2-9/4; 9/6; 9/8	737
Burnt Strip Mountain	2005	10	8/26-9/4	2451
Center	2005	4	8/26; 8/31; 9/2-9/3	69
Reynolds Lake	2005	4	9/2-9/3; 9/7-9/8	261
Rockin	2005	2	9/2-9/3	101
Signal Rock	2005	8	9/1-9/8	1372
Boundary	2006	4	9/2-9/5	190
Meadow	2006	4	9/2-9/5	246
North Elk	2006	4	9/2-9/5	185
Potato	2006	3	7/30-7/31; 8/2	912
Red Mountain	2006	5	8/31-9/4	1099
Cascade Complex*	2007	9	9/7-9/15	4329
Castle Rock	2007	12	8/20-8/31	8568
Cottonwood	2007	7	8/24-8/30	1244
Fisher Point	2007	17	8/11-8/18; 8/25-8/27; 8/29-9/3	2610
Goat	2007	16	8/10-8/12; 8/25-8/30; 9/7-9/12	2703
Lolo	2007	15	8/11-8/18; 8/24-8/26; 8/29-8/31; 9/3	1372
LoonZena	2007	9	8/22-8/30	1610
Monumental	2007	10	7/27-7/31; 8/3-8/7;	2829
Monumental-North Fork**	2007	5	8/26-8/30	2829
Monumental-Yellow***	2007	6	8/9-8/14	12985
North Fork	2007	5	8/11-8/15,	6133
Papoose	2007	7	8/28-9/3	287
Raines	2007	6	8/25-8/30	1579
Rattlesnake	2007	12	7/18-7/22; 8/9-8/15	8999
Red Bluff	2007	8	8/23-8/30	3317
Riordan	2007	15	7/26-7/31; 8/3-8/5; 8/7; 8/26-8/30	5397
Rombo Mountain	2007	6	8/25-8/30	1194
Sandy	2007	7	7/28-7/31; 8/3-8/4; 8/6	3343
Shower Bath	2007	6	8/25-8/30	150

Tag	2007	20	8/7-8/12; 8/28-8/29; 8/31-9/3; 9/7-9/14	5240
Trapper Ridge	2007	4	7/27-7/28; 730-7/31	420
Wyman #2	2007	18	8/11-8/18; 8/22; 8/25-8/31; 9/2-9/3	4963
Yellow	2007	5	8/3-8/7	993
Castro	2011	11	9/1-9/11	457
Coyote Meadows	2011	3	9/7; 9/11-9/12	107
Hells Half	2011	7	9/7-9/8; 9/10-9/14	225
Indian	2011	4	7/24-7/27	59
Saddle	2011	20	8/22-8/27; 8/30; 9/1-9/8; 9/10-9/14	9526
Salt	2011	13	8/27-9/8	5220
Up Top	2011	11	9/4-9/14	2145
West River Side	2011	6	8/24-8/29	495
	Total Fire Days: 353			Total Area: 111,397 ha

* Cascade Complex includes North Fork, Monumental, Yellow, Sandy, and Riordan fires after they were mapped as one IR perimeter.
** Monumental North Fork includes the Monumental and North Fork fires after they were mapped as one IR perimeter.
*** Monumental Yellow includes Monumental, North Fork, Sandy, and Yellow fires after they were mapped as one IR perimeter.

Appendix B: Forested vegetation types within study area

Forested Existing Vegetation Type groups used in selecting areas within progression days. The Landfire Existing Vegetation Type layer represents the species composition at a given site.

EVT Code	EVT Description
2011	Rocky Mountain Aspen Forest and Woodland
2045	Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest
2046	Northern Rocky Mountain Subalpine Woodland and Parkland
2047	Northern Rocky Mountain Mesic Montane Mixed Conifer Forest
2050	Rocky Mountain Lodgepole Pine Forest
2053	Northern Rocky Mountain Ponderosa Pine Woodland and Savanna
2055	Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland
2056	Rocky Mountain Subalpine Mesic-Wet Spruce-Fir Forest and Woodland
2061	Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland
2062	Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland
2159	Rocky Mountain Montane Riparian Systems
2160	Rocky Mountain Subalpine/Upper Montane Riparian Systems
2161	Northern Rocky Mountain Conifer Swamp
2166	Middle Rocky Mountain Montane Douglas-fir Forest and Woodland
2167	Rocky Mountain Poor-Site Lodgepole Pine Forest
2227	*Pseudotsuga menziesii* Forest Alliance
2228	*Larix occidentalis* Forest Alliance

Appendix C: Descriptions of topography predictors

All values and indices were calculated from a 30 m DEM.

Aspect

Aspect represents the direction in degrees from north in which the exposure faces.

Slope

Slope represents the percent change of elevation over a specific area.

Slope Cosine Aspect Index

Calculation indicating combinations of slope and aspect, higher values are those areas that are steeper slopes or more northern aspects (Stage 1976).

Topographic Radiation Aspect Index

Assigns values to a circular aspect variable. Values of 0 indicate north-northeast aspects, and a value of 1 to south-south-westerly aspects (Roberts and Cooper 1989).

Heat Load Index

Calculates solar radiation so that the highest values are southwest and the lowest values are northeast and also accounts for steepness of the slope (McCune and Keon 2002).

Compound Topographic Index

Calculates topographic convergence were higher values represent drainages and lower values represent ridges or rises. (Moore et al. 1993).

Topographic Position Index

Calculates slope position by subtracting a central mean from the surrounding elevation by use of annular ring sizes. Higher values indicate ridges, with negative values indicating valleys, and 0 indicating flat areas (Weiss 1972). Calculated at 1-150; 150-300; 300-2000m annular rings.

Elevation Relief Ratio

Describes how ridged the surface. Small values indicate areas of features standing above surrounding level surfaces, with high values indicating level surfaces with depressions. (Pike and Wilson 1971). Calculated at 90, 450, 810 m radius circles.

Martonne's Modified Dissection Coefficient

Describes terrain dissection within an area. Higher values indicate large changes in elevation, with lower values indicating small changes in elevation (Evans 1972). Calculated at 90, 450, 810 m radius circles.

References

Evans, I.S. 1972. General geomorphometry, derivatives of altitude, and descriptive statistics. Pages 17–90 in R. J. Chorley, editor. Spatial analysis in geomorphology. Harper & Row, New York, New York, USA.

McCune, B. and D. Keon. 2002. Equations for potential annual direct incident radiation and heat load. Journal of Vegetation Science 13: 603-606.

Moore, I.D., P. Gessler, G.A. Nielsen, and G. A. Peterson. 1993. Terrain attributes: estimation methods and scale effects. Pages 189–214 in A. J. Jakeman, M. B. Beck, and M. McAleer, editors. Modeling change in environmental systems. Wiley, London, UK.

Pike, R.J. and S.E. Wilson. 1971. Elevation relief ratio, hypsometric integral and geomorphic area altitude analysis. Bulletin of the Geological Society of America 82: 1079-1084.

Roberts, D.W. and S.V. Cooper. 1989. Concepts and techniques of vegetation mapping. Pages 90–96 in P. Ferguson, P. Morgan, and F. D. Johnson, editors. Land classifications based on vegetation: applications for resource management. General Technical Report INT-GTR-257. USDA Forest Service, Intermountain Research Station, Ogden, Utah, USA.

Stage, A.R. 1976. Notes: An expression for the effect of aspect, slope, and habitat type on tree growth. Forest Science 22: 457-460.

Weiss, A. 2001. Topographic position and landform analysis. Poster presentation, ESRI User Conference, San Diego, California, USA.

Appendix D: Description of vegetation predictors from Landfire

All vegetation characteristics are represented at a 30 m scale from Landfire datasets. www.Landfire.gov

Environmental Site Potential

The Environmental Site Potential represents the vegetation that could be at a given location. Based on NatureServe's Ecological Systems classification (NatureServe 2011) and represents the natural plant communities that would become established at late or climax stages of successional development in the absence of disturbance.

Existing Vegetation Type

The Existing Vegetation Type layer represents the species characteristics at a given site at the time of classification. Derived from NatureServe's Ecological Systems classification.

Fuel Loading Models

The Fuel Loading Model surface fuel classification system characterizes wildland surface fuel.

Existing Vegetation Cover

Existing Vegetation Cover depicts percent canopy. All vegetation cover was expressed as tree cover.in percentage.

Existing Vegetation Height

The Existing Vegetation Height layer represents the average height of the vegetation. All vegetation height was expressed as tree height.

Canopy Bulk Density

The Canopy Bulk Density layer describes the density (kg m-3) of available canopy fuel in a stand. Generated using Landsat imagery and biophysical gradients to model bulk density.

Canopy Base Height

The Canopy Base Height describes the height from the ground to a forest stand's canopy bottom. Measured as meters only within forested areas.

Fuels Characteristics Classification System

The Fuel Characteristic Classification System characterizes a fuel bed as it might contribute to fire behavior and effects (Ottmar et al. 2007).

Fire Behavior Fuel Models

The Fire Behavior Fuel Models represent fuel loadings of size classes and fuel types within dead and live fuels.

References

NatureServe. 2011. International Ecological Classification Standard: Terrestrial Ecological Classifications. NatureServe Central Databases. Arlington, VA, U.S.A. Data current as of 31 July 2011.

Ottmar, R.D., D.V. Sandberg, C.L. Riccardi, and S.J. Prichard. 2007. An overview of the Fuel Characteristic Classification System-Quantifying, classifying, and creating fuelbeds for resource planning This article is one of a selection of papers published in the Special Forum on the Fuel Characteristic Classification System. Canadian Journal of Forest Research, 37(12): 2383-2393.

Appendix E: Description of weather predictors

Weather was gathered from a gridded 4 km dataset of surface meteorological data. The spatially gridded data is a combination of temporal attributes of regional-scale reanalysis and daily gauge-based precipitation.

Abatzoglou, J.T. 2011. Development of gridded surface meteorological data for ecological applications and modeling. International Journal of Climatology. DOI: 10.1002/joc.3413.

Abatzoglou, J.T., and Brown, T.J. 2011. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology DOI: 10.1002/joc.2312.

http://cloud.insideidaho.org/webApps/metadataViewer/default.aspx?path=G:\data\anonymous\epscor\gridmet\metadata.xml

Minimum and Maximum Temperature

Minimum and maximum temperature measured in Celsius.

Minimum and Maximum Relative Humidity

Minimum and maximum relative humidity expressed as a percentage.

Precipitation

Daily accumulated precipitation as measured in millimeters.

Wind Speed

Mean wind velocity expressed as meters per second.

Wind Direction

Average wind direction expressed as degrees from North.

Duff Moisture Code

The Duff Moisture Code is a rating of the average moisture content of loosely compacted duff layers. This code is calculated using the Canadian Forest Fire Danger Rating System (Van Wagner 1987).

Fine Fuel Moisture Code

The Fine Fuel Moisture Code is a rating of the moisture content of litter and other cured fine fuels. The code is an indicator of the ease of ignition and the flammability of fine fuels. The code is calculated using the Canadian Forest Fire Danger Rating System (Van Wagner 1987).

Downward Shortwave Radiation Flux

Shortwave flux (W m^-2) is a result of specular and diffuse reflection of incident shortwave radiation by the underlying surface.

Energy Release Component (ERC)

Energy Release Component combines the daily temperature, precipitation and humidity that may represent the amount of energy released at the flaming front of a fireline (Deeming *et al*. 1977).

Burning Index (BI)

The Burning Index is a number related to the contribution of fire behavior to the effort of containing a fire (Deeming et al. 1977). The value may be divided by 10 to estimate flame length.

References

Deeming, J.E., R.E. Burgan, and J.D. Cohen. 1977. The National Fire-Danger Rating System--1978. USDA Forest Service General Technical Report INTUS.

Van Wagner, C.E. 1987. Development and structure of the Canadian forest fire weather index system (Vol. 35).

Appendix F: Predictor importance rankings

Importance ranking of predictor variables used in Random Forest regression relating topography, vegetation, daily weather, and climate to dNBR for all points and points within areas of fire growth > 600 ha. Climate predictors were calculated as the percentile from 34 year mean for day of observation for summer fire months: July, August, and September.

Predictor	**Importance Ranking**	
Topography (15)	**All Points**	**> 600 ha**
Martonne's Modified Dissection Coefficient (Evans 1972)		
90 m	*	*
450 m	*	*
810 m	*	*
Elevation Relief Ratio (Pike and Wilson 1971)		
90 m	+	+
450 m	*	*
810 m	+	+
Topographic Position Index (Weiss 1972)		
150 m	+	+
300 m	*	*
2000 m	9	11
Topographic Radiation Aspect Index (Roberts and Cooper 1989)	13	+
Compound Topographic Index (Moore et al. 1993)	+	+
Heat Load Index (McCune and Keon 2002)	14	10
Slope Cosine Aspect Index (Stage 1976)	2	2
Slope (Percent)	16	+
Aspect (Degrees)	+	+
Vegetation (9)		
Environmental Site Potential	3	5
Fuel Loading Models	+	+
Existing Vegetation Cover	1	1
Canopy Bulk Density	*	*
Canopy Base Height	+	+
Existing Vegetation Height	+	+
Existing Vegetation Type	+	
Fuel Characteristic Classification Fuelbeds	6	4
Fire Behavior Fuel Models, Scott and Burgan 40	+	+
Weather (12)		
Maximum Temperature (Degrees Kelvin)	*	*
Minimum Temperature (Degrees Kelvin)	*	*
Maximum Relative Humidity (%)	5	8
Minimum Relative Humidity (%)	8	+
Precipitation (mm)	+	+
Downward Solar Radiation (W m^-2)	*	*
Wind Speed (m/s)	*	*
Wind Direction (Degrees)	+	+

Energy Release Component	17	+
Burning Index	12	*
Duff Moisture Code	7	*
Fine Fuel Moisture Code	*	*
Climate (10)		
Maximum Temperature (Degrees Kelvin)	10	+
Minimum Temperature (Degrees Kelvin)	19	+
Maximum Relative Humidity (%)	18	*
Minimum Relative Humidity (%)	*	*
Downward Solar Radiation (W m^-2)	20	9
Wind Speed (m/s)	15	3
Energy Release Component	+	+
Burning Index	11	7
Duff Moisture Code	+	*
Fine Fuel Moisture Code	4	6
Other		
Wind-Aspect Alignment	+	+

* Predictors removed due to high correlation with other predictors
+ Predictors removed for optimum model

Appendix G: Fine scale wind analysis

WindNinja calculations were obtained from Zack Holden of the US Forest Service in Missoula for the 2007 Rattlesnake Fire to test if fine-scale (30 m) wind direction and speed observations provided a greater contributing influence to variations in dNBR. WindNinja is used to calculate fine-scale, terrain-influenced winds (Forthofer et al. 2003) for input to wildland fire behavior models such as FARSITE and FlamMap. IR perimeter maps for the Rattlesnake Fire from central Idaho covered 12 days of fire weather. Using the 127.5 m minimum spacing between observation points we obtained 1053 wind speed and direction values. This fire was used as a small test case to test if adding fine-scale wind data provided additional explanation for variation in burn severity. As with the analysis of all 42 fires, the 30 m analysis and identical 4 km analysis included removal of highly correlated predictor variable. Wind-Aspect Alignment measurements were calculated based on wind direction from both datasets. With no large change in MSE values for wind specific predicator variables (i.e. wind variables didn't increase in importance) between 30 m and 4 km analyses we didn't conduct optimum Random Forest runs. Using WindNinja data for wind on the 2007 Rattlesnake fire did not increase the explained variation in dNBR. A pseudo R-squared of 0.43 was achieved using WindNinja 30 m data compared to 0.41 for the 4 km data form this single fire. With the large time investment requirement to calculate WindNinja data for the remaining 9,766 randomly located points, we decided not to include WindNinja data for our final analysis across all 42 fires.

Forthofer, J.M., B.W. Butler, K.S. Shannon, M.A. Finney, L.S. Bradshaw, and R. Stratton 2003. Predicting surface winds in complex terrain for use in fire spread models. In 'Proceedings of the Fifth Symposium on Fire and Forest Meteorology and Second Wildland Fire Ecology and Fire Management Congress'. Orlando, FL. (American Meteorological Society).