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Landscape Patterns of Burn Severity in the Soberanes Fire of 2016

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Abstract

The Soberanes Fire started on July 22, 2016 in Monterey County on the California Central Coast from an illegal campfire. This disastrous fire burned for 10 weeks at a record cost of more than $208 million for protection and control. A progressive analysis of the normalized burn ratio from the Landsat satellite showed that the final high burn severity (HBS) area for the Soberanes Fire comprised 22% of the total area burned, whereas final moderate burn severity (MBS) area comprised about 10% of the total area burned of approximately 53,470 ha (132,130 acres). The resulting landscape pattern of burn severity classes from the 2016 Soberanes Fire revealed that the majority of HBS area was located in the elevation zone between 500 and 1000 m, in the slope zone between 15% and 30%, or on south-facing aspects. The total edge length of HBS areas nearly doubled over the course of the event, indicating a gradually increasing landscape complexity pattern for this fire. The perimeter-to-area ratio for HBS patches decreased by just 3% over the course of the fire, while the HBS clumpiness metric remained nearly constant at a relatively high aggregation value. Weather conditions during the Soberanes Fires showed maximum daily temperatures exceeding 30°C on seven different days (including the date of ignition), which puts the HBS to total area burned of this 2016 event near the expected percentage for large wildfires on the California central coast since the 1980s.

Introduction

The central coastal zone of California is a fire-adapted region of forests and shrublands situated on steep hillslopes and across mountain canyons [1]. Wildfires are a naturally occurring phenomenon in Mediterranean ecosystems of the region [2]. Pre-European settlement fire return intervals have been estimated on the order of 30 to 100 years [3,4]. In central and southern California, chaparral vegetation burns more often now than it did before European settlement and modern fire return intervals may now be 10-20 years or less [5].

Over the past 50 years, property losses from wildfires have increased every decade on the California Central Coast, despite higher expenditures for expanded fire suppression and control activities [6]. Rural housing development has increased markedly in this region [7], putting homes and nearby commercial structures at ever-higher risks of destruction by wildfires. Statewide, the costs of protecting these homes from fires have increased by 150% over the past decade, to over $1 billion a year [8]. Areas of post-high burn severity, where there is consumption of practically all vegetation biomass, contributes to chronic problems of local air pollution, soil erosion on steep slopes, and loss of carbon storage.

The Soberanes Fire started on July 22, 2016 around 8 am (Pacific time) from an illegal campfire on the Soberanes Canyon trail in Garrapata State Park along CA Highway 1 in Monterey County. During the next three months, it burned over approximately 53,470 ha (132,130 acres), 94,930 acres in the Los Padres National Forest, and 37,190 acres outside the National Forest, making it the 20th largest ever recorded in the state [9]. The fire was 95% contained on September 23 and 100% contained on October 11, 2016.

There were several features of the Soberanes fire that made it distinctive from most other wildfires in California over recent decades. The blaze threatened many homes and resorts and burned for 10 weeks. It shut down several state parks, destroyed dozens of residential structures and threatened thousands of other buildings. The uncontrolled fire perimeter changed constantly with the varying influences of weather, fuels, and topography [9]. More than 5000 persons were deployed to fight the fire over 83 days. There was one fatality, a bulldozer-operator who died after a rollover.

The Soberanes Fire has been estimated as the most expensive in the United States' history, with management and suppression costs exceeding $208.4 million, according to the National Interagency Fire Center. The record costs were due largely to the amount of time that the fire burned, and the cost of paying firefighters to attempt to contain the blaze on a daily basis. The total estimated cost of the firefighting effort does not yet include the replacement of damaged structures and homes. As of August 1, 2016, damage assessment teams had identified 57 residences and 11 outbuildings destroyed, mostly in the Palo Colorado Canyon. Local roads sustained millions of dollars-worth of damage and shallow wells may see impacts to their water quality [10].

Weather conditions at leading up to the Soberanes Fires were near average for the Monterey County coast, with maximum daily temperatures on July 22 and 23, 2016 reaching 30°C, based on climate records from the National Weather Service station at Big Sur State Park (BSP; 36° 15' N, 121° 47' W). Maximum temperatures exceeded 32°C again on six days between September 19 and 27, 2016 at the BSP station. Both Moritz [11] and Keeley have reported that area burned by wildfires in coastal California chaparral is most closely related to the occurrence of extreme weather conditions at the time of ignition, rather than with the density of vegetation biomass fuel, which can increase with stand age. Elevated air temperature has been shown to strongly influence fire frequency and area burned on the Central Coast [12].

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Although there are many heavily forested areas of Monterey County that have burned over recent decades, the meaning of standard burn severity categories such as low, moderate, and high in Central Coast shrublands is somewhat different from more heavily wooded landscapes in the western United States [13] pointed out that rates of shrub mortality are not always indicative of fire severity in these ecosystems, because all aboveground biomass is typically killed and consumed in high severity burn (HSB) areas, and the effects of the fire are more often a function of the presence or absence of resprouting species. In contrast to HBS areas where 100% of the shrub canopy is normally consumed, Harris et al. [14] characterized moderate burn severity (MBS) in California coastal fires as areas where 40-80% of the shrub canopy was consumed, and where some larger branches (>0.6^{-1} cm in diameter) were still unburned.

The mapping of HBS and MBS classes based on the differenced normalized burn ratio (dNBR) from Landsat satellite images acquired just before and after a fire has been shown to be an accurate predictor of fire severity measured in southern California chaparral ecosystems [15]. In contrast to the strong relationship between the *absolute* dNBR and fire severity, the *relative* dNBR (Miller and Thode, 2007) was only weakly related to fire severity in this region.

The research objective of this current study was two-fold: (1) To understand the progression of landscape patch dynamics of different burn severity classes over the course of the 2016 Soberanes Fire, and (2) To determine the role of topographic variables, such as slope and aspect, on the distribution of different burn severity classes mapped at near 100% fire containment of the Soberanes Fire. This the first study of its kind that has examined the progression of burn severity landscape patterns in California using a series of consecutive Landsat NBR maps.

Burned Area Description

The Soberanes Fire consumed approximately 44,620 ha (110,260 acres) of vegetation cover in western Monterey County between July 22 and September 24, 2016. The terrain of the burned landscape is rugged and undulating (Figure 1), with the steepest elevation gradients on the Pacific U. S. coast around Big Sur [16].

Throughout the coastal landscape of Monterey County, chaparral communities support shrub vegetation, including the species California sagebrush (*Artemisia californica*), coyote brush (*Baccharis pilularis*), sage (*Salvia* sp.), and coast buckwheat (*Eriogonum fasciculatum*) [17]. Redwood stands (*Sequoia sempervirens*) on the Monterey County coast are found most commonly on steep (>50%) lower slopes, at north to north-northwest aspects, and are densest at distances of 15 to 60 m from the nearest surface stream flow [18]. At elevations between 60 m and 850 m, a mixed hardwood/pine-dominated zone has interspersed stands of *Quercus agrifolia* and *Pinus ponderosa* growing most commonly on north-facing slopes and ridge tops [19]. A Coulter pine (*Pinus coulteri*) forest zone may be present at elevations higher than 850 m, predominantly along ridgetops and on moderate slopes of the Santa Lucia range.

The region has a Mediterranean climate of warm, dry summers and cool, wet winters, with localized summer fog near the coast [20,21]. Annual rainfall is highly variable and ranges from about 30 to 150 cm throughout the region, with highest event totals generally falling on the higher mountains in the northern extreme of the study area during winter storms [22]. Mean annual temperature ranges between 10°C and 15°C, from shaded canyon bottoms to exposed ridge tops, respectively [22].

Major wildfires in Monterey County have been common over the past 30 years, starting with the Marble Cone Fire in August 1977, which burned for three weeks and consumed 72,000 ha (178,000 acres). The fire burned over a majority of the Big Sur River watershed. The cause was a lightning strike but no structures were destroyed. The Basin Complex Fire burned 65,890 ha (162,818 acres) for five weeks in June to July, 2008. The cause was lightning and 58 structures were destroyed. At about the same time, the Indians Fire scorched 32,930 ha (81,378 acres) to the east of the Basin Complex for four weeks in June and July, 2008. These two fires eventually joined each other, and together, amount to the biggest fire in Monterey County history. The cause of the Indians Fire was an unattended campfire and 15 structures were destroyed. On December 15, 2013, the Pfeiffer Ridge Fire burned several homes and ultimately burned 370 ha (917 acres) before being
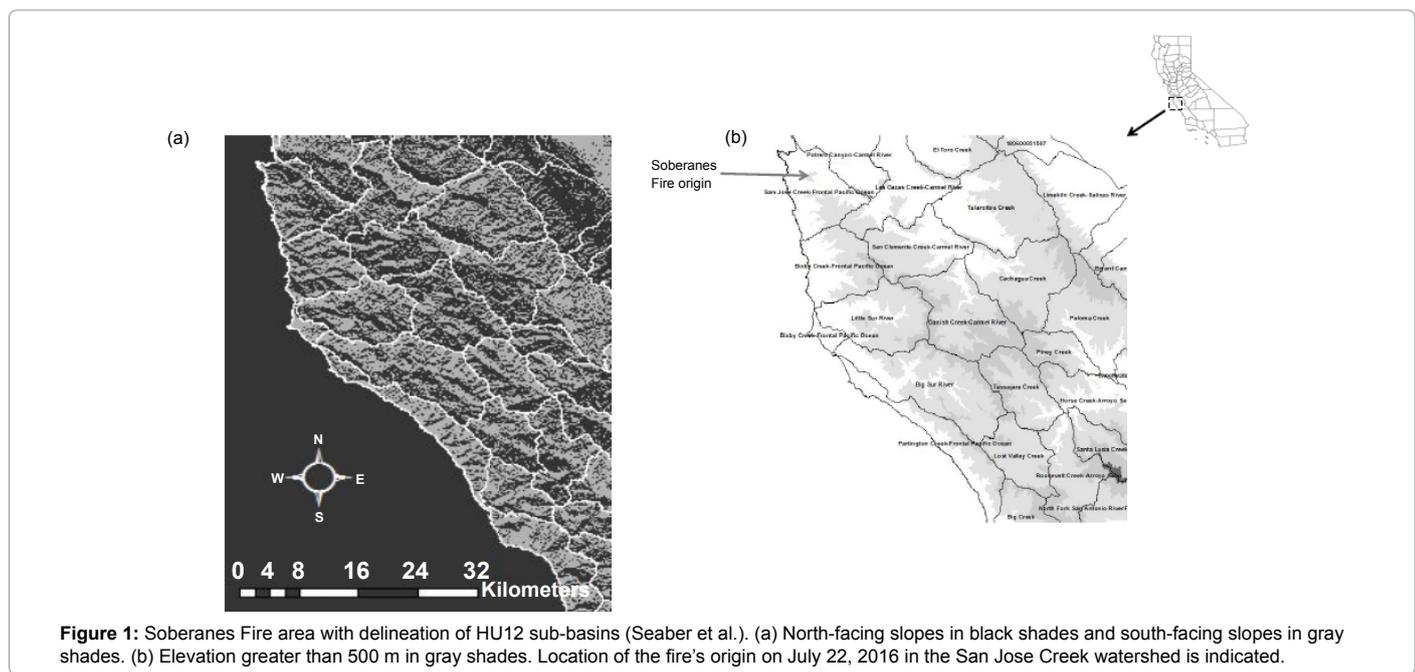

Figure 1: Soberanes Fire area with delineation of HU12 sub-basins (Seaber et al.). (a) North-facing slopes in black shades and south-facing slopes in gray shades. (b) Elevation greater than 500 m in gray shades. Location of the fire's origin on July 22, 2016 in the San Jose Creek watershed is indicated.

brought under control within a few days. The cause was unprotected electrical wiring from the local water company and 34 structures were destroyed. The Tassajara Fire burned 400 ha (1,086 acres) for a week in September, 2015 and spread quickly through grass from a vehicle fire just off Tassajara Road near Cachagua. Twenty structures were destroyed.

Methods

Burn severity classes

Progressive maps of dNBR burn severity classes at 30-m spatial resolution were generated for the Soberanes Fire area from Landsat images (path 43, row 35) obtained on five different dates during 2016: July 22 (pre-fire), August 7, August 23, September 8, and September 24, 2016. All images used in this study were geometrically registered (UTM Zone 11) using terrain correction algorithms (Level 1T) applied by the U. S. Geological Survey EROS Data Center [23]. Landsat surface reflectance products were generated from the L8SR algorithm [24] using a method that uses the scene center for the sun angle calculation and then hard-codes the view zenith angle to 0. The solar zenith and view zenith angles are used for calculations as part of the atmospheric correction. Screening and masking of cloud, fog, and smoke cover was conducted for each NBR image.

The dNBR index [25,26] was computed by comparison of pre- and post-fire infrared reflectance bands from the Landsat sensor, according to the following equations:

$$NBR = (NIR - SWIR)/(NIR + SWIR)$$

$$dNBR = PreFireNBR - PostFireNBR$$

Where NIR is the surface reflectance of wavelengths from 0.76 to 0.9 µm and SWIR is the surface reflectance from 2.08 to 2.35 µm.

The dNBR index (scaled by a factor of 1000 to an integer format) was futher classified into low, moderate and high burn severity classes following the thresholds determined by Miller and Thode [27] based on a composite burn index (CBI) for California forests (Table 1).

Additional spatial data layers

Elevation, slope, and aspect were determined at 30-m spatial resolution from the USGS National Elevation Dataset (NED). Elevation was classified into four categories: <500 m, 500-1000 m, 1001-1500 m, and >1500 m. Slope was classified into three categories: <15%, 15-30%, and >30%. Aspect was classified into two categories: north-facing and south-facing.

River drainage basin boundaries were delineated by the U.S. Geological Survey. The Soberanes Fire burned over portions of the 10-digit (HU10) drainage basins of the Carmel Bay (Pacific Ocean outlet), Big Creek (Pacific Ocean outlet), Carmel River, and Arroyo Seco River watersheds. A total of 33 12-digit (HU12) sub-basins were affected by the Soberanes Fire (Figure 2).
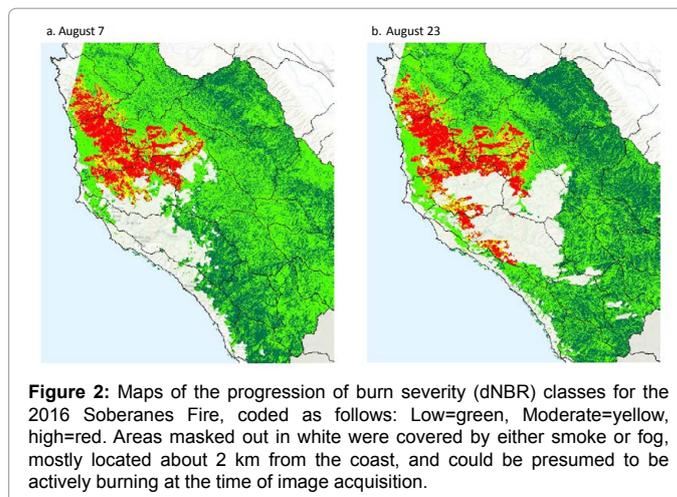

Figure 2: Maps of the progression of burn severity (dNBR) classes for the 2016 Soberanes Fire, coded as follows: Low=green, Moderate=yellow, high=red. Areas masked out in white were covered by either smoke or fog, mostly located about 2 km from the coast, and could be presumed to be actively burning at the time of image acquisition.

Landscape patch metrics

Post-wildfire landscapes are typically composed of a complex mosaic of burn severity patch classes. Landscape metrics for MBS and HBS class patches of each of the fires selected between 1984 and 2015 were computed using the FRAGSTATS program [28]. Class indices from FRAGSTATS quantify the densities and spatial configuration of patches, and therefore provide different metrics to quantify the shapes and aggregation levels of the patch types across and among the burned landscapes.

The simplest index of landscape pattern is patch size. Patch size distribution can be summarized at the class level by a variety of metrics (e.g., mean, median, max and variance). The area-weighted mean patch size is also known as correlation length and indicates the distance that one might expect to traverse the map while staying in a particular patch, from a random starting point and moving in a random direction [29]. The boundaries between patches (or edges) represent another fundamental spatial attribute of a patch mosaic. The most common measures of patch shape complexity are based on the perimeter-to-area ratio. Aggregation indices measure the degree of clumping of patch types and are also referred to as metrics of landscape texture.

For each progressive stage of the Soberanes Fire selected, the following landscape metrics were compared for MBS and HBS classes: Percentage of landscape (PLAND), Area-weighted mean patch area (AREA_AM), Coefficient of variation in patch area (AREA_CV), Total edge (TE), Landscape shape index (LSI), Perimeter-area ratio (PARA), and Clumpiness index (CLUMPY). PLAND is a measure of how much of the landscape is comprised of a particular patch class. AREA_AM provides a patch size metric a function of the number of patches in the class and total class area. TE is an absolute measure of total edge length of a particular patch type. The LSI is a metric of the amount of edge present in a landscape and expresses the perimeter-to-area ratio for the class as a whole. It can be interpreted as a measure of the overall geometric complexity of the class in a given landscape. The higher the LSI, the higher the amount of edge area at the landscape scale. CLUMPY is a metric that ranges from -1 when the patch type is maximally disaggregated to +1 when the patch type is maximally clumped. It returns a value of zero for a random distribution.

Results

Progression of burn severity

Four stages of the Soberanes Fire were mapped using Landsat

Severity Category	Field-measured CBI value	Predicted dNBR	Description
Unchanged	0-0.1	<410	Indistinguishable from pre-fire conditions
Low	0.1-1.24	410-1760	Little mortality of the dominant vegetation
Moderate	1.25-2.24	1770-3660	Mixture of mortality ranging from low to high
High	2.25-3.0	>3660	High to complete mortality

Table 1: Threshold values for the Landsat dNBR classes from CBI analysis by Miller and Thode (2007).

dNBR image results generated from July 22 to September 24, 2016. These dNBR results were verified by daily reports of the fire's progression from the Central Coast Incident Management Team.

Stage 1 - July 22 to August 7: By the end of the first week of August, 2016, the HBS area had spread into the drainage basins of the Soberanes Creek, San Jose Creek, Bixby Creek, Little Sur River, San Clemente Creek (Carmel River), and Danish Creek (Carmel River) (Figure 2a). Total area burned had spread to more than 23,270 ha (57,500 acres), which was equal to an average burn rate of approximately 1370 ha per day (554 acres per day). However, within the first five days of the fire's start, more than 20 homes were destroyed along Palo Colorado Road and the area burned had spread to 6515 ha (16,100 acres). Within 10 days of the fire's start, more than 55 homes had been destroyed.

Stage 2 - August 8 to August 23: By the end of the third week of August, 2016, the HBS area had spread well into Big Sur River basin (Figure 2b). On the east side, the fire advanced toward Miller Mountain and Ventana Cone with firefighters preparing and reinforcing contingency lines from the Los Padres Reservoir to Chews Ridge. Near the town of Big Sur, aircraft were used to slow the southern progression of the fire. Most of the burn activity occurred on the south section of the Big Sur River drainage.

Stage 3 - August 24 to September 8: By the end of the first week of September, 2016, the southwestern HBS area had extended into the Lost Valley Creek basin (Figure 2c). HBS areas continued to be active in the south fork of Big Sur River drainage and on Mocho Creek on the southern-most edge of the fire. There were also active HBS areas on the south slope above the Carmel River near Sulphur Springs Camp. Aerial infrared images showed intense heat in the area burned adjacent to the Los Padres Reservoir due to increased winds on the line near Miller Mountain. Water and retardant drops by aircraft were used to limit further spread of fire in the Carmel and Big Sur River drainages.

Stage 4 - September 9 to September 24: By the end of the third week of September 2016, the Soberanes Fire southeastern HBS area had spread into the Piney Creek, Tassajara Creek, Calaboose Creek, and Roosevelt Creek (Arroyo Seco River) basins (Figure 2d). Unexpected wind gusts pushed the fire over a containment line during the nighttime hours of September 19, leading to a new evacuation order. The strongest winds at this time were experienced above 1000 m elevation, near Chews Ridge and Tassajara Road. Maximum daytime temperatures also exceeded 32ºC on the three days between September 19 and 21 at the nearby BSP weather station. A new HBS spot fire started when the wind shifted unexpectedly to the southwest and reached gusts of 30 to 40 mph, blowing embers across the containment line into the Piney Creek basin. Fire fighters dropped burn-retardant chemicals in Tassajara Canyon and set back-fires along Chews Ridge and into the Piney Creek drainage to bring the fire under greater containment.

Burn severity landscape patterns

Over the 10-week course of the Soberanes Fire, landscape patch metrics for HBS areas changed in several notable ways (Table 2). First, the TE metric progressively increased from about 1.8 million meters on August 7 to 4.4 million meters on September 24. The LSI metric for HBS patches increased by 64% and the HBS AREA patch metric increased as well, from an average of 5665 ha to over 6,790 ha over the same time interval. The PARA for HBS patches decreased by only 3% while the CLUMPY aggregation metric remained nearly constant at a value of 0.88.

The landscape metrics for MBS areas (Table 3) showed that these patches were far more numerous and smaller in average area by nearly a factor of 30, compared to HBS patches from the Soberanes Fire. Nonetheless, metrics for MBS areas progressively changed in some similar ways to the metrics for HBS areas. First, the TE metric more than doubled from August 7 to September 24. The LSI metric for MBS patches increased by 73%, but the MBS AREA patch metric decreased from an average of 349 ha to over 244 ha over the same time interval. In contrast to HBS patches, the PARA for MBS patches increased by 18%, while the MBS CLUMPY aggregation metric decreased from a value of 0.61 on August 7 to 0.52 on September 24.

Final burn severity patterns

Based on the Landsat dNBR burn severity classes derived from Landsat imagery collected on September 24, 2016, the final HBS area for the Soberanes Fire comprised 21.7% of the total area burned, whereas final MBS area comprised 9.6% of the total area burned (Table 4). The combined HBS and MBS area was estimated at 44,623 ha (110,266 acres). Watershed areas that showed the highest coverage of total burned area from the Soberanes Fire (in order starting from the highest) were the Big Sur River, Danish Creek (Carmel River), Little Sur River, Bixby Creek, San Clemente Creek (Carmel River), Las Gazas Creek (Carmel River), Partington Creek, and San Jose Creek. Each of these drainage basins had more than 5900 ha (14,580 acres) burned by September 24, 2016.

Cross-tabulation by elevation classes (Table 5) showed that the combined MBS and HBS class area of the Soberanes Fire was nearly three times higher in the elevation zone between 500 and 1000 m than in the elevation zone below 500 m. The total HBS class was broken

Stage	PLAND	No. PATCHES	TE	LSI	AREA AM	AREA CV	PARA AM	PARA CV	CLUMPY
1 - July 22 to Aug 7	6	1,359	1,842,900	43	5,665	2,499	154	37	0.88
2 - Aug 8 to Aug 23	8	1,578	2,123,910	47	5,239	2,393	155	38	0.88
3 - Aug 24 to Sept 8	12	1,911	3,087,540	54	6,176	2,315	146	36	0.88
4 - Sept 9 to Sept 24	14	2,526	4,404,390	65	6,793	2,351	148	36	0.87

Table 2: Landscape patch metrics of HBS areas for progressive stages of the Soberanes Fire.

Stage	PLAND	No. PATCHES	TE	LSI	AREA AM	AREA CV	PARA AM	PARA CV	CLUMPY
1 - July 22 to Aug 7	3	3,383	3,199,320	102	349	1,363	513	27	0.61
2 - Aug 8 to Aug 23	4	4,192	3,730,890	109	316	1,316	500	28	0.61
3 - Aug 24 to Sept 8	5	7,270	5,341,740	139	366	1,689	579	26	0.55
4 - Sept 9 to Sept 24	6	13,022	8,179,530	176	244	1,524	602	25	0.52

Table 3: Landscape patch metrics of MBS areas progressive stages of the Soberanes Fire.

dNBR class	Area (ha)	Area (acres)	Percent
LBS	97,826	241,734	68.7
MBS	13,644	33,716	9.6
HBS	30,979	76,551	21.7
Total	142,450	352,000	100.0

Table 4: Burn severity class areas of the Soberanes Fire based on Landsat image analysis from September 24, 2016.

Elevation Class (m)	LBS	MBS	HBS	Total MBS + HBS
< 500	49,890	5,273	5,072	10,345
500-1000	35,651	7,006	20,569	27,576
1001-1500	12,353	1,430	5,419	6,849
> 1500	261	6	16	21

Table 5: Burn severity class areas (ha) of the Soberanes Fire based on Landsat image analysis from September 24, 2016 tabulated by elevation classes.

Slope Class	LBS	MBS	HBS	Total MBS + HBS
< 15%	28,383	2,771	4,189	6,960
15-30%	52,950	7,816	19,265	27,081
> 30%	16,823	3,129	7,621	10,750

Table 6: Burn severity class areas (ha) of the Soberanes Fire based on Landsat image analysis from September 24, 2016 tabulated by slope classes.

down into 16% below 500 m elevation, 66% between 500 and 1000 m, and 17% above 1000 m. A separate cross-tabulation by slope classes (Table 6) showed that the combined MBS and HBS class area was nearly three times higher in the slope zone between 15% and 30% than in the slope zone greater than 30%. The total HBS class was broken down into 13% on areas below 15% slope, 62% on areas between 15% and 30% slope, and 25% on areas greater than 30% slope. A third separate cross-tabulation by north-facing (N) versus south-facing (S) aspects showed that total HBS areas were broken down into 39% on N hillslopes and 61% on S hillslopes, whereas total MBS areas were broken down into 56% on N hillslopes and 44% on S hillslopes.

Watersheds with the highest density of HBS area on the slopes greater than 30% included the Big Sur and Little Sur Rivers, Danish Creek (Carmel River), and Piney Creek (Figure 3). The steepest slopes that lost practically all vegetation cover during the Soberanes Fire totaled 7595 ha (18,767 acres), and were centered around the mountainous peaks of Portuguese Ridge, San Clemente Ridge, Bixby Mountain, Skinner Ridge, Island Mountain, Miller Mountain, and Chews Ridge.

Burn severity patterns from the 2008 Basin Complex Fire [30] were overlaid on the 2016 Soberanes Fire burned areas and showed that just over 4430 ha (10,950 acres) of land in Monterey County that burned at HBS during the Basin Complex were re-burned at HBS during the Soberanes Fire (Figure 4). Approximately 50% of this total 2016 re-burned area at HBS from the Basins Complex Fire was distributed throughout the Big Sur and Little Sur River watersheds, followed by 20% in the Danish Creek (Carmel River), 16% in the Piney Creek, and 12% in the Lost Valley Creek drainages. These 2016 re-burned Basins Complex areas at HBS were centered notably on Skinner Ridge, Little Pines, Post Summit, Longwood Ridge, Strawberry Valley, and Chews Ridge within the Soberanes Fire area. In addition, 8,890 ha (21,970 acres) that burned at MBS during the 2008 Basin Complex Fire were burned again at MBS or HBS during the 2016 Soberanes Fire.

Discussion

Results from this progressive Landsat dNBR analysis of the 2016 Soberanes Fire in coastal Monterey County, California showed that
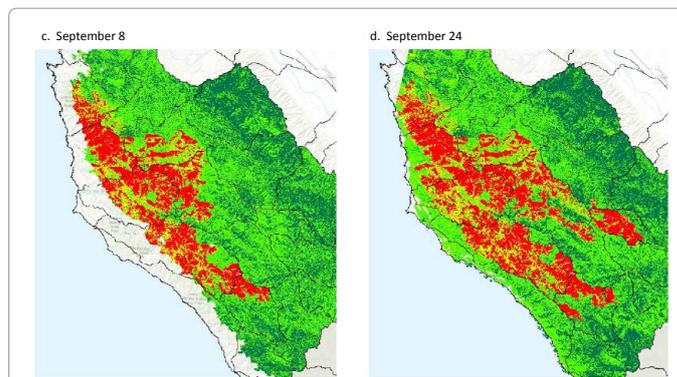

Figure 3: Delineation of HBS areas of the Soberanes Fire on slopes greater than 30% mapped in dark gray shades from Landsat imagery obtained on September 24, 2016.
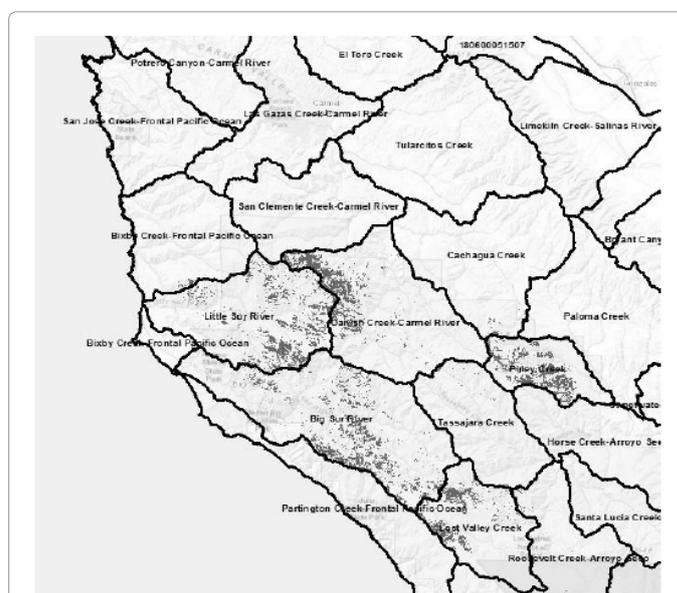

Figure 4: Overalap of HBS areas from both the Soberanes Fire (as of September 24, 2016) and Basin Complex Fire of 2008, mapped in dark gray shades.

the final HBS area for the Soberanes Fire comprised about 22% of the total area burned, whereas final MBS area comprised about 10% of the total area burned of approximately 53,470 ha (132,130 acres). The final pattern of burn severity patterns from the 2016 Soberanes Fire revealed that the majority of HBS was located in the elevation zone between 500 and 1000 m, in the slope zone between 15% and 30%, or on south-facing aspects.

In comparison, a region-wide, Landsat dNBR based analysis by Potter [31] of the largest fires since 1984 on the California south-central coast resulted in an average estimate of the percentage of HBS area to total area burned of 20%. However, three of the four largest fires recorded on the Central Coast, namely the Zaca, Basin Complex, and Day fires, each exceeding 60,700 ha (150,000 acres), have occurred within the past ten years and had a range of HBS percentage area from 17% to 73%.

Potter [31] also reported that nearly 60% of this documented variation in the percentage of HBS to total area burned among the

could be explained by a combination of maximum monthly air temperature at the date of ignition and total precipitation recorded during the previous 12 months. As maximum air temperatures for the month approached 40°C (as a daily average), the percentage of HBS to total area burned frequently exceeded 20%. Weather conditions during the 10 weeks of the Soberanes Fires showed maximum daily temperatures exceeding 30°C on seven different days (including the date of ignition), which puts the HBS to total area burned of 22% near the expected percentage for large wildfires on the California central coast since the 1980s.

Landscape patch analysis results from Potter further implied that, as the total area burned in fires on the southern and central California coast grows, the edge lengths and area complexity (expressed in TE and LSI) of HBS patches also grows at a rapid rate. At the same time, the perimeter-to-area (PARA) of HBS patches decreases gradually and the HBS patches become more aggregated as total burned area grows, expressed as changes in the CLUMPY metric. In contrast, landscapes analysis results for MBS area patterns showed that patches of MBS are more numerous and notably smaller in size than patches of HBS area. Nonetheless, edge length, perimeter-to-area ratio, and the level of disaggregation of MBS areas grow as the relative fraction of HBS core area increases in fires on the south-central California coast.

The progressive patch analysis of the 2016 Soberanes Fire showed patterns typical of past large wildfires in the region. Specifically, TE of HBS areas nearly doubled over the course of the fire and LSI metric for HBS patches increased by more than 50%, indicating a gradually increasing landscape complexity pattern for this fire. The PARA for HBS patches decreased by just 3% while the CLUMPY metric remained nearly constant at a relatively high aggregation value of 0.88. In an opposite pattern, the landscape metrics for MBS areas showed that these patches were far more numerous, smaller in average area by nearly a factor of 30, and substantially more disaggregated, compared to HBS patches from the Soberanes Fire.

Li and Potter [32] analyzed satellite radar images two years after the 2008 Basin Complex Fire in Monterey County and concluded that aboveground biomass (AGB) of shrub covered areas burned in 2008 had regrown to greater than 20 Mg ha^{-1} AGB by 2010 on 27,365 ha (67,620 acres) burned, and to greater than 40 Mg ha^{-1} AGB by 2010 on another 19,290 ha (44,660 acres) burned. In unburned control plots near Big Sur, shrub AGB was measured in 2010 at 47 to 102 Mg ha^{-1}. These results implied that, within three years after the Basin Complex Fire, shrub vegetation regrowth had been rapid and dense on no less than 70% of the total 66,585 ha burned in 2008. Combined with the findings that approximately 14,000 ha of vegetation cover that burned at MBS and HBS area during the Basin Complex Fire (or 21% of the total burned area) were reburned at MBS or HBS during the 2016 Soberanes Fire, it can be concluded that shrub AGB levels in early 2016 were not a major limiting factor to the progression of the Soberanes Fire.

Most of the same conclusions about climate at the time of fire ignition and landscape patterns of stand replacing burned areas derived from this study in central coastal California were also drawn by Harvey et al. in a study of nearly 700 fires in the Northern Rocky Mountain region since 1984 and by Cansler and McKenzie [33] in the northern Cascade Mountain Range. These investigators reported that landscape patterns of stand-replacing fire were strongly controlled by fire size and the proportion of stand-replacing (HBS) area to total fire area, which were, in turn, controlled mainly by climate. Annual moisture deficit, a function of both temperature and precipitation, was highlighted as a

prime controller of fire size in the Northern Rocky Mountain region, similar to the findings of Morgan et al. [34] and Abatzoglou and Kolden [35].

For the Northern Rocky Mountain region, Harvey et al. reported that fire size was controlled in part by topographic roughness, although to a lesser degree than by climate. The shape of HBS patches was almost entirely driven by proportion of HBS area to total fire area, and therefore could be affected indirectly by vegetation structure and slope, in addition to climate conditions at the time of ignitions. When fires in this region reached the proportion of HBS area exceeding 35%, the HBS patch sizes and total core area tended to increase non-linearly. In contrast, landscape patterns on the California central coast showed a more linear increase of HBS patch sizes, total edge lengths, and aggregation metrics of the core HBS areas when the proportion of HBS area exceeded 35%. Harvey et al. reported that, for fires in the Northern Rocky Mountain region, the proportion of stand replacing fire within burn perimeters increased from 22% to 27% over the period of 1984 to 2010.

According to a review by Molinari et al. [36], fire size and severity has recently been growing in southern California. For instance, in Douglas-fir stands of the Los Padres National Forest, Lombardo et al. [37] identified a shift to more severe fires after the late nineteenth century and also noted a shift to predominantly widespread, landscape-scale fires compared to previous, more even mixtures of relatively large and small fires.

Climate change projections for central and southern portions of the state have shown that there is consensus for increasing air surface temperatures in California based on climate model predictions for 1951-1980 compared to 2070-2099 [38], but the magnitude of warming is less certain, with projections ranging between 1°C and >6°C. In contrast to temperature changes, there little certainty as to the direction of change for annual precipitation totals, with some projections indicates more rainfall across the state and others predicting less [39-41].

Nonetheless, California is currently (circa 2013-2016) experiencing one of the hottest and driest period in its recorded climate history (since 1895). Molinari et al. reported that all available weather stations along the California Central Coast have recorded statistically significant increases (from around 1910 to 2014) in at least one of the temperature parameters, mean minimum, mean annual, or mean maximum. Potter found that the number of extreme warm summer days (Tmax >37°C) has increased by several-fold in frequency on the Big Sur coast since the early 1990s [42]. Overall patterns in the station records indicated that diurnal temperature ranges are widening on the Central Coast, with markedly cooler nighttime temperatures (frequently in the wet winter season) followed by slightly higher-than-average daytime temperatures, especially during the warm, dry summer season. These warming drought conditions have already elevated the risk for large HBS wildfires along the Central Coast zone of California.

Acknowledgements

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