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Chaparral recovery following a major fire with variable burn conditions

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ABSTRACT

Wildfires are a common occurrence in California shrublands, maintaining ecosystem functions with the regeneration of key shrub species. The Cedar Fire of 2003 in southern California was unique in that a portion of it burned with wildfire accelerated by dry, strong northeasterly Santa Ana winds that later subsided, while the remaining area burned under an onshore, westerly wind of lower velocity and higher humidity. These nearby areas, having similar terrain, fuel type, and environments, burned under these different conditions. Our goal is to understand the connection between vegetation response to extreme fire events by analysing life-form regrowth in chaparral from the Santa Ana wind driven, Santa Ana backing, and non-Santa Ana fire types. Study sites representing these three fire conditions were based on fire progression maps generated from Moderate Resolution Imaging Spectroradiometer (MODIS) hotspot data. Shrub cover before and six years after the fire were mapped based on a spatial contextual classifier applied to colour infrared orthoimagery, and analysed per slope aspect and angle, elevation, and fire characteristic categories to isolate shrub regrowth patterns. Six years after the fire, shrub cover in the Santa Ana wind driven site was substantially lower than in the other two sites. Such differences in shrub cover at the landscape scale may have resulted from different wind speed, direction, and humidity during the fire, coupled with terrain differences on wildfire behaviour and different rates of recovery associated primarily with moisture availability to plants. The information gathered from this study can help land managers assess shrub regrowth and possibility of vegetation type change after extreme fire events in southern California shrubland ecosystems.

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1. Introduction

Shrublands and forests of Mediterranean-type climate areas of Alta and Baja California are fire prone during summer and fall when fuels are highly flammable. Post-fire chaparral shrublands may exhibit successional characteristics that entail changes in species or even growth form composition. Frequent burns increase the possibility of

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permanent type conversion from shrubs to subshrubs or herbaceous vegetation, especially in coastal sage scrub in southern California (Zedler, Gautier, and McMaster 1983; Keeley, Fotheringham, and Baer-Keeley 2005b; Lippitt et al. 2013). Invasive species can colonize frequently burned areas, changing the composition and fuel characteristics, including ecological function and response to fires and floods (Zedler, Gautier, and McMaster 1983; Conard and Weise 1998).

Large-scale wildfires are responsible for the great bulk of shrubland areas burned in southern California, and these wildfires often occur during Santa Ana wind conditions (Countryman 1974; Westerling et al. 2004). Santa Ana winds occur most frequently during fall months, and are characterized by strong, offshore foehn-type winds and extremely warm, dry conditions (Raphael 2003; Abatzoglou, Barbero, and Nauslar 2013). In October 2003 several large wildfires burned extensive areas of San Diego County, California. One of these wildfire events was the Cedar Fire, which burned a total of 113,429 ha, one of the largest fires in California since burn extent records have been kept (Brillinger, Autrey, and Cattaneo 2009). Because this fire burned during different weather conditions and wind directions, it provides an opportunity to study possible differences between fire behaviours and ecosystem response to them. Our study takes advantage of the varying wind regimes, and therefore fire spread conditions, during the Cedar Fire by examining the extent to which the different burn conditions influence post-fire recovery of chaparral. Currently there is no clear understanding of the effects of Santa Ana wind-driven fire on chaparral.

This study contributes to the literature by comparing chaparral recovery from three burn conditions in the same time period for nearby areas having similar vegetation, climate, and topography, and by the exploration of a spatial-contextual classification routine (Overwatch Geospatial Feature Analyst software) applied to high spatial resolution imagery to map vegetation growth form types before and after the Cedar Fire. This work furthers the development of semi-automated image analysis for vegetation growth form and land-cover classification. The application of spatial-contextual classifiers is relatively novel for growth form (i.e. shrubs, subshrubs, herbs, and bare) classification in a Mediterranean-type shrubland. This follows work by Stow et al. (2008) on object-based image analysis (OBIA) approaches for monitoring shrubland habitat reserves, though strictly speaking Feature Analyst software does not utilize a true OBIA approach (Tsai, Stow, and Weeks 2011).

Our study takes a landscape ecological approach to examining chaparral regrowth patterns and attempts to infer fire behaviour and moisture availability effects on such regrowth. With such an approach, we attempt to also infer landscape-scale processes from the differential recovery patterns of vegetation growth form types mapped from imagery taken just before and six years after the wildfire event. Stratification of the study subareas according to slope gradient and aspect units, in an attempt to control for topographic influences on fire behaviour and post-fire moisture availability, provides a type of replication of results for each large subarea. Viedma et al. (2015) demonstrated that burn severity could be modelled with high predictability when stand structure is coupled with other important predictor variables such as rate of fire spread of the propagating front, burn conditions, and topographic variables such as slope aspect and convexity or concavity of slope. Previous studies on post-fire chaparral regrowth do not examine differential recovery from disparate fire conditions at the same time and in close proximity. The Cedar Fire created a unique opportunity to examine recovery patterns of post-fire chaparral at three sites that burned respectively during Santa Ana wind driven, Santa Ana backing, and non- Santa Ana fire conditions.

The objectives of this study were to: (1) describe the general study area characteristics, inter-site differences, and data sets used to characterize these sites, as well as the nature of fire spread through this area during the Cedar Fire event; (2) determine the validity of using a spatial-contextual classifier applied to high spatial resolution aerial imagery to reliably map chaparral growth forms and estimate their areal extents; (3) quantify areal cover proportions of growth-form types (particularly shrubs) one year prior to and six years after fire in a chaparral ecosystem; and (4) evaluate the amount and distribution of growth forms (particularly shrubs) between pre-fire and post-fire images and between Santa Ana wind-driven (SA), Santa Ana backing (SAB), and Non-Santa Ana (NSA) parts of the area burned by the Cedar Fire, in order to discern if effects of different burn conditions, and post-fire environmental factors are observable and separable in the regrowth patterns of chaparral landscapes.

2. Study area and fire event

We selected, studied, and compared three sites, each 37 km^2 in area, within the Cedar Fire perimeter (Figure 1). In this section we describe the nature of the Cedar Fire, the characteristics of the study area and the environmental data used to assess these characteristics, as well as how the three study sites within the broader study area were selected. We note that these sites mostly differ in location from those studied by Blodgett et al. (2010), as much area of the original sites had burned since the Cedar Fire. Physical characteristics of the full study area include mostly poorly accessible semi-arid hill and mountainous terrain characterized by a substantial amount of exposed soil and granitic outcrops.

The great bulk of land cover for the general study area is chaparral with lesser amounts of coastal sage scrub admixed. Only chaparral areas were analysed in this study, though some riparian corridors consisting mostly of tree forms traverse through the study sites (and were subsequently masked out). We used vegetation community digital maps (ca. 1995 and 2011) in ArcGIS shapefile format from the San Diego Association of Governments SanGIS/SANDAG geographic information system (GIS) Data Warehouse to delineate chaparral and non-chaparral areas (San Diego Association of Governments 2013). All three sites contain mostly mixed chaparral community types dominated in varying proportions by evergreen sclerophyllous shrubs, most notably chamise (*Adenostoma fasciculatum*.), woollyleaf ceanothus (*Ceanothus tomentosus*), hoaryleaf ceanothus (*Ceanothus crassifolius*), Eastwoodliumanzanita (*Arctostaphylos glandulosa*), and scrub oak (*Quercus berberidifolia*). Patches of chamise chaparral dominated by *A. fasciculatum* also occur within all three study sites. Species compositional information for these two chaparral types and coastal sage scrub was obtained from the Natural Resources Conservation Service (2012).

The three study sites were delineated based on the following criteria: (1) wholly burned under one the three primary fire conditions (specified below), (2) composed primarily of mixed or chamise chaparral communities, (3) all sites in relatively close proximity with similar terrain characteristics, (4) did not burn since 2003, and (5) sites have the same areal extent. One of the study sites is located within that part of the fire

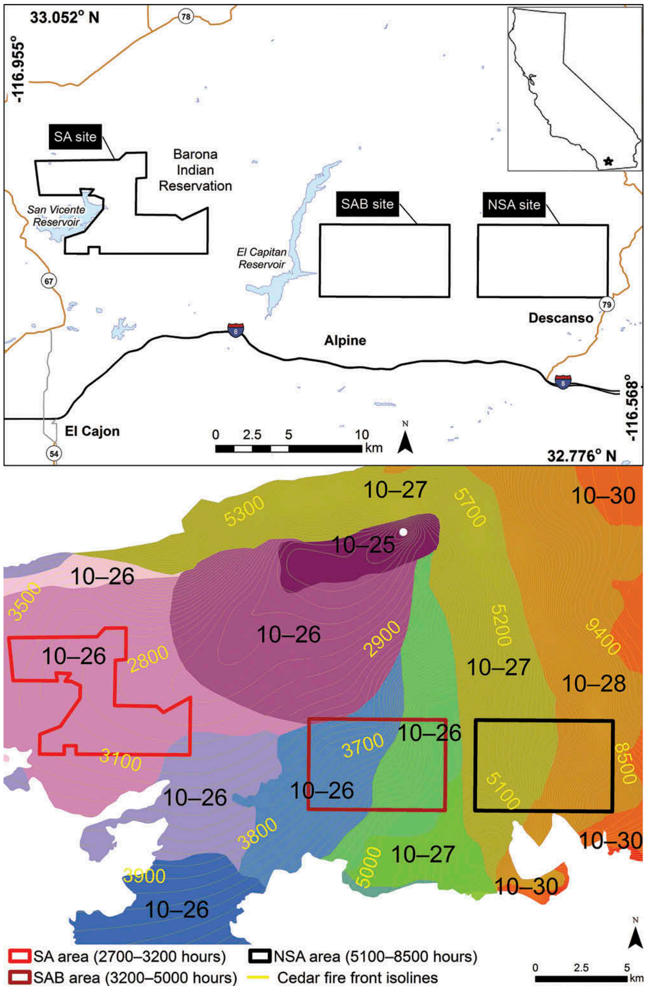

Figure 1. Top: Site location map in San Diego, California, USA. Inset shows approximate location of study area in California. Bottom: Cedar Fire Progression, San Diego, California, USA. The white dot is where the fire began on 25 October 2003 at 1900 hour. The yellow isolines approximate the leading edge of the fire at hourly intervals from 1900 hour on 25 October to 9900 hour (0500, on 29 October), based on interpolation of Moderate Resolution Imaging Spectroradiometer (MODIS) imagery hotspot data. Colour polygons in Figure 1 are fire progression polygons generated by California Department of Forestry and Fire Protection. Both sources of fire progression data were used to delineate the three study sites that represent different burn conditions and types of fire progression.

that burned during classic Santa Ana (SA) wind conditions, that is, offshore flow characterized by very high air temperatures, very low humidity, and high wind speeds (Raphael 2003). The perimeter of this study area is irregular in order to avoid a reservoir, some urban areas, and stands associated with fires that burned since 2003. The other two study sites are located south and east of the SA site, within the lower portion of the area studied by Blodgett et al. (2010). The site that we refer to as Santa Ana backing (SAB) burned in an easterly direction (i.e. opposite the predominant wind direction) during the time of the Santa Ana winds. The third study site burned after the Santa Ana

Table 1. Study site aspect and slope angle proportions.

Proportion (%)	SA	SAB	NSA
N, NE, NW	39	42	33
S, SW	23	23	28
E, W, SE	38	35	39
0.0–16.7°	09	08	12
16.7–45.0°	40	51	60
45.0–73.6°	51	42	29

winds ceased, under more moist, onshore wind conditions (Non-Santa Ana or NSA). A 1.8 km buffer was created between the two lower study sites to ensure adequate separation of burn types (Figure 1).

Elevation, slope angle, and slope aspect information for the study sites (Table 1) are based on data extracted and derived from U.S. Geological Survey digital elevation data (10 m raster). (Details on the slope angle and aspect procedures are described in Section 3.) Both the SA and NSA sites have more pronounced elevation ranges with large areas of rocky outcrops and granite rather than the SAB site. Elevation of the SA site ranges between 186 and 984 m above mean sea level. Elevation of the SAB site ranges between 232 and 898 m above mean sea level. The NSA site elevation ranges between 777 to 1524 m above mean sea level. There is little overlap in elevation range between the NSA site and the other two study sites. The areal extent of slope azimuths facing north, south, east, and west are approximately evenly distributed among the three sites.

Mean annual precipitation increases with elevation from west to east in the study area, as represented in Spatial Climate Data obtained from the Parameter Elevation Regression on Independent Slopes Model (PRISM) Climate Group at Oregon State University (2014). Remote Automated Weather Stations (RAWS) weather station data for the Alpine, Descanso, and Pine Hills locations were used to characterize weather conditions prior to, during, and after the Cedar Fire (RAWS USA 2011). PRISM raster data sets were subset by study site and processed to table format using the Zonal Statistics tool in ArcMap. The 30-year PRISM data set for 1981–2010 gives the range of average annual precipitation estimates within the SA study site at 406–478 mm, 427–493 mm for the SAB study site, and the NSA study site at 504–726 mm. Mean average annual temperatures decrease with increasing elevation as one progresses inland, and are 18.4ºC for El Cajon (elevation = 143 m) located near site one, 17.5ºC for Alpine (518 m) located in site two, and 14.8ºC in Descanso Junction (elevation = 1027 m) located in site three (National Oceanic and Atmospheric Administration 2016).

Soils within the study sites consist mainly of sandy, rocky, and loamy soil types (Soil Survey Staff 2011). As of this study, almost 25% of the NSA site has not been mapped. However, of the parts mapped, the SA and NSA sites are very similar in soil type. They both have 24% acid igneous rock land and a similar amount of very rocky coarse sandy loam. The SAB site stands out with less than 2% acid igneous rock outcrops. Although the SAB site has less rocky land, the soils are similar in type and composition (Bowman 1973).

We obtained a GIS layer from the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (FRAP) (2010) that depicts historical fire perimeters. These fire data indicate that from 1900 to 2003 there were many small fires in all three study sites, and both the SAB and NSA sites burned in 1950. A section of the SAB site burned in 1999 and was masked out of the analysis because it had not recovered prior to the Cedar Fire. About one-fourth of the SA study site had no recorded fire history prior to 2003. Stand ages at the time of burn for the majority of the SAB and NSA sites were 53 years. Stand ages for the SA site were varied and complex. The upper portion of the SA site contained mostly immature shrubs while stand ages in the lower half were over 40 years, with many parts having no recorded burn history.

The progression of the Cedar Fire is portrayed in Figure 1. Fire progression information was derived from Moderate Resolution Imaging Spectroradiometer (MODIS) hotspot data and from fire progression polygons mapped by the California Department of Forestry and Fire Protection (CalFire) (http://map.sdsu.edu/firenet/files/datadownload.htm; last visited 16 March 2016. MODIS hotspot data provided by the USDA Forest Service Remote Sensing Applications Center (RSAC 2012) (http://firemapper.sc.egov.usda.gov/modispts/modis_fire_2003_365.e00.gz) was the primary source. Centroid point locations of the 1 km thermal infrared data set incorporates MODIS data from both Aqua and Terra satellites along with the day and time of data capture. Data capture was approximately every 8–12 hours. The points were parsed to remove duplicate points, brightness intensities below the 400 measure, and any locations not on the leading edge of the fire perimeter. We subsequently interpolated these leading edge hotspot locations using spline interpolation tools in ArcGrid to derive fire progression surface and isochrones. These isochrones approximate the active fire front therefore depict the general fire spread dynamics in one-hour intervals beginning at 1900 hour on 25 October 2003 and continuing over the next several days, with 2500 corresponding to 0100 hour on 26 October 2003. The map is useful for delineating and examining general zones of differing fire conditions and behaviour, but the relatively low frequency of observation and coarse spatial resolution associated with the MODIS data, means it should not be used for detailed reconstruction of the wildfire dynamics. It was, however, useful and appropriate for selecting the three study sites (SA, SAB, and NSA sites delineated on Figure 1) that represent different wildfire burn conditions and fire spread behaviour in a general sense.

The Cedar Fire progressed rapidly in a southwesterly direction, being fanned by a windy and dry Santa Ana weather condition. This fast spreading fire burned the SA site over a period of five hours, between 2700 and 3200 hour on 26 October. The fire continued burning towards the southwest under dry, high-wind conditions with its southernmost perimeter veering southeastward then eastward around El Cajon Reservoir and continuing southeastward as a backing fire. Isochrones depict the fire front burning the SAB site over a period of 18 hours at 3200–5000. Wind conditions changed on the morning of 27 October, which can be seen in the pattern deviation between the maroon SAB and black NSA site outlines. The fire continued eastward in a slower progression under moister, onshore flow, burning the NSA study site over a period of 34 hours, from 5100–8500.

During the first night of the Cedar Fire, winds gusted between 8 and 13 m s^{-1} from the northeast at the Pine Hills and Alpine RAWS, and up to 18 m s^{-1} at the Descanso RAWS. The mean relative humidity at Alpine and Descanso ranged between 4% and 6% at that time. The SA study site burned during these conditions. The fire continued burning around and to the southeast of El Capitan Reservoir against the prevailing wind beginning later the evening of 26 October. Throughout the night of 26 October, winds were still gusting from the northeast at maximum speeds between 4 and 12 m s^{-1} at all three stations. The mean relative humidity ranged between 7% and 11% at Alpine and Descanso. The SAB area located east of El Capitan Reservoir burned during this time period. The wind changed direction the morning of 27 October, which was recorded first at the Alpine station from 0900 to 1100, then at the Descanso station beginning about 1700. For the duration of the day and night of 27 October, the Cedar Fire burned with a mild westerly (onshore) wind averaging under 1 m s^{-1} with minimal gusts up to 5 m s^{-1}. The mean relative humidity at the Alpine and Descanso sites rose steadily from 8% to 24% during the day. It was during these conditions that the NSA study site burned.

Wind direction at the time of burning for the SA and SAB study sites was primarily from the north and northeast according to the Remote Automated Weather Station (RAWS) weather station data for Pine Hills, Alpine, and Descanso. Given the predominant wind direction, the Cedar Fire burned the SA site most rapidly over slopes with north- and east-facing aspects, 315°–360º and 0°–135º, which cover approximately 47% of the SA area. Within the SAB study site, slopes with north- and west-facing aspects (1°–45º and 225°–360º), were burned uphill and were most directionally affected by the backing fire. These slopes cover approximately 56% of the SAB area. On the morning of 27 October, the wind changed direction, coming from the northwest at the Alpine station from 0900 to 1600 hour and at the Descanso station from 1700 to 2400 hour. During these times, slopes with west-facing aspects (180°–360º), which cover approximately 58% of the NSA site, were uphill of the fire in the NSA study site.

A Burned Area Emergency Response (BAER) survey for the Cedar Fire created by the Northern BAER Team, Department of Interior, in November 2003 provided information on burn severity following the Cedar Fire (Figure 2). Most chaparral in the study area was classified as being burned at a moderate severity level with patches of low and non-burned areas. The NSA site had the largest area of moderate burn. The SAB site had similar moderate burn area, much smaller patch sizes, and three times the number of low severity and unburned patches. The SA site had less moderate burn area in very small patches, interspersed with over 2700 low burn severity and unburned patches. The SA average burn area sizes were much smaller with a more patchy appearance than either than SAB or NSA sites. The general trend indicates a more even burn as the fire progressed from west to east (Blodgett et al. 2010).

3. Methods

We performed spatial contextual, machine learning classification of high spatial resolution visible and near-infrared airborne orthoimagery captured a year before and six years after the fire to map pre- and post-fire growth form type distributions of the study sites. We examined true shrub (main component of chaparral) cover proportions between the three study sites and stratified by terrain classes (slope, steepness, and aspect). The accuracies of the growth form maps were assessed, and classification errors were used to adjust for bias in the shrub cover estimates.

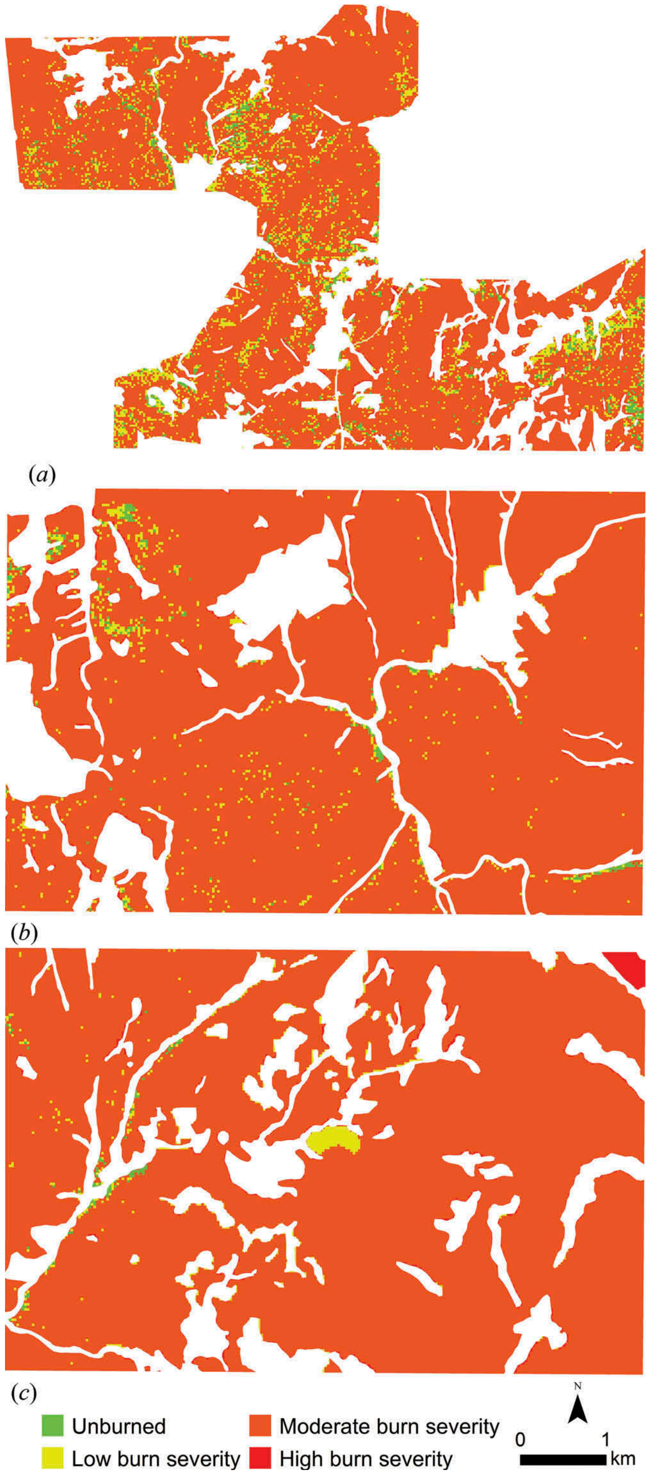

Figure 2. Burned Area Emergency Response (BAER) maps of burn severity level for (*a*) Santa Ana wind (SA), (*b*) Santa Ana backing (SAB), and (*c*) Non-Santa Ana (NSA) study sites, San Diego County, California, USA.

3.1. *Image classification*

We acquired and used Digital Orthoimage Quarter Quadrangle (DOQQ) tiles for vegetation growth form mapping. Pre-fire imagery was captured from 28 May to 3 June 2002 and processed as part of the USGS Earth Explorer National Aerial Photo Program. The spectral coverage is green, red, and near-infrared wavebands based on scanned colour infrared (CIR) aerial photographs with a 1 m ground sample distance. Post-fire imagery was captured in late May and early June 2009 from the USGS National Agricultural Imaging Program (NAIP). The spectral coverage includes blue, green, red, and near-infrared wavebands derived from large format digital cameras having a 1 m ground sample distance (GSD). All individual images are georeferenced in the UTM 11 coordinate system, NAD 83 datum.

We mosaicked May/June, 2009 DOQQ tiles and then extracted subsets for each study site. The mosaicked imagery was overlain with the vegetation community map of San Diego County as an aid in delineating areas of predominant chaparral composition. We created a mask using the vegetation community layer to exclude the riparian, oak and conifer forest, wetland, sage scrub, urban and agricultural cover types from the analysis. The FRAP fire perimeter layer was also overlain in order to avoid areas that burned after 2003. We delineated regions of interest (ROI) from within subset images for each of the three study areas, and training samples were extracted from these ROI. As with any supervised image classification, training sites (ROIs) were selected for pixels with pure and known growth form types, and to represent a range of conditions and signatures (e.g. different topographic exposures and substrates). The classification scheme consists of true shrub, transitional shrub, sub-shrub, herbaceous, rocks, and bare soil classes. The transitional shrub class was necessary since immature shrubs are interspersed with sub-shrubs, herbs, soil, and rock, vary in appearance/signature, and appear/reflect distinctly different than true shrubs.

We performed the image classification using Feature Analyst (Overwatch Geospatial) image classification software running as an extension to ArcMap 10 (ESRI). At least 360 training objects consisting of spatially contiguous pixels that represent homogeneous vegetation growth form and land-cover types were selected to create training data for image classification. The aspect layer enabled us to select training samples of class types from south- (equatorward-), north- (poleward-), east-, and west-facing slopes. We delineated 60 training sites for each cover class, evenly divided between the three study areas. Shrub growth-form types cover at least 60% of the total study area, so 120 of the 360 samples were selected for this class, following Dobrowski et al. (2008). We visited portions of the study sites with printouts of the Google Earth high spatial resolution imagery for inspection and identification of samples and vegetation types in the field to assist in selection of training sites and reference data for accuracy assessment.

We created growth form maps using the training data and multispectral imagery as inputs to Feature Analyst software. The automated feature extraction method uses the spatial and spectral information of colour, texture, and pattern attributes of the training samples in a neural network classifier. An iterative classification process was implemented wherein each class was individually assessed for inclusion and exclusion of image features, ensuring that growth form types were reliably identified and assigned appropriate class labels. Various custom options in Feature Analyst such as moving kernel size and contextual patterns, feature type selection, and minimum patch size were explored to create the classification product that was deemed most reliable through visual image interpretation. A minimum patch size of 4 m^2 was selected to help eliminate spurious classified pixels and misclassification of heterogeneous land-cover distributions within classes.

After initial classification and confirmation, we combined the true shrub and immature (transitional) shrub categories. The soil and rock categories were very similar in composition so we combined them for the final classification and assessment. Pre- and post-fire growth form maps are portrayed in Figures 3–5.

3.2. *Accuracy assessment*

Accuracy was assessed for the two (2002 and 2009) growth form maps, in different manners. The emphasis was on determining the accuracy of the shrub (true shrub)

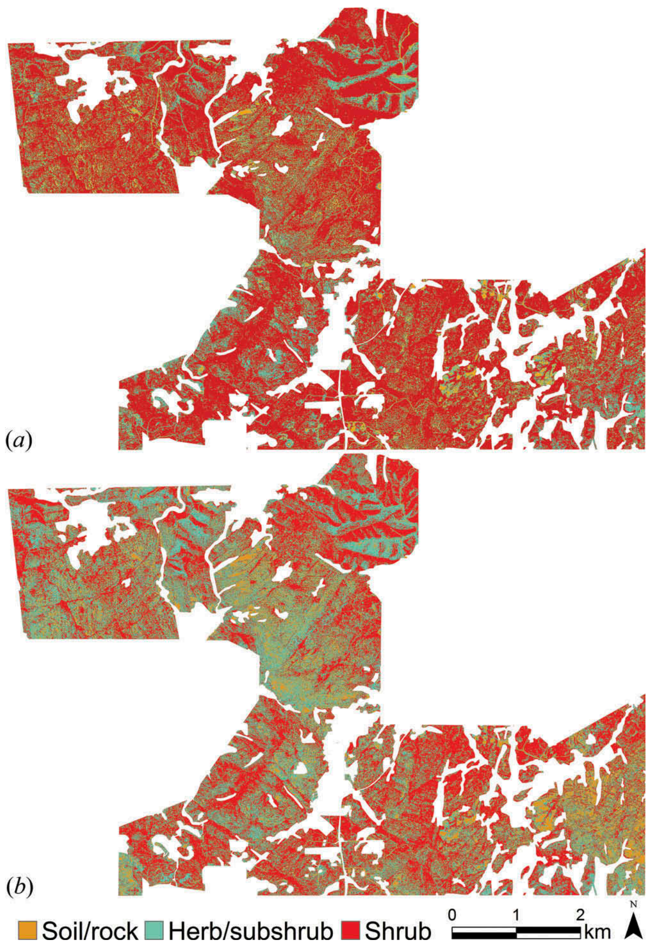

Figure 3. Growth form maps of the Santa Ana wind (SA) study site, San Diego, California, USA for (*a*) 2002 (pre-fire), and (*b*) 2009 (six years post-fire) derived from spatial contextual classification of colour infrared digital orthoimagery.

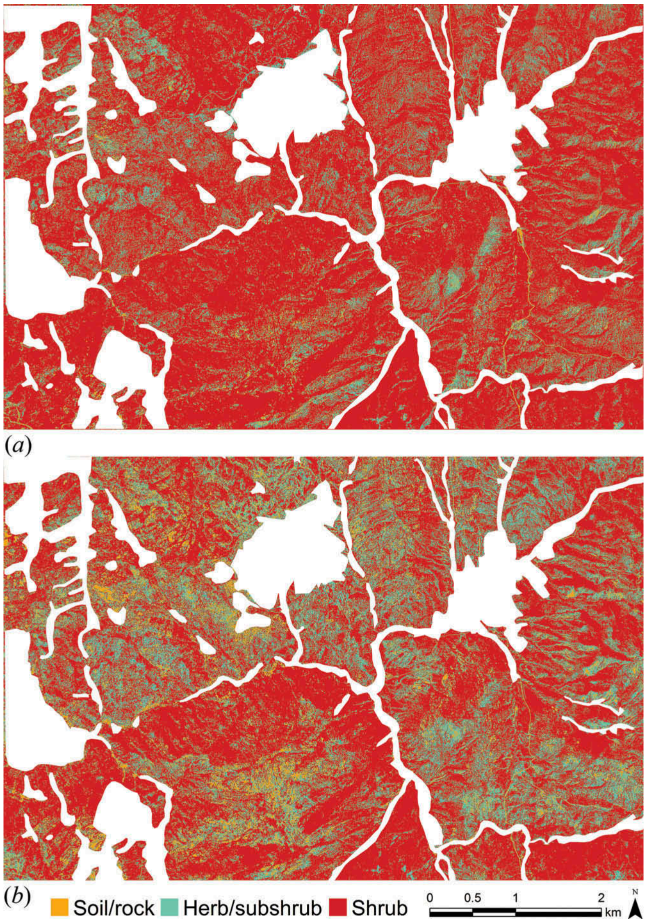

Figure 4. Growth form maps of the Santa Ana backing (SAB) study site, San Diego, California, USA for (a) 2002 (pre-fire) and (b) 2009 (six years post-fire) derived from spatial contextual classification of colour infrared digital orthoimagery.

growth form class, to determine if there was classification bias when estimating the proportion of shrub cover for each study site and map date. As the image classification and accuracy assessment was conducted in 2012, we relied on visual interpretation of the 2002 CIR orthoimage used for image classification and true colour Google Earth imagery to generate reference data for assessing the accuracy of the 2002 growth form map. Reference data were not generated for the SAB study site because of access limitations associated with the impenetrable nature of the shrub cover, the mountainous topography, and the exclusion of entry onto tribal, federal, and private lands. The SAB site is positioned between the other two study sites with similar vegetation and terrain.

We generated 250 random pixel samples to assess accuracy of the 2002 growth form map. A 2 × 2 pixel block (2 × 2 m ground dimensions) was evaluated visually on the Google Earth image when pre-fire (mostly early 2003) coverage was available, and on the CIR orthoimagery when it was not. We ended up with 194 test samples for the SA

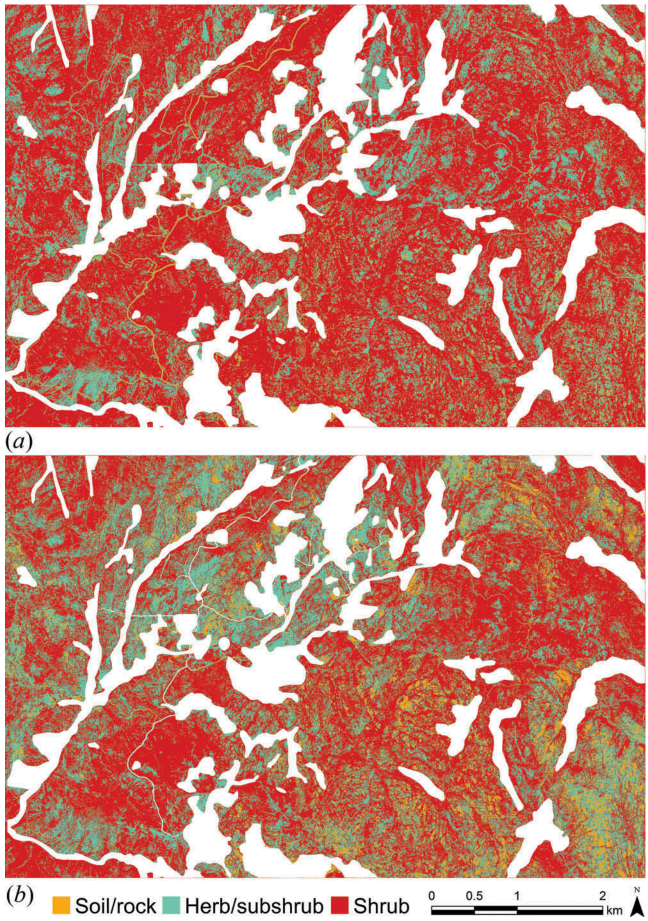

Figure 5. Growth form maps of the Non-Santa Ana (NSA) study site, San Diego, California, USA for (a) 2002 (pre-fire) and (b) 2009 (six years post-fire) derived from spatial contextual classification of colour infrared digital orthoimagery.

and 225 for the NSA sites after removing random samples that were located on built surfaces or were not interpretable.

For the 2009 map, we conducted field sampling to observe growth form types at stratified random sample sites on the ground. Such direct field observations was particularly useful since it was challenging to visually determine growth form types of recovering vegetation that was six years old at the time of the 2009 image acquisition. The three-year lag between the image acquisition and ground observations may create uncertainty in the accuracy assessment, although differences (i.e. transformations) in the growth form types (as compared to canopy cover and stature) over that time period should have been minimal.

We sampled 210 ground reference points for the SA study site, and 239 reference points for the NSA study site to assess the accuracy of the 2009 classified maps. The reference point locations were derived using a simple random point selection algorithm within a buffer along accessible roads and trails using ArcGIS software. Steep terrain and dense shrub canopies makes it difficult to traverse the study areas, so sampling was conducted within 20 m on either side of roads and trails. We converted the reference point locations to keyhole markup language (KML) format and plotted them on recent high spatial resolution imagery in Google Earth. The images were then printed for location and field confirmation. We located all points with a handheld GPS device, and noted and photographed each where necessary.

We used the test sample data to create an error matrix, as the cross-tabulations of mapped classes and the reference (test data) to assess the accuracy of the pre-fire and recovery growth form and land-cover maps (Congalton and Green 2009). Overall, user and producer's accuracies were derived from the error matrices. The number of samples was based on an expected overall accuracy of 85% with a 5% confidence interval based on a standard level of agreement for many land-cover and land-use mapping products (Jensen 2005).

3.3. *Application of accuracy assessment results to shrub cover fractions*

We incorporated information about errors in fractional cover estimated from the contingency tables to adjust shrub cover proportions derived from the image classification products for each study site and year. Details on the resultant classification accuracies are discussed below and summarised in Tables 2 and 3. We computed the adjustments to class areal amounts by subtracting the commission error (percentage of overestimate) from the omission error (percentage of underestimate) for the shrub class, then multiplying the areal amount by a positive result or dividing by a negative result to obtain more reliable shrub cover proportions (Stow et al. 2013).

Table 2. Accuracy assessment results – 2002 growth form map. Diagonal elements (in bold) depict agreement.

		SA 2002 Reference					
		Soil/ Rock	Herb/ Subshrub	Shrubs	Totals	User's accuracy (%)	Commission error (%)
Classification	**Soil/Rock**	**56**	1	0	57	98	2
	Herb/SS	6	**51**	1	58	88	12
	Shrubs	0	6	**73**	79	92	08
	Totals	62	58	74	**180**		
	Producer's accuracy (%)	90	88	99	Total points:	194	
	Omission error (%)	10	12	01	Total accuracy:	93	
		NSA 2002 Reference					
		Soil/ Rock	Herb/ Subshrub	Shrub	Totals	User's accuracy (%)	Commission error (%)
Classification	**Soil/Rock**	**64**	1	0	65	99	02
	Herb/SS	9	**58**	8	75	77	23
	Shrubs	0	4	**81**	85	95	05
	Totals	73	63	89	**203**		
	Producer's accuracy (%)	88	92	91	Total points:	225	
	Omission error (%)	12	08	09	Total accuracy:	90	

Table 3. Accuracy assessment results – 2009 growth form map. Diagonal elements (in bold) depict agreement.

		SA 2009 Reference					
		Soil/ Rock	Herb/ Subshrub	Shrubs	Totals	User's accuracy (%)	Commission error (%)
Classification	**Soil/Rock**	**48**	7	0	55	87	13
	Herb/SS	1	**46**	7	54	85	15
	Shrubs	0	3	**100**	103	97	03
	Totals	49	56	107	**194**		
	Producer's accuracy (%)	98	82	94	Total points:	212	
	Omission error (%)	02	18	07	Total accuracy (%):	92	
		NSA 2009 Reference					
		Soil/ Rock	Herb/ Subshrub	Shrubs	Totals	User's accuracy (%)	Commission error (%)
Classification	**Soil/Rock**	**53**	4	0	57	93	07
	Herb/SS	1	**58**	9	68	85	15
	Shrubs	0	2	**116**	118	98	02
	Totals	54	64	125	**227**		
	Producer's accuracy (%)	98	91	93	Total points:	243	
	Omission error (%)	02	09	07	Total accuracy (%)	93	

3.4. *Terrain analysis*

We created a presence/absence (true shrub/not true shrub) raster layer for each study site from the 2002 and 2009 analysis to individual layers. The shrub presence layer was intersected with the stratified slope and aspect layers to estimate the amount of shrub regrowth on each of the terrain units. We stratified elevation data into nine equal interval classes. We grouped the DEM data for each site into three slope, four aspect, and nine elevation classes or strata. Slope classes are: less than 30% (0.0°–16.7°), 30–100% (16.7°–45.0°), and over 100% (>45.0°) slope incline. Aspect orientations followed Blodgett et al. (2010), based on the expected influence of solar heating on fire behaviour (Medler and Yool 1997), and were grouped into the comparatively more mesic north-facing slopes, drier east- and west-facing slopes, still drier south-facing slopes, and flat area.

4. Results

4.1. *Accuracy of plant growth form maps*

Results of the growth form map accuracy assessment address the first research question. High agreement between the growth form maps and the reference points revealed that the machine-learning classifier was effective for use on high-spatial resolution imagery when classifying growth form types for post-fire chaparral.

The overall accuracy of the pre-fire (2002) growth form cover map for the SA study site is 93%. The highest agreement is in the shrub class with 99% producer's and 92% user's accuracies. The overall accuracy for the NSA study site pre-fire growth form map is

90% agreement with the reference information. The shrub class has 95% user's and 91% producer's accuracies (Table 2).

The overall accuracy of the 2009 post-fire SA growth form map is 92% agreement with the reference information. The shrub class exhibits the highest overall accuracy with user's accuracy of 97% and producer's accuracy of 94%. The overall accuracy of the 2009 post-fire NSA growth form map is 93%. The shrub class has 98% user's and 93% producer's accuracies (Table 3). We emphasize post-fire changes in the shrub proportions of each study site, so the very high shrub classification accuracies suggest that shrub change estimates are also highly accurate.

4.2. *Adjustment of growth form cover proportions*

Adjusted shrub cover proportion estimates and information about their derivation are provided in Table 4. Given the absence of ground-based reference data for the SAB study site, we averaged fractional errors from SA and NSA sites and used them to adjust areal cover estimates for the SAB study site. The adjustment for 2002 was a decrease of 1% in shrub cover, which did not change the 85% cover amount. The adjustment for 2009 increased the shrub area from 69% to 71%. The application of these new proportions changed a 16% decrease of shrub cover to a 14% decrease in shrub cover from pre-fire amounts.

4.3. *Growth form cover proportions*

4.3.1. *Pre-fire class proportions*

Based on the adjusted image classification results of imagery captured prior to the Cedar Fire, shrub cover in the study sites ranged from 76% to 85%. The SAB site had the highest proportion of shrubs. The NSA and SA sites had a similar, lower proportion (approximately 76–78%) of shrub cover as depicted in Figures 3–5.

4.3.2. *Post-fire class proportions*

According to the image classification results for imagery captured six years after the Cedar Fire, shrub cover was substantially less than prior to the Cedar Fire. In 2009, only about half of the SA study site is classified as shrub cover, while roughly two-thirds of the NSA site is mapped as shrub cover. Approximately 71% of the SAB site in 2009 is

Table 4. Shrub cover adjustments based on accuracy assessment.

Shrub adjustments (%)			
SA 2002		**NSA 2002**	
Omission	+1.4	Omission	+8.9
Commission	−7.6	Commission	−4.7
Adjustment:	−6.2	Adjustment:	+4.3
SA 2009		**NSA 2009**	
Omission	+6.5	Omission	+7.2
Commission	−2.9	Commission	−1.7
Adjustment:	+3.6	Adjustment:	+5.5
Application to SAB shrub proportions:			
2002	−1.0		
2009	+4.5		

Table 5. Post-fire change in class proportions from 2002 to 2009.

	SA	SAB	NSA
Absolute change in class proportions (%)			
Soil/Rock	04	04	04
Herb/SS	17	11	10
Shrub	−21	−15	−13
Relative change in class proportions (%)			
Soil/Rock	65	154	89
Herb/SS	97	89	54
Shrub	−28	−17	−17

classified as shrubs, such that the SAB still had the highest amount of shrub coverage. This is to be expected as shrub regrowth can take up to two decades to fully re-establish pre-fire cover conditions. However, inter-site differences in shrub cover change from before and after the fire are substantial, as documented below. Non-shrub elements covered much more area than they did before the fire in all three study sites, particularly within the SA site (Figure 3).

4.3.3. *Class proportion changes*

According to the error adjusted, image-derived maps of growth forms for 2009, shrub cover was substantially lower and herb/subshrub cover higher on all sites six years following the Cedar fire. The areal extent of shrubs mapped in the SA study site was 21% lower than pre-fire amounts, but only 15% and 13% lower in the SAB the NSA sites respectively. Herb/subshrub cover post-fire is substantially greater in the SA area at 17% while the SAB and NSA study sites portray only 10–11% greater herb/subshrub cover (Table 5).

4.3.4. *Shrub proportions per aspect class*

Shrub cover changes over the six years are summarized by total study site and by aspect classes in Table 6. Expressed as absolute percentage change, the least change occurred in the NSA study site and greatest in the SA study site on all aspects. The NSA site exhibited the least cover change at 15% absolute difference, with the SAB site at 20%, and the SA site at 26% absolute change. On north-facing slopes, shrub cover was 4% and 3% lower than pre-fire amounts on the NSA and SAB sites, respectively. Shrub cover was much lower on north-facing slopes in the SA area at 10% below pre-fire amounts. South-facing slopes exhibited the least shrub regrowth on all sites. Relative changes in growth form cover are more dramatic. On the NSA site, post-fire shrub cover change ranges from a 6% to a 21% reduction. Similarly, the SAB site experienced maximum 27% relative reduction in shrub cover. The greatest change is seen in the SA site with up to 41% reduction in shrub cover.

4.3.5. *Shrub proportions per slope angle class*

Amount and change of pre- and post-fire shrub cover for each slope-angle class are presented in Table 7. Absolute change in shrub cover for the sites is similar on slopes of less than 45°. For the steepest slope-interval class of over 45°, the SA site experienced twice the absolute decrease in shrub cover of the SAB and NSA sites. In terms of relative

Table 6. Proportional amount and change in shrub cover by date and study site per slope aspect class.

2002 cover (%)	SA	SAB	NSA
N, NE, NW	79	89	85
S, SW	64	74	71
E, W, SE	71	79	75
2009 cover (%)			
N, NE, NW	69	86	81
S, SW	38	54	56
E, W, SE	51	68	63
Absolute change	(%)		
N, NE, NW	−10	−04	−05
S, SW	−26	−20	−15
E, W, SE	−20	−11	−12
Relative change (%)	(%)		
N, NE, NW	−13	−04	−06
S, SW	−41	−27	−21
E, W, SE	−29	−14	−16

Table 7. Amount and change in pre- and post-fire shrub cover by study site per slope angle (in degrees) class.

Shrub (%)	SA	SAB	NSA
2002			
0.0–16.7°	71	77	72
16.7–45.0°	74	82	77
>45.0°	72	84	79
2009			
0.0–16.7°	60	69	61
16.7–45.0°	58	69	66
>45.0°	51	76	69
Absolute change (%)			
0.0–16.7°	−11	−08	−11
16.7–45.0°	−15	−12	−11
>45.0°	−21	−08	−01
Relative change (%)			
0.0–16.7°	−16	−11	−15
16.7–45.0°	−21	−15	−15
>45.0°	−29	−01	−12

change, the SA site exhibited a reduction of 29% shrub cover while the other two sites decreased 10–12% shrub cover.

5. Discussion and conclusions

The Cedar Fire burned and spread rapidly at first under dry, high wind Santa Ana conditions and then a few days later turned and burned more slowly in the opposite direction for almost a week. This resulted in an area within the final fire perimeter where the fire had burned under different conditions and seemingly, different fire conditions and behaviours, within similar chaparral types and topographic characteristics. Though this may be a unique opportunity to conduct a landscape-level study of fire spread effects on chaparral shrub recovery, both the remote sensing and fire ecology results are interesting. The site that burned under the Santa Ana conditions had 17% absolute and 11% relative change in lower shrub cover (essentially more limited recovery). We cannot definitively state that the lower amount of shrub recovery in the Santa Ana site is due to the fire conditions and behaviour, since site differences in post-fire moisture variability can also influence recovery. However, the topographic characteristics (and likely soil moisture) of that site is very similar to one of the other two sites that had much greater recovery, which had similar shrub change/recovery than the third site that is slightly more mesic and had more dissimilar topographic characteristics.

The spatial contextual, machine learning classifier applied to the high spatial resolution orthoimagery was successful at differentiating between and mapping shrubs, non-shrub vegetation, and bare ground growth form classes. This automated feature extraction approach used both spatial and spectral-radiometric information and iterative classification process to classify the growth form types. While the software is commercial, proprietary, and 'black box' in nature, we found that various custom options such as adjusting kernel sizes, contextual search patterns, and minimum patch size enabled refinements to optimize the classification accuracy. The disadvantage is that the parameter settings are somewhat *ad hoc*, not particularly transferable, and challenging to replicate. However, the high accuracy of the growth form cover maps, particularly for the shrub class, provided high confidence in the pre- and post-fire shrub cover amounts and proportions.

Changes represented in growth form maps indicate that there were substantial differences in the amount and distribution of shrub changes, mostly associated with post-fire recovery, between the three study sites. In all sites, post-fire shrub cover is less than pre-fire amounts, as would be expected after around six years of regrowth. A slightly higher proportion of exposed rock and soil and much greater coverage of subshrubs and herbaceous vegetation are evident for 2009 for all three study sites. The SA site experienced substantially less shrub regrowth and had more subshrub/herb cover six years post-fire and had two to three times lower amounts of shrub cover than either than SAB or NSA site.

Shrub recovery extent was highest on all north-facing slope aspects, less extensive on east- and west-facing aspects, and much less on south/southwest aspects. These shrub recovery patterns are consistent with observations of Keeley (1986, 2000) who noted that obligate re-sprouting shrub species such as scrub oak and Eastwood's manzanita occur most commonly on mesic, poleward-facing slopes and that obligate seeding shrub species such as the woollyleaf ceanothus and hoaryleaf ceanothus tend to occur most commonly on more xeric equatorward-facing slopes. Chamise, a facultative re-sprouting shrub that also produces post-fire seedlings, also occurs most commonly on xeric equatorward-facing slopes in the study area and elsewhere (Keeley 2000). The NSA site has the greatest proportion of south-facing slopes, and experienced the highest recovery of the three sites on those slopes. Slope-aspect proportions on the SA and SAB sites are similar; however, shrub cover was lower for all aspect classes within the SA site. The relative change (percentage in 2009 relative to 2002) in shrub cover for the SA site was twice the decrease as for the SAB or NSA study sites on all aspects.

Shrub recovery in the study area and period exhibits an apparent association with slope gradient, and to a lesser extent precipitation. Moisture availability is strongly controlled by terrain characteristics. The SA site has 10–20% more slopes over 45° than the other two sites. About one-third (1 km^2) of the highest slope gradients were on south-facing aspects. These slopes had the lowest extent of shrub regrowth. Coupled with the SA site receiving the lowest precipitation, this may help explain slower shrub recovery on these steeper slopes, whether from terrain effects on fire behaviour and/or on post-fire soil moisture availability.

The association of shrub recovery with elevation differences is also apparent. Shrub cover was shown to be positively related to elevation by Keeley and Keeley (1981) which is clearly associated with precipitation increase. Much of the NSA site is located in a higher, more-inland location that receives greater amounts of orographically induced precipitation.

Differences in shrub recovery also may have been influenced by factors associated with fire behaviour such as fire spread rate, burn intensity and fire severity (Lentile et al. 2007). The duration of fire spread across the SA study site is estimated to be 5 hours (0.5 m s^{-1}), 18 hours for the SAB site (0.1 m s^{-1}), and 34 hours for the NSA site (0.1 m s^{-1}). Weise and Biging (1996) found that higher wind velocities, such as those associated with a Santa Ana wind condition, pushed flames upslope (mostly on N-/NE-facing slopes on the SA site) and were strong enough to overcome flame buoyancy downslope (mostly on S-/SW-facing slopes on the SA site), pushing the fire forward at a greater rate of speed. In the same study, a backing fire, such as in the SAB site, had little relationship between slope and wind velocity. Additionally, a fire with a light tailwind, such as on the NSA site, also seemed to be unaffected by slope and wind velocity interactions. Mermoz and Kitzberger (2005) and Keeley, Brennan, and Pfaff (2008) found that fire severity was not correlated with elevation, slope incline, aspect, or estimated annual solar insolation in shrublands.

Differences in fire spread rate and intensity inferred above along with the BAER burn severity maps of remnant vegetation suggest that fire behaviour may be partly responsible for differences in post-fire shrub extent between the sites. Faster fire-spread rates and lower severity burn may be associated with lower extent of post-fire shrub regrowth Keeley, Brennan, and Pfaff 2008). Keeley, Fotheringham, and Baer-Keeley (2005a) found that sub-shrub and perennial herbaceous cover is inhibited by high-severity fires in chaparral and sage scrub environments. Some chaparral seeds require scarification by heat and smoke in order to germinate. If a fire has too short a burn time, scarification will not occur (Keeley and Zedler 1978). An abundance of low-severity burned areas and unburned remnant patches in the SA study site were evident after the Cedar Fire. This site had the lowest amount of shrub recovery. The shorter burn residence time of the SA study site may have not been enough to scarify many of the seeds that rely on that process. Fire spread rates and burn severity within the SAB site were intermediate, as was the shrub regrowth proportions, relative to the SA and NSA study sites. Native species would have been better able to become re-established at that site with few invasive plants to cover the soil immediately post-fire. The longer burn time of the NSA site may have facilitated scarification. The NSA site had a much slower fire spread rate, the highest extent of moderate burn severity, and the highest extent of shrub regrowth.

Factors such as fire behaviour, moisture availability, historical land use, invasive species and previous fires likely interacted to influence shrub regrowth patterns at the three sites. Regrowth patterns may also have been aided or impeded by various physical characteristics inherent in each study site. In this study, it also appears that fire behaviour was an important factor for the patterns of shrub regrowth, the reproduction of chaparral species, and potential for herbs or subshrubs to grow or expand in more vulnerable areas. After examining shrub regrowth extent over all areas, we found that the SA site had significantly less shrub regrowth over all slope-aspects.

Atmospheric scientists have largely understood for decades the general patterns and dynamics of Santa Ana winds at the synoptic scale. However, more recent research has focused on the complex linkage between Santa Ana wind behaviour and terrain, and how they influence wildfire behaviour in southern California (Moritz et al. 2010). Further, Jin et al. (2014) identify the influence of atmospheric controls such as relative humidity and antecedent precipitation on wildfire behaviour in southern California during periods with and without Santa Ana winds. The results reported here highlight the possible influence of variable atmospheric conditions such as wind speed, direction, and humidity coupled with terrain differences on wildfire behaviour and the possible influences it may exert on post-fire recovery patterns of chaparral at the landscape scale.

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