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Quantifying the influence of previously burned areas on suppression effectiveness and avoided exposure: a case study of the Las Conchas Fire

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Abstract. We present a case study of the Las Conchas Fire (2011) to explore the role of previously burned areas (wildfires and prescribed fires) on suppression effectiveness and avoided exposure. Methodological innovations include characterisation of the joint dynamics of fire growth and suppression activities, development of a fire line effectiveness framework, and quantification of relative fire line efficiencies inside and outside of previously burned areas. We provide descriptive statistics of several fire line effectiveness metrics. Additionally, we leverage burn probability modelling to examine how burned areas could have affected fire spread potential and subsequent exposure of highly valued resources and assets to fire. Results indicate that previous large fires exhibited significant and variable impacts on suppression effectiveness and fire spread potential. Most notably the Cerro Grande Fire (2000) likely exerted a significant and positive influence on containment, and in the absence of that fire the community of Los Alamos and the Los Alamos National Laboratory could have been exposed to higher potential for loss. Although our scope of inference is limited results are consistent with other research, suggesting that fires can exert negative feedbacks that can reduce resistance to control and enhance the effectiveness of suppression activities on future fires.

Additional keywords: burn probability modelling, fire-on-fire interactions, landscape conditions, wildland fire management.

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Introduction

The evolution of wildfire incidents through time follows an uncertain trajectory influenced by natural variability and limited control of suppression operations (Thompson 2013). Though contemporary fire modelling systems can effectively capture fire weather variability and provide probability based information to support decision making (Calkin et al. 2011a; Finney et al. 2011), less is known regarding the degree of control that suppression operations exert over wildfire dynamics (Finney et al. 2009; Holmes and Calkin 2013). Partial controllability can manifest in a variety of ways in the incident management environment, for example fire line production rates may be lower than expected, incomplete or inadequate fire lines and/or fuel breaks may burn over, and aerially delivered retardant drops may be misplaced. In practice these elements can lead to limited suppression effectiveness, and on rare occasions, intentionally ignited prescribed fires may escape control efforts.

A broader element of partial controllability relates to the succession of landscape conditions as influenced by past land and fire management decisions. In a well-known feedback loop, referred to as the 'wildfire paradox', the long-term effect of suppression efforts that limit fire growth through aggressive fire exclusion can over time promote excessive fuel accumulation and lead to conditions whereby wildfires that escape initial containment efforts burn with higher intensities and are more difficult to control (Arno and Brown 1991; Calkin et al. 2014; Collins et al. 2013). Conversely, areas that have in the recent past experienced wildland fire (i.e. wildfire and prescribed fire) can exhibit reduced severity or reduced size (Cumming 2001; Collins et al. 2009; Wimberly et al. 2009; Arkle et al. 2012; Cochrane et al. 2012; Teske et al. 2012; Haire et al. 2013; Hoff et al. 2014; Parks et al. 2014; Parks et al. 2015). Proactive reduction of hazardous fuel loads can similarly influence localised and landscape scale fire behaviour, particularly in areas treated with prescribed fire (Finney et al. 2007; Moghaddas *et al.* 2010; Syphard *et al.* 2011*a*; Stephens *et al.* 2012). These fire-on-fire and fire treatment interactions are complex and variable, influenced by burning conditions, incident response, location, extent, initial severity, site productivity and age of the previous disturbances (Collins *et al.* 2010; Holden *et al.* 2010).

Wildland fire and planned fuels treatments may also influence the effectiveness of suppression activities. In some instances suppression effectiveness was enhanced because of the presence of fuel treatments, while in others fuel treatments were only effective because of the presence of suppression resources (Moghaddas and Craggs 2007; Syphard *et al.* 2011*b*). The empirical evidence to comprehensively evaluate these influences is limited (Hudak *et al.* 2011). Therefore key questions remain about how previously treated areas can alter fire intensity and fire spread, and how these changes in fire behaviour could change the opportunities and effectiveness of incident strategies and tactics. Such information is critical for developing risk informed and cost-effective incident management strategies, as well as for designing pre-fire landscape management strategies.

In this paper, we present a multipart case study intended to yield insights into the role of areas previously burned by wildland fire on suppression effectiveness and avoided loss. We leverage recent fire modelling techniques (Cochrane *et al.*) 2012) with a new approach to characterising daily fire and suppression dynamics using a variety of data sources. Our case study focuses on the 2011 Las Conchas Fire, which burned over 63 000 ha on federal, state, county, tribal and private lands, and which threatened the Los Alamos National Laboratory (LANL) and the city of Los Alamos, New Mexico, USA. The Las Conchas Fire burned through multiple large fire scars that varied in age, size and severity, most notably the Cerro Grande Fire, an escaped prescribed fire that similarly threatened Los Alamos in 2000. Though the Cerro Grande Fire was itself a high loss event (235 structures destroyed), results herein corroborate first-hand accounts that during the later Las Conchas Fire, the footprint of the Cerro Grande Fire reduced extreme fire behaviour and enhanced suppression effectiveness, likely preventing significant additional losses associated with the Las Conchas Fire (Reese 2011).

Methods

Case study overview: the Las Conchas Fire

The Las Conchas Fire ignited when a tree fell onto a power line, and was discovered on the afternoon of 26 June 2011. The fire burned through the Jemez Mountains in New Mexico, in the south-western United States (US). The fire burned in a variety of fuel types, primarily mixed conifer in the higher elevations, ponderosa pine in the middle elevations, and pinyon pine, oak brush, and grass fuels in lower elevations. Fire behaviour in the mixed conifer stands exhibited the highest rates of spread and contributed to the majority of spot fires, with spotting distances of up to 3 km. The alignment of terrain, dry fuels and gusty winds contributed to rapid spread, with the fire burning over 23 000 ha on the first day of initial attack, including a run to the east and south-east that destroyed many homes on the Cochiti Mesa and in the Cochiti Canyon.

The Las Conchas Fire burned through multiple large fire scars and other previously treated areas (Fig. 1). The South Fork

Fire (2010) and Oso Fire (1998) reportedly provided fire crews with opportunities to conduct burnout (i.e. intentionally setting a fire inside a control line to consume fuel ahead of the fire edge) and holding operations along the northern and north-eastern flanks of the Las Conchas Fire. Interestingly, in the previous year the northward movement of the South Fork Fire was slowed by areas recently treated with prescribed fire. The Cerro Grande Fire (2000) reportedly slowed the spread of the Las Conchas Fire (specifically noted on the Incident Status Summary (ICS-209) form dated 07 July) and facilitated ground and aerial suppression operations. Areas of the San Miguel Fire (2009), which was a lightning caused fire that was managed for resource benefits, either did not re-burn or did so at low severity, according to Monitoring Trends in Burn Severity (MTBS) data (www.mtbs. gov). By contrast areas of the Dome Fire (1996) that were re-burned by the Las Conchas Fire consisted of heavy fuel loading of dead and down logs, oak brush, and locust, with high rates of spread.

Fire line construction and suppression effectiveness

For analysis of suppression resource use and fire line construction we relied largely on information provided by incident management personnel, and spatial data and incident information collected on-site at the incident command post over 28 June-13 July 2011. The temporal scope of our entire analysis extends from the ignition date (26 June) through 21 July 2011, after which no additional fire growth was reported. Additional data sources included archived ICS-209 forms, incident action plans (IAPs), and online access to the Wildland Fire Decision Support System (https://fam.nwcg.gov/fam-web/; http://wfdss. usgs.gov/wfdss/WFDSS_Home.shtml, accessed 21 September 2015). We analysed spatial layers produced and uploaded to the National Interagency Fire Centre's (NIFC) file transfer protocol site by incident geographic information system (GIS) specialists. Active fire perimeters were mapped from night time National Infrared Operations (NIROPS) thermal imagery; flights began on 27 June 2011 and continued on a daily basis through 21 July 2011. Some perimeters were also updated during the daytime operational period based on intelligence brought in to the Operations unit from field personnel. In cases where multiple perimeters were uploaded to the NIFC site, we always used the daily perimeter with the latest time stamp. Time-series maps of fire line construction were created with global positioning system tracks brought to the GIS specialist from incident personnel, as well as by digitising fire line from information acquired from incident Operations staff. We recorded all entries delineated as 'completed' fire line in the Fire Incident Mapping Tool (FIMT), and removed duplicate entries but otherwise made no changes to line location or reported completion date. We made no changes to fire perimeter spatial data.

Using Division Group Assignment List (ICS-204) forms embedded in IAPs, we summarised daily assignments for all suppression resources on each division. Divisions are part of the incident command organisational hierarchy, above individual resource packages such as hand crews, and below the branch level having responsibility for a geographic area of incident operations. The number of divisions varied over the course



Fig. 1. Las Conchas Fire perimeter and locations of areas previously treated by wildfire or prescribed fire since 1996.

of the incident and reached over 20, although the staffing levels for divisions also varied with date and assignment. In total we analysed 677 unique resource assignment records that spanned the time period 28 June–21 July 2011. We categorised daily suppression assignments as relating primarily to fire line construction or to other activities. The former category includes construction of direct, indirect, and contingency fire lines, while the latter category includes holding or mopping up previously constructed fire lines, point protection, staging, and rehabilitation. We assigned each record to a single category on the basis of what we perceived to be the principal activity, recognising that division-level assignments can span a range of activities. In addition to assignment categorisation we identified all instances where the ICS-204 forms made mention of the terms 'burnout,' 'burn ops,' or 'firing' to determine the extent to which resource assignments related to burnout operations. This is admittedly a coarse filter that does not quantify actual burnout operations, but is a proxy as comprehensive spatial data on burnout operations was unavailable.

As a descriptive statistic of daily suppression activities, we calculated the productive potential (*PP*) of all assigned suppression resources. *PP* values are calculated using published fire line production rates (Broyles 2011; Holmes and Calkin 2013) for each type of ground resource (hand crews, bulldozers, etc.,

Metric	Condition	Possible interpretations			
$\overline{T_r}$	$T_r > 1$	Suppression strategy full perimeter control			
Total to perimeter ratio		 Significant amount of fire line that burned over 			
		• Significant amount of indirect or contingency line that never engaged fire			
	$T_r < 1$	• Suppression strategy not full perimeter control			
Er	$E_r \approx 1$	 All indirect or contingency line ultimately engaged fire 			
Engaged to total ratio		 Significant effort devoted to construction of direct fire line 			
	$E_r < 1$	 Significant effort devoted to construction of indirect or contingency line 			
$HE_{r_{s}}HT_{r}$	$Hx_r \approx 1$	• Engaged fire line effective in all locations			
Held to engaged/total ratios	$Hx_r < 1$	• Engaged fire line not effective in all locations			
REI	REI > 1	• Proportion of held line greater than proportion of engaged line			
Relative efficiency index		• Higher efficiency within analysis area relative to all engaged fire line on the entire incident			
	REI < 1	• Proportion of held line less than proportion of engaged line			
		• Lower efficiency within analysis area relative to all engaged fire line on the entire incident			

Table 1.	Summary of primary metrics developed to calculate fire line effectiveness
	Note that Hx_r indicates an identical interpretation for HE_r and HT_r

exclusive of water tenders), using the Broyles (2011) finding that resources are effectively building line for roughly 1/3 of their assigned shift length. Shift lengths ranged from 12–15 h; most (65%) were 15 h. *PP* values do not reflect actual line construction on the incident, but rather allow for an equivalent comparison between days with varying amounts and types of suppression resources assigned to line construction and non-line construction activities.

To summarise actual fire line construction and suppression effectiveness we introduce an analytical framework with four primary ratio metrics. First, let P be the length of the final fire perimeter, T the total amount of fire line completed, E the total amount of fire line that engaged the fire, and H the total amount of fire line that held (i.e. did not burn over) when engaged by the fire. Here we use the phrase 'burn over' exclusively in the context of fire line, not firefighters or firefighting equipment, and to describe an event in which the fire spreads over or across a control line. We considered any fire line segment as engaged if located along or within the final fire perimeter, and as held if located along the final fire perimeter. Next, using the subscript r to denote ratios, define $T_r = T/P$, $E_r = E/T$, $HE_r = H/E$, and $HT_r = H/T$ as the ratios of total to perimeter, engaged to total, held to engaged, and held to total, respectively. Note that $H \le E \le T$, meaning that E_r , HE_r , and HT_r can't exceed 1.0 by definition.

We further attributed fire line segments according to reported construction dates, dates engaged and burned over (where applicable), the type of construction, and whether they were constructed within areas previously burned by wildland fire. In some cases fire line segments may not have been reported until days after construction, but we had no consistent informational basis for changing reported dates. We calculated engaged and burned over dates by overlaying daily fire perimeters with fire line locations. The fire line data contained three types of fire line (completed, hand, and bulldozer), which for simplicity we grouped into two categories: non-mechanical (completed and hand) and mechanical (bulldozer). Per GIS Standard Operating Procedures (NWCG 2014), completed line refers to fire line constructed without mechanical means that can serve as a control line, which is a broader term that can also include natural barriers such as rock outcroppings and the outlines of previously burned areas. We partitioned the location of fire line into nine non-overlapping areas: fire line built outside of previously burned areas and fire line built within the Dome Fire (1996), the Lummis Fire (1997), the Oso Fire (1998), the Unit 29 Fire (1998), the Unit 38 prescribed fire (1999), the Cerro Grande Fire (2000), the San Miguel Fire (2009), and the South Fork Fire (2010). If past treatments overlapped, we attributed the fire line segment with the most recent treatment. We used the ESRI ArcGIS platform to attribute fire line segments and to calculate T, E, and H values.

Lastly, as a more comprehensive metric of effectiveness we quantified relative efficiency indices (*REIs*) for fire line. We calculated *REI* values for unique analysis areas differentiated according to whether the line was built within the aforementioned previously burned areas. Let E_A and E_T be the lengths of engaged line within the analysis area and the total length of engaged line, respectively. Next let H_A and H_T be the lengths of held line within the analysis area and the total length of held line, respectively. Then, the *REI* within the analysis area (*REI_A*) can be calculated as shown in Eqn 1. By definition, *REI* = 1.0 for the entire fire, as the analysis area encompasses the total length of engaged and held line. The size of an analysis area will therefore vary with each fire.

$$REI_A = \frac{H_A/H_T}{E_A/E_T} \tag{1}$$

Table 1 briefly summarises the four metrics we use and how they may be interpreted. In addition to the influence of fire weather and burning conditions, E_r , HE_r , and HT_r values are reflective of choices regarding the type, amount, and location of completed fire line. Further, E_r , HE_r , and HT_r values may be influenced by choices regarding the timing, extent, and location of intentional burnout operations that could result in previously completed line ending up within the final fire perimeter.

Burn probability and comparative exposure

We modelled the influences of previous wildfires and planned management activities on the progression of the Las Conchas Fire using the fire growth simulation program FARSITE (Finney 2004). In addition to a digital elevation model FARSITE requires surface and canopy fuels maps (e.g. fire behaviour fuel model, canopy cover, stand height, canopy base height, and canopy bulk density) to model fire spread across the landscape. These spatial layers were obtained from the LANDFIRE project, a national level program providing up-to-date geospatial data products to support wildland fire management (Rollins 2009; Ryan and Opperman 2013; Nelson et al. 2013). We used the 2010 version of LANDFIRE data products (LF2010). FARSITE also requires weather (e.g. temperature and relative humidity) and wind speed observations, which we obtained from the Jemez Remote Automated Weather Station (RAWS) located \sim 9 km from the Las Conchas origin. All FARSITE simulations were run at 30 m and hourly resolution between 1300 on 26 June and 1900 on 05 July. These dates capture the majority of days where fire weather conditions were conducive to fire growth.

In accordance with Cochrane *et al.* (2012), we divided the modelling framework into two sets of simulations designed to isolate the effects of different fuel types and patterns on fire outcomes. In the first set of simulations we selected the surface and canopy fuels that best represented the actual landscape, shaped by the culmination of all historical disturbances up to and immediately preceding the Las Conchas Fire. Although we calibrated FARSITE (e.g. Stratton 2006, 2009) to approximate the observed evolution of the Las Conchas Fire, none of the spatial features representing the constructed fire lines were used to impede the simulated fire growth. Hence the simulations were qualitatively realistic, but did not perfectly match the true fire perimeter.

In the second set of simulations we altered the surface and canopy fuels in the LF2010 spatial layers to create a 'counterfactual' landscape unaffected by recent disturbances (documented in the LANDFIRE and MTBS archives) since 1996. We removed fire scars and fuels treatments from the LF2010 spatial layers by matching grid cells within and outside disturbed areas based on similar environmental site potential, biophysical settings, topography, and if possible the pre-disturbance fuels characteristics retrieved from the 2008 version of the LANDFIRE data. For both the actual and counterfactual landscapes, we simulated 10 instances of the Las Conchas Fire to account for stochasticity induced by the varying numbers, locations, and ignition probability of spot fires. Cochrane et al. (2012) found that 10-30 simulations adequately captured the variability in the simulated fire extents due to spotting while avoiding intractable computational times. Since each simulated fire extent is unique, aggregating the two sets of 10 raster outputs produces two burn probability maps indicating the likelihood that a ground cell would have burned in the absence of suppression activities: one for the actual or 'treated' landscape, and one for the counterfactual or 'untreated' landscape. Finally, we took the difference of the two burn probability maps (i.e. counterfactual minus actual) to calculate the change in likelihood that a ground call would have burned in the absence of previous fire scars and suppression activities.

Comparison of the actual and counterfactual burn probability maps highlights altered fire spread pathways induced by recent disturbances and sets the stage for comparative exposure

analysis, which examines the variable likelihood that fire susceptible highly valued resources and assets (HVRAs) will interact with a wildfire under different landscape conditions or alternative fire management scenarios (Scott et al. 2012; Ager et al. 2013). Comparative exposure levels are calculated by overlaying HVRA maps with the burn probability difference layer, multiplying HVRA area and burn probability difference within each 30 m pixel, and summing these values across all pixels housing each HVRA. Here we focus on exploring the exposure of the community of Los Alamos and the Los Alamos National Laboratory (LANL), the protection of which had been a major concern throughout the incident. To map the community of Los Alamos we used the number of building clusters from county cadastral data (Calkin et al. 2011b) as well as a population density layer (Haas et al. 2013). To map the LANL we used a 1 km buffer around the centroid of the Laboratory's Main Campus, clipped to include only LANL land ownership.

Results

Fire line construction and suppression effectiveness

Fig. 2 summarises daily and cumulative *PP* values for all assigned suppression resources. To reiterate, these *PP* values are not actual amounts of line construction, but rather indicate the combined 'strength' of all the various suppression resources assigned to the fire on any given day. The stacked vertical bars indicate daily *PP* values for line construction and other activities, while the graphed lines represent the accumulated fraction of total *PP* over the time period. Daily fire size is also presented in a black line, scaled to its final fire size.

Although the total proportion of PP allocated to line construction (55.04%) was fairly even with PP for other activities (44.96%), there is a discernible difference in the timing of these suppression activities. The horizontal distance between the blue line (line construction) and the red line (other activities) indicates that line construction efforts are concentrated earlier in the evolution of the incident, as expected. Indirect line construction assignments accounted for 82.98% of all line construction activities, followed by direct line (13.29%), and contingency line (3.73%). As for non-line construction activities, mop-up and holding assignments accounted for 74.41% of all other activities, followed by point protection (13.46%), rehabilitation (8.39%) and staging (3.74%). All assignments related to fire line (i.e. construction and mop-up/holding assignments) accounted for 88.50% of total PP. Burnout operations were mentioned in 263 of the 677 resource assignment records, the collective PP of which comprised 46.49% of overall cumulative PP and 84.47% of cumulative PP specific to line construction assignments.

Fig. 2 also indicates a significant time lag between fire growth and the mobilisation of suppression resources to construct fire line. The Las Conchas Fire grew to 37.70% of its final fire size before assignment of any suppression resources (exclusive of initial attack efforts). By 01 July, the Las Conchas Fire had already reached 68.85% of its final size, yet line construction activities had only reached 22.93% of their total *PP*, and other activities had only reached 4.72% of their total *PP*. Three days later, the Las Conchas Fire had grown to 78.83% of its final size, with line construction and other activities at 51.45% and 17.92% of their total *PP* values, respectively. Line construction



Fig. 2. Daily and cumulative production potential (*PP*) of suppression resources assigned to line construction and other activities. The stacked vertical bars indicate daily *PP* values for line construction and other activities, while the graphed lines represent the accumulated fraction of total *PP* over the time period. As a point of comparison daily fire size is illustrated in a black line. Cumulative *PP* values and cumulative fire size are all scaled according to the fraction of total, left *y*-axis.

activities begin to taper off significantly after 08 July, at which point the Las Conchas Fire had reached 89.57% of its final size.

Fig. 3 presents the temporal progression of actual completed fire line on the Las Conchas Fire, broken down according to accumulated total, engaged, and held amounts. Suppression resources produced 481 779 m of fire line, 393 187 m (81.61%) of which engaged the Las Conchas Fire, and 287 595 m (59.69%) of which successfully held. The total amount of completed line was 67.06% of the cumulative PP of line construction assignments. Whether this percentage accurately reflects the realised production capacity or indicates that the default rates are overestimated is ambiguous. Our singular assignment categorisation scheme could be missing division of suppression effort across multiple assignments that were not directly related to line construction. However, our assumption that all 'completed' fire line was actually constructed fire line is almost certainly an overestimate, recognising that line could have been delineated to match natural fire barriers, roads, or areas where fire growth potential was assumed to be minimal.

Results in Fig. 3 exhibit the same temporal lag between fire growth and line construction shown in Fig. 2. Also consistent with Fig. 2, the slope of the line construction curves in Fig. 3 are steep early on and then taper off as suppression efforts transition into mop-up/hold and rehabilitation activities. Beginning 07 July

the total and engaged curves begin to separate, with the magnitude of the difference increasing from that point forward. The amount of held line follows a similar pattern to that of engaged line, although it does not monotonically increase due to periodic burn over events. In particular three pulses of burned over line on 06 July, 11 July, and 17 July collectively account for 82.47% of all line that burned over. The burn over event on 11 July corresponds to a known burnout operation from New Mexico State Highway 4 to a previously established fire line, intended to burn a relatively small unburned patch to reduce potential spotting of firebrands across the highway onto LANL property. This burnout operation is responsible for the apparent poor performance of completed line in the Unit 29 Fire and the Unit 38 prescribed fire. We revisit the other burn over events in the next section.

Fig. 4 displays daily perimeter growth as well as the location and type of all actual fire line completed. The total length of the Las Conchas Fire perimeter was 356 310 m, leaving ~68 715 m of uncontrolled fire edge, primarily along the north-western flank of the fire. The value of total completed line to final fire perimeter (T_r) was 1.352, which reflects the influence of line that burned over as well as line that never engaged. Incidentwide E_r , HE_r , and HT_r values were 0.816, 0.731, and 0.597, respectively.



Fig. 3. Cumulative amounts of total (*T*), engaged (*E*), and held (*H*) fire line; recall that $H \le E \le T$. As a point of comparison daily fire size is illustrated in a black line, but now in terms of total fire size (ha), right *y*-axis.

Table 2 summarises fire line effectiveness results according to line type and whether line was built within or outside of previously burned areas. Results indicate that mechanical line was less likely than non-mechanical line to engage the fire. Further, when mechanical line was engaged it was less likely to hold. Non-mechanical line accounted for 84.20% of total line construction, 94.91% of all engaged line, and 97.20% of all held line. Mechanical line had E_r and HE_r values of 0.264 and 0.606 respectively, whereas non-mechanical line had E_r and HE_r values of 0.922 and 0.750 respectively. Much of the mechanical line that never engaged the Las Conchas Fire was completed beyond the northern and eastern flanks of the fire (Fig. 4).

Fire line effectiveness differed within and outside of previously burned areas, and highlights the predominant role of the Cerro Grande Fire (Table 2). Competed line within the Cerro Grande Fire accounted for 44.64% of engaged line and 68.02% of held line within previously burned areas. E_r values within individual previously burned areas were higher than outside of burned areas for all but two previously burned areas (Cerro Grande, $E_r = 0.493$; South Fork, $E_r = 0.559$). HE_r values within individual previously burned areas were more variable, performing better (Lummis, $HE_r = 1.000$; Oso, $HE_r = 0.982$; Cerro Grande, $HE_r = 0.866$; South Fork, $HE_r = 0.963$), and worse relative to line completed outside of previously burned areas (Dome, $HE_r = 0.504$; Unit 29, $HE_r = 0.000$; Unit 38, $HE_r =$ 0.151; San Miguel, $HE_r = 0.004$). Fire line within these four previously burned areas collectively accounted for 82.08% of all line burned over within previously burned areas, but only 30.31% of the total amount of line that burned over. E_r and HE_r values aggregated across all previously burned areas were 0.648 and 0.616 respectively, reflecting the large amounts of line that didn't engage in the Cerro Grande Fire, and the large amounts of line that burned over in the Unit 38 prescribed fire and the San Miguel Fire. For non-mechanical line, E_r values within individual previously burned areas were higher than outside of burned areas for all but the Cerro Grande Fire where $E_r = 0.737$, with a similar pattern for HE_r values.

Fig. 5 present fire line *REI* values, separated according to whether they burned within previously burned areas. The stacked bars represent the amount of completed and engaged line that held and burned over. To reiterate, *REI* for the entire incident is 1.0 by definition. Completed line outside of previously treated areas performs slightly better than incident-wide statistics, due primarily to high rates of burn over in select treated areas, in particular Unit 38 and the San Miguel Fire. Within four treated areas, fire line had overall *REI* values of less than one. Completed fire line in the Lummis Fire (*REI* = 1.367), Oso Fire (*REI* = 1.343), Cerro Grande Fire (*REI* = 1.184), and the South Fork Fire (*REI* = 1.316) outperformed line built outside of previously burned areas, and accounted for 94.06% of all held line in previously burned areas. The total amount of burned over line in the areas with *REI* values below one is less



Fig. 4. Daily perimeter growth (left panel) and completed fire line (right panel) for the Las Conchas Fire. Fire line locations largely correspond to the final fire perimeter, with a few uncontrolled edges on the north-western flanks.

than the amount of held line within the Cerro Grande Fire alone, and the Cerro Grande Fire accounted for 69.05% of all held line in previously burned areas.

Data uncertainties and line effectiveness

Though we cannot definitively state how or why most of the major pulses of burned over line occurred, analysis of their location and reported completion date combined with daily IAPs, perimeters, and NIROPS imagery does suggest possible answers. The first pulse of burn over on 06 July corresponds to fire line located in the San Miguel Fire in the south-eastern flank (Fig. 4), where it is possible that some of the fire line designated as 'completed' was not actually constructed line, but instead delineated with the premise of using the San Miguel Fire perimeter as a natural barrier to fire spread. We are not able to confirm this because the Fire Incident Mapping Tool (FIMT) does not offer GIS specialists the option to differentiate between 'completed' and 'control' line. Analysis of IAPs indicates that fewer personnel were assigned along this flank of the fire, and

Table 2. Fire line effectiveness results, broken down according to line type, whether or not the line was built inside of previously burned areas, and amount of total fire line that engaged and held

Amounts of constructed fire line are reported in meters in the white rows, with corresponding dimensionless E_r and HE_r values reported in the grey row below each respective white row and highlighted in italics. Note that the table only reports T_r for the entire incident. Also note the table doesn't present HT_r values, which can be determined by multiplying E_r and HE_r values, and for which the relationship $HT_r \leq HE_r$ always holds

	Overall			Non-mechanical line			Mechanical line		
	Total	Engaged	Held	Total	Engaged	Held	Total	Engaged	Held
All									
	481 779	393 187	287 595	404 312	372 722	279 537	77 467	20 465	8 0 5 8
	1.352	0.816	0.731	_	0.922	0.750	_	0.264	0.394
Outside of previo	ously burned a	reas							
	325 317	291 771	225 170	296 963	280 125	219784	28354	11 645	5 386
	_	0.897	0.772	_	0.943	0.785	_	0.411	0.463
Within previous	y burned areas	8							
Dome	2534	2534	1276	2534	2534	1276	0	0	0
	_	1.000	0.504	_	1.000	0.504	_	_	-
Lummis	3245	3245	3245	3245	3245	3245	0	0	0
	_	1.000	1.000	_	1.000	1.000	_	_	-
Unit 29	735	735	0	735	735	0	0	0	0
	_	1.000	0.000	_	1.000	0.000	_	_	_
Oso	8829	8628	8473	8259	8259	8259	569	369	213
	_	0.977	0.982	_	1.000	1.000	_	0.648	0.579
Unit 38	16134	15 665	2373	15 665	15 665	2373	468	0	0
	_	0.971	0.151	_	1.000	0.151	_	0.000	_
Cerro Grande	100 970	49 784	43 104	56 086	41 334	40 646	44 884	8450	2458
	_	0.493	0.866	_	0.737	0.983	_	0.188	0.291
San Miguel	16781	16781	62	25 442	25 442	62	0	0	0
-	_	1.000	0.004	_	1.000	0.004	_	_	_
South Fork	7235	4043	3892	4043	4043	3892	3192	0	0
	_	0.559	0.963	_	1.000	0.963	_	0.000	_

were directed to 'look for opportunities to check spread' rather than construct direct or indirect fire line.

The burn over event on 17 July occurred along the northwestern flank of the Las Conchas Fire. However, we have reason to believe this was at least in part an artefact of issues with interpretation of NIROPS imagery used to generate fire perimeters rather than an actual burn over event. Information from the NIROPS imagery on 17 July states that the perimeter was updated to reflect an area 'previously thought unburned' rather than recent fire growth. IAP information confirms planned burnout operations in the area on 29 June and 30 June, and satellite imagery dated 30 June (a fortuitous coincidence) clearly indicates active burning in the area. Our interpretation is therefore that daily perimeters in late June based on a snapshot of observed infrared (IR) hotspots did not fully capture the extent of the burned area. What remains uncertain is whether or not line mapped as completed in this area corresponds to actual constructed line or to natural barrier to fire spread due to burnout operations.

To examine the sensitivity of results to these uncertainties, we recalculated E_r and HE_r values after excluding these two events. Although it would be technically possible to examine changes in fire line effectiveness metrics from removing burn over events from any specific day or set of days, here we focus on these two significant events for which we have strong reason to believe they were not in fact burn over events. Specifically we assume that line mapped as completed was not actually constructed, therefore there was no built line that could burn over. In both cases the effect is to reduce the amount of line that engaged, and to increase the amount of line that held. Within the San Miguel Fire, E_r and HE_r values both increased to 1.00, although only over a completed line length of 62 m along the final fire perimeter. Within all previously burned areas, the E_r value dropped from 0.648 to 0.606, while the HE_r value increased from 0.616 to 0.737. Outside of previously burned areas, the E_r value dropped from 0.897 to 0.882, while the HE_r value increased from 0.772 to 0.895.

Burn probability and comparative exposure

Fig. 6 maps differences in spatial burn probabilities from the treated (existing conditions) and untreated (counterfactual) landscape simulations. Panel A illustrates simulated burn probabilities on the existing conditions landscape calibrated to match observed fire growth, although suppression activities were not modelled and we did not constrain simulations to perfectly match the final Las Conchas Fire perimeter. Differences between the simulated and observed perimeter are particularly prominent along the central western flank of the fire, where some of the earliest completed line was mapped. Panel B illustrates simulated burn probabilities on the counterfactual landscape without previously burned areas, which have a noticeably larger footprint than panel A. Aggregating fire size results across simulated perimeters, the expected area burned on the treated landscape is 80 849 ha, and 103 879 ha on the untreated landscape. Simulation results therefore suggest the



Fig. 5. Relative Efficiency Index (*REI*) values for completed fire line within and outside of previously burned areas, along with the total amount of engaged fire line that held and burned over. Note the dashed line connecting unique *REI* values is not meant to denote a functional relationship but to facilitate visualisation.

Las Conchas Fire could have grown over 20 000 ha (28.49%) larger in the absence of previously burned areas. Panel C presents the difference in simulated burn probabilities. Per the legend, areas with positive burn probability differences (orange to red coloration) represent areas where the treatments likely prevented fire spread. With few exceptions (likely due to stochastic spotting), the Las Conchas Fire was likely to grow significantly larger on the counterfactual landscape devoid of recent disturbances. The greatest area of potential growth is along the north-eastern flank, extending through and well beyond the scars of the Oso Fire and the Cerro Grande Fire.

Table 3 summarises comparative exposure analysis results, with exposure levels partitioned into 10 probability zones; 5 for prevented spread and 5 for promoted spread. Overall expected exposure levels are calculated using the midpoint of each probability zone. Results indicate significantly higher exposure levels on the untreated landscape. That is, in the absence of the Cerro Grande and other fire scars, the community of Los Alamos and the LANL were more likely to interact with the Las Conchas Fire. Expected increases in exposure levels are 663 building clusters, 2637 individuals, and 92 acres of the LANL would be impacted by the Las Conchas Fire. Thus, the potential for loss is significantly higher on the hypothetical landscape where recent wildland fires and fuels treatments were excluded.

Discussion

We introduced a novel suppression evaluation framework with multiple elements: (1) characterisation of the temporal progression of suppression activities and resource assignments according to their productive potential; (2) spatiotemporal intersection of daily fire line construction and fire perimeter growth; and (3) quantification of fire line effectiveness using various metrics $(E_r, HE_r, \text{ and } REI)$ based on proportions of fire line that engaged the fire perimeter and did not burn over when engaged. We applied this framework on a case study of the Las Conchas Fire, and expanded the framework to explore the role of previously burned areas on suppression effectiveness. We further used burn probability modelling to provide a complementary analysis of how previously burned areas influenced likely fire spread and growth potential, based on methods introduced by Cochrane et al. (2012). We expanded the burn probability modelling approach to provide a new comparative exposure analysis, assessing potential exposure of the community of Los Alamos and the LANL to fire on a counterfactual landscape without the influences of recent wildland fire.

The two modelling approaches evaluating fire line effectiveness and comparative burn probabilities provide more information when interpreted in tandem rather than separately. Calculating E_r , HE_r , and *REI* values can help determine if changes in burn probability are likely due to the influence of previously burned areas or suppression actions. Some of the discernible differences between the observed and simulated progression of the Las Conchas Fire, particularly along the western flank of the fire (see Figs 4 and 6), were likely due to suppression activities that we did not model with FARSITE. If there was a well validated model of suppression effectiveness in FARSITE, and if we were able to input the exact timing



Fig. 6. Comparative burn probability and HVRA exposure results for the Las Conchas Fire. Panels A and B illustrate simulated burn probability results on the existing conditions and counterfactual landscape, respectively. Panel C provides the difference in burn probability, and Panel D overlays HVRA locations on top of the burn probability difference layer.

Table 3. Modelled changes in HVRA exposure levels, broken down according to probability zone and whether treatments likely promoted or prevented fire spread

Values presented are total exposure levels by probability zone, and the overall expected value is calculated as the sum of exposure levels multiplied by the midpoint of each respective probability zone. The next positive exposure levels indicate the previously burned areas prevented fire spread

General treatment effect	Probability zone	Communit	y of Los Alamos	Los Alamos National Laboratory	
		Building clusters	Number of individuals	Hectares	
Promoted spread	100-80 (-)	0	0	0	
_	80-60 (-)	0	0	0	
	60-40 (-)	0	0	0	
	40-20 (-)	-3	-2	-3	
	20-0 (-)	-178	-35	-60	
Prevented spread	0-20(+)	857	270	68	
	20-40 (+)	281	318	19	
	40-60 (+)	299	426	15	
	60-80 (+)	366	1327	24	
	80-100 (+)	84	334	9	
Overall expected value		633	2637	92	

and location of fire line construction and other suppression activities into FARSITE simulations, then perhaps there would be no need to calculate the fire line effectiveness metrics. This is because we would be able to directly assess the influence of previously burned areas and fire line construction all within the same simulation framework. However, as previously discussed, there is some degree of uncertainty over the actual versus reported construction date of fire line, and we have very limited information on the spatial extent of burnout operations or how they may have influenced fire spread. Further, the lack of reliable data that would be necessary to validate a model of fire line effectiveness is one reason for pursuing this very analysis. It is conceivable that our fire line effectiveness metrics could be used to quantify the permeability of fire lines input as barriers to fire spread within FARSITE simulations; this is left for future research.

Our case study revealed several insights into the dynamics of the Las Conchas Fire. First, the fire exhibited rapid growth under extreme weather conditions and the cumulative productive potential of line construction efforts did not reach peak potential until most of the area had already burned, from which point fire growth discernibly dampened under mostly milder conditions. This is reflective of the time required for mobilisation of large-scale suppression operations as well as the reality that management efforts often have limited scope of control over fire activity during extreme fire events.

Second, most line construction efforts built indirect line, much of which could have served as an anchor for burnout operations. Thus there may have been limited opportunities for fire line to be directly engaged by a flaming front. This suggests potentially greater utility of the fire line effectiveness framework on other fires with more direct fire line construction or less burnout operations.

Third, previously burned areas exhibited significant and variable impacts on suppression effectiveness and fire spread potential, but in aggregate likely helped avoid greater loss. Results largely corroborate recent research as well as field observations and incident manager perceptions of the utility of previously burned areas. Fire line efficiencies indicate that the Cerro Grande, Lummis, Oso, and South Fork fires in particular likely contributed to enhanced suppression effectiveness. Counterfactual fire growth simulations suggest that the presence of previously burned areas substantially reduced burn probabilities across the larger landscape, and in turn significantly reduced probable exposure levels for the community of Los Alamos and the LANL. Since the simulations do not explicitly model suppression – under either the actual conditions or the counterfactual landscape – it is possible that additional suppression effort could have limited growth and HVRA exposure levels to less than what is shown in Fig. 6 and Table 3. Yet we can infer that fire line efficiencies would have been lower had many of these burned areas not been there, likely leading to greater demand for fire line construction, and resulting in additional firefighter exposure and higher suppression costs.

Fourth, results of our analysis highlight the influence of human factors, in particular choices regarding line location and burnout operations. The relatively poor performance of mechanical fire line reflects unobserved decision processes about perceived risks; fire managers may have opted to construct mechanical line in areas with more active fire behaviour predisposing these lines to a higher probability of burning over. The presence of previously burned areas likely expanded opportunities for burnout operations, suggesting for instance utility of the Unit 38 prescribed fire not captured within our framework. Lines that ultimately burn over may provide utility by buying time for suppression resources to prepare for larger burnout operations.

Perhaps the most striking result of our analysis was the role of the Cerro Grande Fire. Among previously burned areas, the Cerro Grande had significant interactions with the Las Conchas Fire in terms of area burned and amount of completed fire line, as well as for the direction and magnitude of its influence on fire line effectiveness and potential fire spread. This prompts the question of whether the Cerro Grande Fire can be reframed from a disaster to a disaster that helped avert further disaster.

Developing a broadly applicable framework for characterising suppression effectiveness is challenging, and our results have a limited scope of inference. A full accounting would necessarily capture heterogeneity in the spatiotemporal patterns of environmental conditions, fire behaviour, and the full spectrum of suppression operations. These factors underscore the value of case studies as an important vehicle for in-depth analysis of previous fires (e.g. Bostwick *et al.* 2011; Hudak *et al.* 2011; Maditinos and Vassiliadis 2011). Even at the level of a single event, much of the necessary information can be difficult or infeasible to obtain and properly interpret, in particular comprehensive spatial data on the usage and effectiveness of all suppression resources. Notably, due to data limitations, our analysis did not account for the timing and location of burnout operations or aerial suppression activities. Additionally, there exists uncertainty over the degree to which mapped 'completed' fire line actually represents constructed fire line.

Nevertheless, findings of this case study could have important policy and management implications. A growing body of research suggests that past fires can exert controls on the spread of future fires (Parks et al. 2015), and our results further suggest that past fires may reduce resistance to control and enhance suppression effectiveness. In addition to the role of past fires in enhancing socioeconomic and ecological outcomes (Miller et al. 2012; North et al. 2012; Stephens et al. 2012; Houtman et al. 2013; Parks et al. 2014), our research indicates their presence can also expand opportunities for how future fires are managed. That is, prudent use of wildland fire could serve to broaden the degree of control fire managers can exert over current and future wildfire activity. In the best case, this could create a positive feedback where expanding the footprint of fire on the landscape could lead to increased benefits and reduced management costs (Calkin et al. 2014; Calkin et al. 2015).

Of course, due to significant uncertainty and variability regarding the conditions under which previously burned areas may interact with wildfire, it is unrealistic to predict that allowing more areas to burn today will always yield future benefits, and significant losses associated with wildfire must be acknowledged. Fire managers must balance potential undesired effects of fire, and operate within the flexibility afforded by fire management policy. A significant challenge to the recommendation to expand wildland fire on the landscape is that those fires that pose the highest risk to communities and human development may also be the fires that are likely reduce future risk the most. Clearly, we are not suggesting that we should encourage more fires like the Cerro Grande. However, by managing fires that pose low risk to HVRAs for resource benefit and reduced future risk, opportunities for more resource benefit fires will expand as more treated area potentially limits high damaging events.

Our case study also points to avenues for future investigation into suppression effectiveness. At the scale of the single incident, researchers would ideally be able to obtain finer-scale spatiotemporal information on variables related to fire line characteristics (e.g. line width), fire environment characteristics (e.g. localised wind conditions), treatment characteristics (e.g. initial severity and time since disturbance), landscape characteristics (e.g. topography and vegetation), suppression activities (e.g. timing and location of burnout operations), and human factors (e.g. strategic objectives and decision processes). A principal need is improved standards and metrics for data

collection on suppression operations. Mechanical line built by bulldozers is typically well recorded in order to guide subsequent rehabilitation efforts; similar diligence in reporting nonmechanical line, perhaps incorporating additional metadata in the FIMT on whether it is a natural feature or actual construction, would likely help. Further, diligence in reporting the location and planned extent of burnouts, paired with local observations of fire behaviour and remotely sensed imagery during burnout operations, would go a long way in helping understand the scope and influence of burnout operations. Rigorous statistical analysis quantifying the probability of fire line engaging and holding as a function of some of these factors, while accounting for potential spatial and temporal autocorrelation, may yield insights useful to fire managers deciding where to locate line. Evaluation frameworks could be expanded to consider activities beyond line construction, and to tie evaluation metrics back to explicit and measurable suppression objectives that have both a spatial and temporal component. At a broader scale, evaluating a much larger suite of wildfires that vary across geographic areas, suppression objectives, and suppression activities would be beneficial. As we stated earlier, fires with significant effort devoted to direct line construction may prove more amenable to the line effectiveness evaluation framework. Lastly, fire effects analysis, resource valuation, and suppression cost modelling could also be integrated to expand upon the quantification of possible outcomes beyond HVRA exposure.

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References

- Ager AA, Vaillant NM, McMahan A (2013) Restoration of fire in managed forests: a model to prioritize landscapes and analyze tradeoffs. *Ecosphere* **4**(2), art29. doi:10.1890/ES13-00007.1
- Arkle RS, Pilliod DS, Welty JL (2012) Pattern and process of prescribed fires influence effectiveness at reducing wildfire severity in dry coniferous forests. *Forest Ecology and Management* 276, 174–184. doi:10.1016/J.FORECO.2012.04.002
- Arno SF, Brown JK (1991) Overcoming the paradox in managing wildland fire. *Western Wildlands* **17**(1), 40–46.
- Bostwick P, Menakis J, Sexton T (2011) How fuel treatments saved homes from the 2011 Wallow fire. Available at http://www.fs.usda.gov/Internet/ FSE_DOCUMENTS/stelprdb5318765.pdf [Verified 3 September 2015].
- Broyles G (2011) Fireline production rates. USDA Forest Service, National Technology & Development Program, Fire Management Report 1151–1805 (San Dimas, CA)
- Calkin D, Thompson MP, Ager AA, Finney MA (2011a) Progress towards and barriers to implementation of a risk framework for US federal wildland fire policy and decision making. *Forest Policy and Economics* 13(5), 378–389. doi:10.1016/J.FORPOL.2011.02.007
- Calkin DE, Rieck JD, Hyde KD, Kaiden JD (2011*b*) Built structure identification in wildland fire decision support. *International Journal of Wildland Fire* **20**(1), 78–90.

- Calkin DE, Cohen JD, Finney MA, Thompson MP (2014) How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences of the United States of America* 111(2), 746–751. doi:10.1073/PNAS.1315088111
- Calkin DE, Thompson MP, Finney MA (2015) Negative consequences of positive feedbacks in US wildfire management. *Forest Ecosystems* 2(1), 1–10. doi:10.1186/S40663-015-0033-8
- Cochrane M, Moran C, Wimberly M, Baer A, Finney M, Beckendorf K, Eidenshink J, Zhu Z (2012) Estimation of wildfire size and risk changes due to fuels treatments. *International Journal of Wildland Fire* 21(4), 357–367. doi:10.1071/WF11079
- Collins BM, Miller JD, Thode AE, Kelly M, Van Wagtendonk JW, Stephens SL (2009) Interactions among wildland fires in a longestablished Sierra Nevada natural fire area. *Ecosystems* 12(1), 114–128. doi:10.1007/S10021-008-9211-7
- Collins BM, Stephens SL, Moghaddas JJ, Battles J (2010) Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes. *Journal of Forestry* **108**(1), 24–31.
- Collins RD, de Neufville R, Claro J, Oliveira T, Pacheco AP (2013) Forest fire management to avoid unintended consequences: A case study of Portugal using system dynamics. *Journal of Environmental Management* 130, 1–9. doi:10.1016/J.JENVMAN.2013.08.033
- Cumming SG (2001) A parametric model of the fire-size distribution.. Canadian Journal of Forest Research **31**(8), 1297–1303. doi:10.1139/ X01-032
- Finney MA (2004) FARSITE: fire area simulator model development and evaluation. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-4 Revised. (Fort Collins, CO)
- Finney MA, Seli RC, McHugh CW, Ager AA, Bahro B, Agee JK (2007) Simulation of long-term landscape-level fuel treatment effects on large wildfires. *International Journal of Wildland Fire* 16(6), 712–727. doi:10.1071/WF06064
- Finney M, Grenfell IC, McHugh CW (2009) Modeling containment of large wildfires using generalized linear mixed-model analysis. *Forest Science* 55(3), 249–255.
- Finney MA, Grenfell IC, McHugh CW, Seli RC, Tretheway D, Stratton RD, Brittain S (2011) A Method for Ensemble Wildland Fire Simulation.. *Environmental Modeling and Assessment* 16(2), 153–167. doi:10.1007/S10666-010-9241-3
- Haas JR, Calkin DE, Thompson MP (2013) A national approach for integrating wildfire simulation modeling into Wildland Urban Interface risk assessments within the United States. *Landscape and Urban Planning* 119, 44–53. doi:10.1016/J.LANDURBPLAN.2013.06.011
- Haire SL, McGarigal K, Miller C (2013) Wilderness shapes contemporary fire size distributions across landscapes of the western United States. *Ecosphere* 4(1), art15. doi:10.1890/ES12-00257.1
- Hoff V, Teske CC, Riddering JP, Queen LP, Gdula EG, Bunn WA (2014) Changes in severity distribution after subsequent fires on the North Rim of Grand Canyon National Park, Arizona, USA. *Fire Ecology* **10**(2), 48–63. doi:10.4996/FIREECOLOGY.1002048
- Holden ZA, Morgan P, Hudak AT (2010) Burn severity of areas reburned by wildfires in the Gila National Forest, New Mexico, USA. *Fire Ecology* 6(3), 77–85. doi:10.4996/FIREECOLOGY.0603085
- Holmes TP, Calkin DE (2013) Econometric analysis of fire suppression production functions for large wildland fires. *International Journal of Wildland Fire* 22(2), 246–255. doi:10.1071/WF11098
- Houtman RM, Montgomery CA, Gagnon AR, Calkin DE, Dietterich TG, McGregor S, Crowley M (2013) Allowing a wildfire to burn: estimating the effect on future fire suppression costs. *International Journal of Wildland Fire* 22(7), 871–882. doi:10.1071/WF12157
- Hudak AT, Rickert I, Morgan P, Strand E, Lewis SA, Robichaud PR, Hoffman CM, Holden Z (2011) Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central, Idaho, USA, Gen. Tech. Rep. RMRS-GTR-252. Fort Collins,

CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 60 p.

- Maditinos Z, Vassiliadis C (2011) Mega fires: can they be managed effectively?. *Disaster Prevention and Management* **20**(1), 41–52. doi:10.1108/09653561111111072
- Miller J, Skinner C, Safford H, Knapp EE, Ramirez C (2012) Trends and causes of severity, size, and number of fires in northwestern California, USA. *Ecological Applications* 22(1), 184–203. doi:10.1890/ 10-2108.1
- Moghaddas JJ, Craggs L (2007) A fuel treatment reduces fire severity and increases suppression efficiency in a mixed conifer forest. *International Journal of Wildland Fire* 16(6), 673–678. doi:10.1071/WF06066
- Moghaddas JJ, Collins BM, Menning K, Moghaddas EE, Stephens SL (2010) Fuel treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada. *Canadian Journal of Forest Research* 40(9), 1751–1765. doi:10.1139/X10-118
- National Wildfire Coordinating Group (NWCG) (2014) GIS Standard Operating Procedures on Incidents. National Wildfire Coordinating Group, PMS 936. Available at http://www.nwcg.gov/sites/default/ files/products/gstop_0.pdf [Verified 21 September 2015]
- Nelson KJ, Connot J, Peterson B, Martin C (2013) The LANDFIRE Refresh strategy: updating the national dataset. *Fire Ecology* 9(2), 80–101. doi:10.4996/FIREECOLOGY.0902080
- North M, Collins BM, Stephens S (2012) Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *Journal of Forestry* 110(7), 392–401. doi:10.5849/JOF.12-021
- Parks S, Miller C, Nelson C, Holden Z (2014) Previous Fires Moderate Burn Severity of Subsequent Wildland Fires in Two Large Western US Wilderness Areas. *Ecosystems* 17(1), 29–42. doi:10.1007/S10021-013-9704-X
- Parks SA, Holsinger LM, Miller C, Nelson CR (2015) Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression.. *Ecological Applications*. doi:10.1890/ 14-1430.1
- Reese A (2011) Previous burn, restoration work helped spare Los Alamos from catastrophe. Available online at: http://www.nytimes.com/gwire/ 2011/07/07/07greenwire-previous-burn-restoration-work-helped-sparelo-38246.html. [Verified 1 December 2014]
- Rollins MG (2009) LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire* 18(3), 235–249. doi:10.1071/WF08088
- Ryan KC, Opperman TS (2013) LANDFIRE- A national vegetation/ fuels data base for use in fuels treatment, restoration, and suppression planning. *Forest Ecology and Management* 294, 208–216. doi:10.1016/ J.FORECO.2012.11.003
- Scott J, Helmbrecht D, Parks S, Miller C (2012) Quantifying the threat of unsuppressed wildfires reaching the adjacent wildland-urban interface on the Bridger-Teton National Forest, Wyoming, USA. *Fire Ecology* 8(2), 125–142. doi:10.4996/FIREECOLOGY.0802125
- Stephens SL, McIver JD, Boerner RE, Fettig CJ, Fontaine JB, Hartsough BR, Kennedy PL, Schwilk DW (2012) The effects of forest fuelreduction treatments in the United States. *Bioscience* 62(6), 549–560. doi:10.1525/BIO.2012.62.6.6
- Stratton RD (2006) Guidance on spatial wildland fire analysis: models, tools, and techniques. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS GTR-183. (Fort Collins, CO)
- Stratton RD (2009) Guidebook on LANDFIRE fuels data acquisition, critique, modification, maintenance, and model calibration. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-200. (Fort Collins, CO)
- Syphard AD, Scheller RM, Ward BC, Spencer WD, Strittholt JR (2011a) Simulating landscape-scale effects of fuels treatments in the Sierra Nevada, California, USA. *International Journal of Wildland Fire* 20(3), 364–383. doi:10.1071/WF09125

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- Syphard AD, Keeley JE, Brennan TJ (2011*b*) Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California. *International Journal of Wildland Fire* **20**(6), 764–775. doi:10.1071/WF10065
- Teske CC, Seielstad CA, Queen L (2012) Characterizing fire-on-fire interactions in three large wilderness areas. *Fire Ecology* 8(2), 82–106. doi:10.4996/FIREECOLOGY.0802082
- Thompson MP (2013) Modeling wildfire incident complexity dynamics. *PLoS One* **8**(5), e63297. doi:10.1371/JOURNAL.PONE.0063297
- Wimberly MC, Cochrane MA, Baer AD, Pabst K (2009) Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. *Ecological Applications* 19(6), 1377–1384. doi:10.1890/08-1685.1