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Estimation of wildfire size and risk changes due to fuels treatments

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Abstract. Human land use practices, altered climates, and shifting forest and fire management policies have increased the frequency of large wildfires several-fold. Mitigation of potential fire behaviour and fire severity have increasingly been attempted through pre-fire alteration of wildland fuels using mechanical treatments and prescribed fires. Despite annual treatment of more than a million hectares of land, quantitative assessments of the effectiveness of existing fuel treatments at reducing the size of actual wildfires or how they might alter the risk of burning across landscapes are currently lacking. Here, we present a method for estimating spatial probabilities of burning as a function of extant fuels treatments for any wildland fire-affected landscape. We examined the landscape effects of more than 72 000 ha of wildland fuel treatments involved in 14 large wildfires that burned 314 000 ha of forests in nine US states between 2002 and 2010. Fuels treatments altered the probability of fire occurrence both positively and negatively across landscapes, effectively redistributing fire risk by changing surface fire spread rates and reducing the likelihood of crowning behaviour. Trade offs are created between formation of large areas with low probabilities of increased burning and smaller, well-defined regions with reduced fire risk.

Additional keywords: FARSITE, fire behaviour, fire extent, fire management, fire modelling, fire risk, fire spread.

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Introduction

Large wildfires are characteristic of many ecosystems (Keane *et al.* 2008), but the frequency of large wildfires has increased several-fold in recent decades throughout the western United States (Westerling *et al.* 2006). These conditions have resulted from a combination of human land-use practices, altered climates and shifting forest and fire management policies. In drier forested ecosystems (e.g. *Pinus ponderosa*), fire exclusion over several decades has resulted in unnatural fuel buildups that are now leading to fires of uncharacteristic size and severity (Agee and Skinner 2005). Average fire season lengths have increased by over 2 months owing to earlier springs and later winters in mountainous regions (Westerling *et al.* 2006). Sprawling human populations continue to spread into flammable ecosystems, with over 44 million homes now located in the wildland–urban interface (Radeloff *et al.* 2005).

As a consequence, many ecosystems and human populations have become increasingly vulnerable to large and severe fires. Fire suppression costs in the United States have risen dramatically (National Wildfire Coordinating Group 2009). In inflation-adjusted dollars, federal agency appropriations for wildland fire responses averaged US\$1.3 billion annually for 1996–2000, growing to US\$3.1 billion for 2001–05, owing to the combined costs of fire suppression and fuels reduction activities (US GAO 2007). Congress enacted the Healthy Forests Restoration Act (HFRA) in 2003 (US Congress 2003) to reduce wildfire risk to communities and watersheds, increase the commercial value of forest biomass, promote detection and information-gathering on forest insect and disease infestations, and protect, restore and enhance forest ecosystem components. Specific ecological purposes included promoting recovery of endangered species, increasing biological diversity and enhancing productivity and carbon sequestration (US Congress 2003). In practice, this legislation has expanded fuels treatments activities, including forest thinning, mastication and prescribed burning among others, currently altering fuels on upwards of 1.2 million ha of land each year (National Wildfire Coordinating Group 2009; Hudak *et al.* 2011).

Fuels treatments reduce the quantity, depth and both vertical and horizontal continuity of fuels to mitigate potential fire behaviour and fire severity (Graham *et al.* 2004). Prescribed burns with or without previous mechanical thinning of vegetation are intended to emulate natural processes during weather conditions that are unlikely to create extreme fire behaviour. Prescribed burns are generally economically effective for reducing loadings of live understorey and fine dead fuels. However, smoke management and the risk of escaped fires often bring this management technique into conflict with human values. Mechanical thinning has been put forth as a viable alternative to prescribed burning, particularly for treating canopy fuels. Methods include low thinning, which removes the smallest-diameter trees first, and selection thinning, which removes the largest trees, among many others (Agee and Skinner 2005).

Beyond economic and ecological disputes regarding the feasibility and effects of the various fuel treatments lies the question of their actual effectiveness for mitigating site and landscape-level wildfire disturbances. Studies of hypothetical landscapes and spatial patterns of treatments show treatment densities of 20–30% to be highly effective, especially if placed in the context of expected fire and wind conditions (Finney 2001; Loehle 2004). Finney *et al.* (2007) suggest that optimal spatial treatment patterns exist for landscapes, which require as little as 1% of the landscape to be treated per year for substantial benefits. Real-world fuels treatments have also proved effective for reducing the ecological severity of fires both within and downwind of treated sites (Pollet and Omi 2002; Finney *et al.* 2005; Raymond and Peterson 2005; Cram *et al.* 2006; Martinson and Omi 2008; Wimberly *et al.* 2009). Treatment size and shape have important influences. Within treatments, greater width results in less mortality deeper into the treated area as fire behaviour becomes less intense owing to the reduction in available fuels. Outside larger treated areas, 'shadowing' effects of reduced severity can occur on their leeward sides as fires sweeping around treatments burn with less intensity as they spread orthogonally or contrary to the prevailing wind direction. The effectiveness of all types of treatments varies over time as dead fuels decompose and vegetation regrows (Agee and Skinner 2005; Finney *et al.* 2005). A preconception exists that fuel treatments may have little or no effectiveness under extreme fire conditions (Bessie and Johnson 1995), but this contention is strongly disputed (Agee and Skinner 2005) with recent evidence from the Rodeo and Chediski fires confirming that, even under extreme weather conditions, wildland fire severity can be mitigated by fuel treatments (Finney *et al.* 2005; Cram *et al.* 2006).

Missing in the literature, however, is any quantitative assessment of the effectiveness of existing fuel treatments at reducing the size of actual wildfires or how they might alter the risk of burning across the landscape. Both empirical and modelling research has focussed on predicted or observed fire behaviour and severity on a stand scale (Hudak *et al.* 2011) or failed to incorporate actual weather and fuel conditions, ignitions or behaviour of past wildfire events (Finney *et al.* 2007; Ryu *et al.* 2007; Ager *et al.* 2010). Until recently, comprehensive analysis of the landscape effects of fuel treatments has not been practical for several reasons, including the relatively small number of implemented fuel treatments that had burned, limited information about the spatial distribution of treatments and wildfires, a lack of fuels information at landscape scales, and insufficient data and computational capacity for remotely sensed monitoring and spatial analyses of fires and their effects. Here, we report a method for utilising existing data and tools to estimate the effectiveness of existing fuels treatments for altering fire risk and wildland fire sizes.

Methods

Our study examined the effects of more than 72 000 ha of wildland fuel treatments (1300 individual treatments) involved in 14 large wildfires that burned 314 000 ha in forested ecosystems spread across nine USA states between 2002 and 2010 (Table 1). Wildland fire perimeters were acquired from the Monitoring Trends in Burn Severity (MTBS) database (Eidenshink *et al.* 2007). Fuel treatment involvement, type, age and spatial attribute information was gained directly from personnel at each of the individual land-management units. Wildfires were selected to cover a wide range of sizes (365 to 186 878 ha) and amount of treated lands (5.3 to 57.1%). Research teams conducted field visits at eight of the selected wildland fire sites and measured burn severity in a total of 215 Composite Burn Index (CBI) plots (Key and Benson 2006) to validate the MTBS fire perimeter, burn severity and fuels treatment data (cf. Wimberly *et al.* 2009).

Data sources

To investigate landscape-level influences of the treatments, we used the FARSITE modelling system (Finney 2004) to simulate the observed wildfire progression and spread rates. Model simulations were parameterised with LANDFIRE fuels and topographic data layers. LANDFIRE provides consistent and comprehensive digital maps of vegetation composition, structure, wildland fuels and topographic data at a 30-m resolution for the United States (Rollins and Frame 2006; Rollins 2009). The expanded set of 40 standard fire behaviour fuel models (Scott and Burgan 2005) was used in all simulations. Relevant weather conditions and wind velocities before and during each wildfire were acquired from individual Remote Automated Weather Stations (RAWS) in the vicinity of each fire. RAWS data were imported to FireFamily Plus (Bradshaw and McCormick 2000) to summarise temperature, precipitation, humidity, and wind speed and direction in a format compatible with FARSITE. Fuels treatment maps were acquired as shape files from responsible land-management personnel (cf. Wimberly *et al.* 2009). Fuel treatments included silvicultural thinning, mastication, prescribed fire, and thinning followed by prescribed fire. Historic wildfire boundaries, fire ignition locations and, when possible, daily fire progression maps for each fire were also acquired from the responsible land-management units. In addition, the spatiotemporal progression of actively burning fire

Table 1. Information for 14 wildfires and associated fuels treatments that were involved in the respective wildfires
The eight fires in italic were visited by field teams to validate fire severity and fuels treatments information

Fire name	State	Fire year	Fire size (ha)	Treated (ha)	Number of treated areas	Percentage previous wildfire	Planned treatments (%)	Total land treated (%)
Antelope	CA	2007	9352	1924	45	64.7%	35.3	20.6
Borrego	NM	2002	5211	1647	48	57.0%	43.0	31.6
Boulder	OR	2002	19 630	1104	200	1.9%	98.1	5.6
Camp 32	MT	2005	365	134	10		100.0	36.7
Ham Lake[A]	MN	2007	18 963	6309	107	0.5%	99.5	33.3
Kelsay	OR	2003	528	101	22		100.0	19.1
Meridian	MI	2010	3073	567	45		100.0	18.5
Moonlight	CA	2007	26 596	2765	21	53.0%	47.0	10.4
Otter Creek	OR	2007	1217	603	46		100.0	49.5
Ricco	SD	2005	1438	398	28		100.0	27.6
Rodeo	AZ	2002	186 878	53 579	567	41.5%	58.5	28.7
School	WA	2005	20 923	1221	62		100.0	5.8
Warm	AZ	2006	23 575	1261	79		100.0	5.3
West (wildland fire use, WFU)	AZ	2006	851	486	20		100.0	57.1

[A]US portion of the Ham Lake Fire only. Total fire size including the Canadian portion was 28 574 ha.

fronts was derived from the Forest Service's Active Fire Mapping Program, based on MODIS (Moderate Resolution Imaging Spectroradiometer) fire detection points (see http://activefiremaps.fs.fed.us/, accessed 9 February 2012). Additional information, including daily fire behaviour data during each of the individual fire events, was acquired from Incident Status Summary (ICS 209) fire reports (see http://fam.nwcg.gov/fam-web/, accessed 15 August 2011).

Analysis methods

Recognition of linkages between parameters and their effects on overall fire behaviour within modelled simulations is critical to producing robust calibrations of the degree of influence that weather, topography and fuels have on actual wildfire behaviour (Fig. 1). Scaling calibration, whereby interrelated parameters are adjusted through multipliers so as to retain proportional relationships to each other, overcomes limitations in recent fuel treatment simulation research (Martinson and Omi 2008) and model weaknesses (Stratton 2006, 2009; Cruz and Alexander 2010) by matching observed fire behaviour to observed weather and fuel conditions, thereby producing realistic, albeit relative, evaluations of the effects of fuels treatments.

The majority of fuels treatments have been implemented since the Healthy Forests Restoration Act was signed in December of 2003 (US Congress 2003); therefore, the LANDFIRE 1.0.0 data layers that were used, which are from ~2001, do not accurately represent fuels and vegetation structure in many treated forests at the time of the selected wildfires. To reflect the reported treatment activities and forest conditions at the time of each wildfire, we adjusted the relevant fuels and structure data to more accurately represent conditions existing within each treatment area, before calibrating each fire simulation. Treatment updates were based on regional silviculture books, the Forest Service Activity Tracking System (FACTS) database's activity code descriptions and information given by local land managers.

To conduct the analyses, an initial FARSITE simulation was calibrated to approximate the observed daily fire behaviour and progression of each wildfire. Fire spread rates and behaviour are functions of wind velocity, terrain, and fuel type, quantity, moisture and structure. Many fire-modelling systems, including FARSITE, rely on integration of Rothermel's (1972, 1991) surface and crown fire spread rate models and Van Wagner's (1977, 1993) crown fire transition and propagation models. Recognising the substantial underprediction biases for crown fire behaviour in these systems (Cruz and Alexander 2010), all input variables were evaluated and, if needed, modified to match observed fire behaviour. Maps of surface and canopy fuels are often imprecise and unsupported by experimental validation (Scott and Reinhardt 2001, 2005; Stratton 2006, 2009). Erroneous estimates of canopy cover (CC) propagate throughout the fire-modelling system by altering surface wind speeds and fuel moistures, affecting fire spread rates, whereas inaccurate crown base heights (CBH), crown bulk densities (CBD) and foliar moisture contents (FMC) produce unrealistic thresholds for passive and active crown fire initiation (Fig. 1). Characterisation of the heterogeneity of surface fuel conditions across the United States is limited to a set of 40 surface fuel models (Scott and Burgan 2005), producing additional need for calibration to localised conditions. Distinguishing between inherent biases in the modelling system and erroneous estimates in LANDFIRE data can be quite difficult. We chose to first scale canopy fuels data, as underestimates of crown fire behaviour were most prevalent, and fuels data can be easily adjusted by FARSITE or Geographic Information System (GIS) software.

Universal updates, primarily through percentage multipliers, were applied to landscape fuels (i.e. surface-fuel model type, CBH, CBD, FMC and CC) and weather (primarily wind) variables to correct for known biases, following procedures

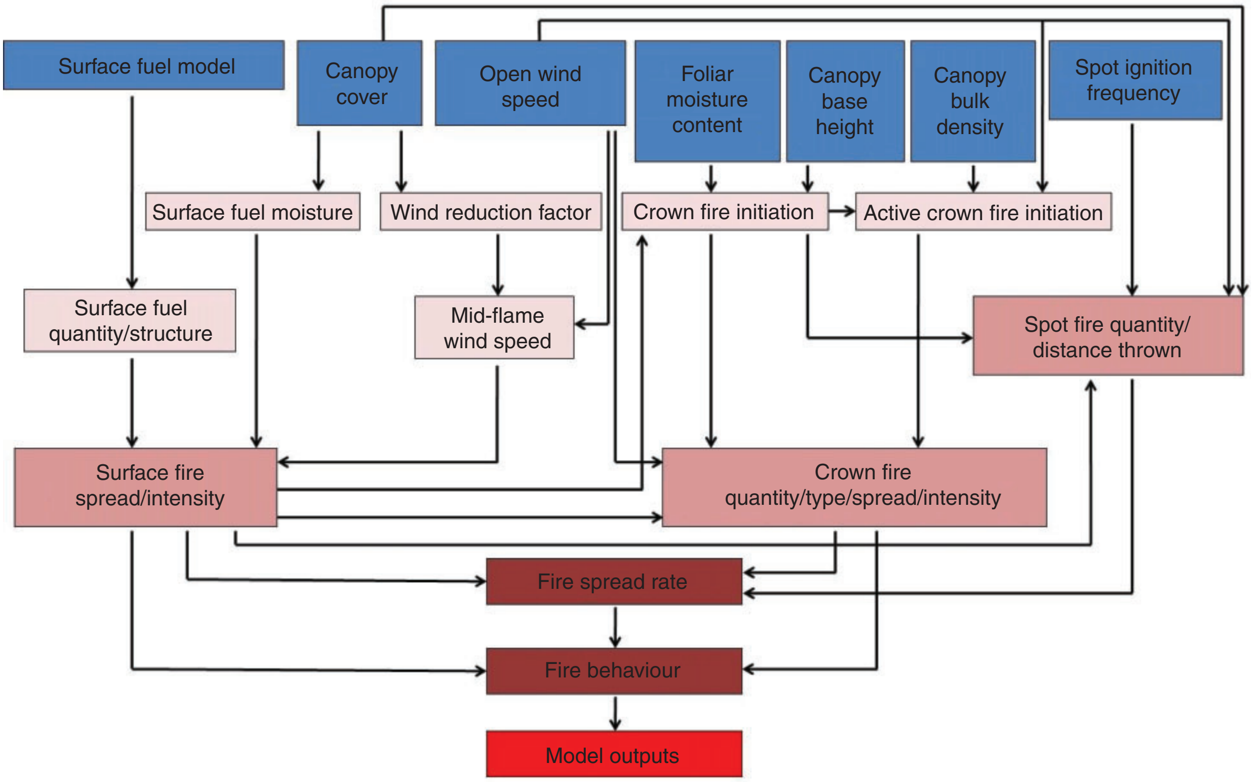

Fig. 1. Flow diagram of linkages between model inputs and individual model components. Parameters modified in the fire simulation calibration process (blue) are used to create interim components (light pink) within the three major models (dark pink) that calculate spatiotemporal fire characteristics (dark red) used to derive the landscape model outputs (bright red) within the FARSITE fire spread modelling system.

similar to Stratton (2006, 2009). For example, wind speed and surface-fuel type substantially influence both surface and crown fire intensities, spread rates and the thresholds for passive and active crown fires. RAWS station data are often obtained many kilometres away from the active burning zone, and local winds are influenced by topography and vegetation in the vicinity of a fire. Therefore, all wind speeds, or only those during known periods of extreme fire spread, were scaled by percentage multipliers, in possible conjunction with surface fuel model changes, until both fire spread rates and behaviour matched observations, to control for biased data. If surface spread rates were accurate, but the quantity of passive or active crown fire was suspect, then CBH, FMC and CBD were scaled to produce observed behaviour without affecting surface spread rates. Because of the semi-empirical nature of fire models, we maintained the values of the inputs within initial experimental ranges (e.g. >67% foliar moisture content and <83 km h^{-1} wind speed (Cruz and Alexander 2010)). This maintained proportional relationships among inputs, under the assumption that the quantitative values of these inputs are not as important as the linear and non-linear relationships among them in determining their cumulative influence on calculated fire behaviour.

Pre- and post-fire Landsat imagery and MTBS fire severity estimates were used to verify the appropriateness for simulating observed fire behaviour of the fuels adjustments within treated areas. For example, if MTBS showed low fire severity within a fuel treatment, then crown fire could not have occurred in these areas. Changes to surface fuel models or canopy base heights were constrained to be in line with known treatment practices while also producing simulated fire behaviour consistent with observed fire effects in treated areas.

All wildfires that were simulated experienced crown fire behaviour. During crown fires, large numbers of firebrands are lofted into the air, frequently resulting in downwind spot fires. Spot fires can greatly accelerate wildfire spread rates and often bypass potential barriers to fire spread (e.g. roads, rivers, lakes, fuel treatments). FARSITE simulates this behaviour by estimating firebrand numbers and sizes based on empirical data from different tree species. The distances travelled, spatial distribution and number of still-burning firebrands that reach the ground are calculated based on particle size distribution, wind velocities and fire intensity (lofting height) (Albini 1979). The modeller sets the fraction of embers that result in new fire ignitions. We adjusted this fraction to calibrate our simulation with observed fire behaviour, although the range of values used was small (~0.5–1.0% ignition frequency) (Stratton 2006, 2009). Because of this stochastic behaviour, model simulations are unique each time they are run, even though all parameters remain unchanged.

Once realistic simulations, qualitatively similar to observed fire progressions, were achieved, the same simulation parameters were used for all subsequent analyses of the respective fires. Owing to the stochastic results caused by the varying numbers and locations of spot fires, multiple simulations of each fire were conducted. We experimented with up to 100 repeated simulations but settled on 10–30 simulations as adequate for establishing likely fire extents, with the final number dependent on variability in final simulated perimeters and the computational time required for each simulation. It is noteworthy that, regardless of the total number of days that individual wildfires burn, most of the area burned generally occurs during a relatively few hours or days, when extreme weather conditions result in rapid fire spread. The period of each day's active fire growth (burn periods) was determined by weather events and observed fire behaviour. Insufficient data existed to explicitly model fire suppression activities. Suppression activities can reduce or stop fire spread along fire fronts but can also increase area burned, sometimes substantially, when fuels are intentionally burned in front of a fire to break fuel continuity and prohibit spread. Model simulations were not constrained or forced to generate perimeters that matched MTBS fire perimeters.

Subsequently, a second set of simulations, equal in number to the original 'treated' simulations, was used to derive new probability maps of the likely fire extent that would have occurred over the time periods of the respective wildfires in the absence of existing landscape fuel treatments, the 'untreated' landscape. Treatments conducted before LANDFIRE image acquisition (1999–2001), thus already included in the treated landscape, were replaced by estimates of fuel quantity and structure similar to surrounding untreated areas for the untreated simulations. Between the treated and untreated simulations, no other spatial or temporal parameters were changed, isolating the influence of fuels treatments on realised fire behaviour and spread for each wildfire. Neither the treated nor untreated simulations included fire suppression activities.

The multiple simulations of each wildfire were used to derive maps of the probability of each area burning and tabular results of the range, average and variance of simulated fire extents (Table 2). By overlaying the two probability maps and calculating the difference in the spatial probability of burning between the treated (actual) and untreated (hypothetical) landscapes for each 30-m pixel, we created maps of the probability that any given location had experienced altered fire risk because of the presence of the fuels treatments (Fig. 2). To examine the relative effects of planned and unplanned (previous wildfires) fuels treatments, their separate effects were calculated by comparison of each type of treatment, in the absence of the other, with an untreated landscape (as above) for three fires (Antelope, Borrego, Moonlight) where previous wildfires comprised roughly half of the total treated area (65, 57, 53%) (Table 3).

Results

Analysis of simulation results from the 14 wildfires indicates that fuels treatments reduced the average size of any given wildfire by an estimated 7.2%, with amount of change correlated with the proportion of the landscape treated (Spearman's correlation $\rho = 0.692$, $n = 14$; $P = 0.008$). The size effects were highly variable among fires, ranging from -63.6 to 46.1%. Eleven of the fourteen individual wildfires had net size reductions (average -13.2%) in burned area owing to the combined effects of all landscape fuels treatments, whereas three had average increases in area burned (average 24.1%) (Table 2).

Areas with altered fuels included 46 000 ha (64%) of planned treatments (thinning, mastication and prescribed fire) and 26 000 ha (36%) of unplanned treatments (previous wildfires). Nearly all (99.8%) of unplanned treatment areas were contained within four of the modelled wildfires. Within the fires we examined in detail for differences between planned and unplanned treatments, the effects were mixed. In the Antelope fire, unplanned treatment effects were similar to that of the planned treatments, with burn prevention to burn promotion area ratios of 3.5 : 1 and 4.4 : 1. However, the spatiotemporal patterning of the Antelope fire's spread resulted in synergistic interaction between planned and unplanned treatments effects such that the combination of all treatments yielded a 15.1 : 1 burn prevention to promotion ratio (Fig. 3). In the Borrego fire, the planned treatments had a 6.6 : 1 prevention to promotion ratio whereas unplanned treatments were a net promoter of fire spread with a 0.6 : 1 ratio. The two treatment types combined yielded a mid-range ratio of 2.4 : 1 for overall effectiveness. Planned treatments in the Moonlight fire effectively reduced fire size (3.5 : 1) whereas previous wildfire areas weakly promoted fire spread (0.9 : 1); however, the interaction of the two treatment types yielded increased effectiveness (5.1 : 1) when combined. Throughout the remainder of the Results section, fuel treatments refer to the combined effects of planned and unplanned treatments.

The combined model simulations (treated and untreated) for all fires indicate that fuels treatments altered probability of fire occurrence across an area averaging 105% that of the actual wildfires (42% increased, 63% decreased risk), with ~5 ha of altered risk per hectare of treated land. Large landscape regions experienced both increased and decreased risks of fire spread for each fire event as a function of fuels treatment presence, with ~2 ha of increased risk for every 3 ha at reduced risk of burning. The amounts of both increased (Spearman's correlation $\rho = 0.745$, $n = 14$; $P = 0.0033$) and decreased ($\rho = 0.842$, $n = 14$; $P = 0.0002$) areas of risk were positively correlated with the amount of area treated. Five of the 14 wildfires had more area at increased risk than decreased risk because of the fuel treatments (Table 2). However, the probability distributions differed between the two risk classes, with most areas of promoted risk having low probability and progressively smaller areas at higher probabilities, whereas areas at reduced risk had proportionately more areas of higher probability. For example, 11% of areas at reduced risk were highly likely (>0.9) to have been saved from burning because of treatments, whereas <1% of areas at increased risk of burning were highly likely to have burned owing to fuel treatments.

Weighting areas of altered risk by their respective altered burn probabilities shows that areas likely to have burned because of treatments tended to have low spatial predictability, with 62% occurring in regions of <0.3 increased burning risk, and only 4% occurring in regions of very high (>0.9) likelihood of burning. Conversely, areas saved from burning by treatments were more spatially predictable, with 34% occurring in regions of very high (>0.9) burn prevention probability and a similar amount (34%) occurring in areas of low (<0.3) burn prevention probability. Across the 14 wildfires, an extra 4 ha burned owing to fuels treatments for every 10 ha where fire was prevented because of them (Table 2).

Table 2. Model simulation data for 14 wildfires

Multiple simulations were run for treated and untreated conditions to account for stochastic fire behaviour under extreme conditions of these large fires. Significantly different in size from untreated, Welch two-sample *t*-test: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; ****, $P < 0.0001$

Fire name	Number of untreated and treated simulations	Average[A] untreated fire size (ha)	Average[A] treated fire size (ha)	Average change in area burned due to treatments	Land at increased risk of burning (ha)	Land at decreased risk of burning (ha)	Probable area burned owing to treatments (ha)	Probable area not burned owing to treatments (ha)	Promoted area burned per hectare treated (ha)	Prevented area burned per hectare treated (ha)
Antelope	10, 10	9821 (483)	7718**** (389)	−21.4%	928	4822	150	2252	0.08	1.17
Borrego	20, 20	8074 (1302)	7618 (1128)	−5.7%	1236	3934	325	788	0.20	0.48
Boulder	20, 20	20 205 (305)	21 422**** (263)	6.0%	4132	546	1247	44	1.13	0.04
Camp 32	20, 20	399 (62)	478**** (47)	20.0%	399	305	195	131	1.46	0.98
Ham Lake	20, 20	18 805 (1052)	17 072* (3044)	−9.2%	16 976	8266	3649	5382	0.58	0.85
Kelsay	20, 20	666 (120)	973**** (127)	46.1%	955	326	339	27	3.36	0.27
Meridian	10, 10	4172 (157)	3852** (211)	−7.7%	561	1476	93	427	0.16	0.75
Moonlight	10, 10	35 491 (1413)	32 645*** (1439)	−8.0%	4532	8537	708	3583	0.26	1.30
Otter Creek	30, 30	1380 (102)	1274*** (102)	−7.7%	370	467	131	154	0.22	0.25
Ricco	10, 10	1109 (133)	1070 (187)	−3.5%	490	435	80	107	0.20	0.27
Rodeo	10, 10	279 914 (5558)	273 999 (12 622)	−2.1%	36 950	60 044	7339	14 013	0.14	0.26
School	10, 10	26 418 (618)	22 179**** (596)	−16.0%	653	10 561	83	4319	0.07	3.54
Warm	20, 20	27 774 (6459)	27 703 (3130)	−0.3%	4723	10 433	1447	2673	1.15	2.12
West (wildland fire use, WFU)	10, 10	3035 (48)	1106**** (19)	−63.6%	35	2456	8	1975	0.02	4.06

[A]Numbers in parentheses are the standard deviations of the multiple simulations.

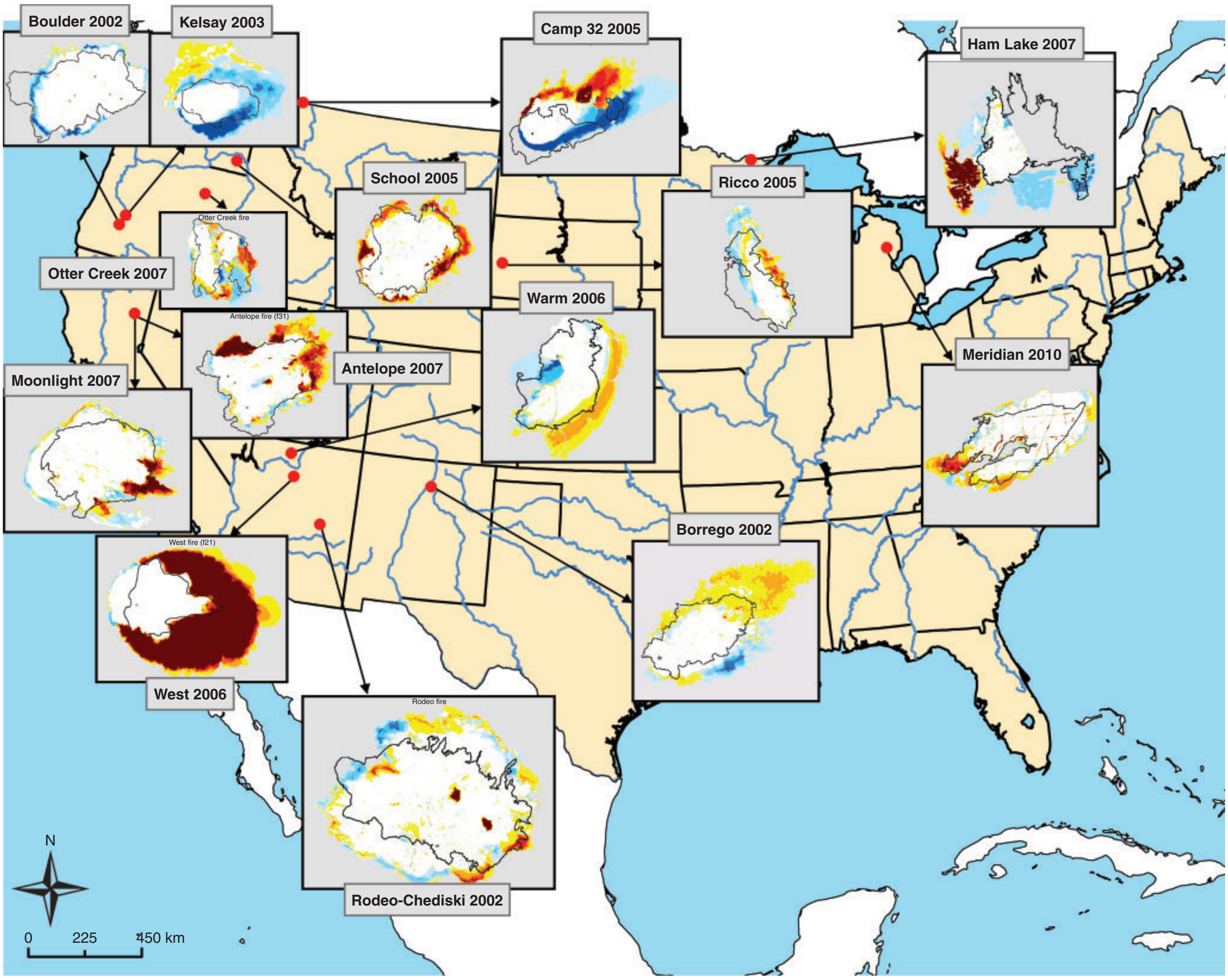

Fig. 2. Location and maps of changed fire risk for the 14 large wildfires that were simulated in this study. Probability of fire prevention (warm colours) and fire promotion (cool colours) because of fuels treatments encompassed by the wildfires (black lines) are greater for darker colours. Areas in white experienced no change in fire risk due to treatments.

Table 3. Comparison of planned and unplanned treatments for three wildfires

Unplanned treatments comprise small previous wildfires that were burned in the subsequent large wildfires examined in this study

Fire	Combined treatments			Planned treatments only			Wildfires only		
	Promoted (ha)	Prevented (ha)	Ratio	Promoted (ha)	Prevented (ha)	Ratio	Promoted (ha)	Prevented (ha)	Ratio
Antelope	150	2252	15.1	321	1128	3.5	311	1367	4.4
Borrego	325	788	2.4	117	765	6.6	411	258	0.6
Moonlight	708	3583	5.1	750	2596	3.5	1723	1598	0.9

In terms of net efficiency, fuels treatments ranged between preventing 4 ha of burning (West) for every hectare treated, to causing 3 ha of burning for every treated hectare (Kelsay). On average, treatments prevented 1.8 ha of burning for every hectare burned because of treatments, but there was a dichotomy between fires where treatments were effective and those where they were detrimental. In the 11 fires where treatments reduced fire size, treatments prevented 4.9 ha of burning for every hectare of promoted burning. Conversely, the three fires (Boulder, Camp 32, Kelsay) with augmented burning because of treatments had 4.6 ha of increased burning for every hectare of fire prevention.

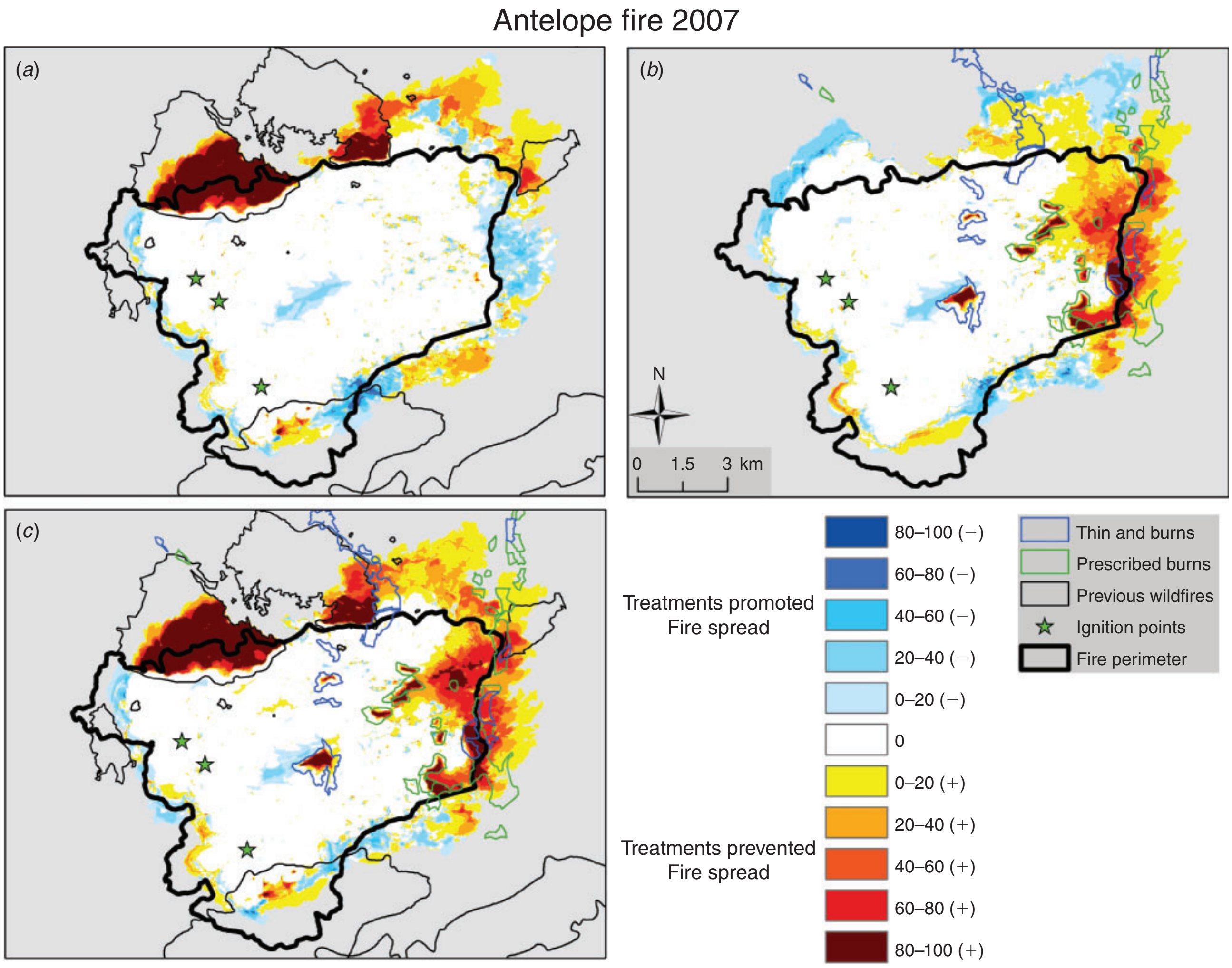

Fig. 3. Depiction of a comparison of the effects on fire risk caused by planned (35%) and unplanned (65%) fuels treatments burned in the 2007 Antelope fire in California. Panel (*a*) depicts the fire probability effects of only unplanned treatments (previous wildfires); panel (*b*) shows the effects of only planned fuels treatments; and panel (*c*) shows the combined effectiveness of the two treatment types.

Discussion

Our simulation experiment was not designed to model fire suppression activities or to exactly replicate historical fire behaviour. Instead, the goal of our approach was to generate realistic scenarios of fire spread and fire behaviour based on actual landscapes, existing fuel treatment patterns and variable weather conditions under which historical fires burned. Once these scenarios had been established, we used them to evaluate counterfactual scenarios under which treatments did not exist. Thus, our results should be viewed as extensions of previous simulation experiments used to evaluate treatment effectiveness (e.g. Finney 2001; Loehle 2004; Finney *et al.* 2007) that incorporate greater realism and provide a better understanding of the range of treatment effects that are likely to occur in actual wildfires.

Although fuels treatments are known to alter fire behaviour and severity within treated forests (Pollet and Omi 2002; Finney *et al.* 2005; Raymond and Peterson 2005; Cram *et al.* 2006; Martinson and Omi 2008; Wimberly *et al.* 2009), the landscape effects of such treatments have heretofore been undocumented for actual wildfires. The method we present provides a means of estimating spatial probabilities of burning as a function of the extant fuels treatments for any wildland fire-affected landscape.

Fuels treatments effectively redistribute fire risk on the landscape. This is done by altering fire behaviour in two different ways: changing fire spreading rates and reducing the likelihood of crowning behaviour. Fuels treatments are designed to reduce the loading and continuity of potential fuels, horizontally and vertically, thereby changing the availability of fuels and the rate at which they are consumed. The effectiveness of such treatments will vary as a function of the type, amount, size, spatial distribution and intensity of treatments, time since implementation, ecosystem type, topography and weather conditions at the time and geographic location of burning. Therefore, there can be no absolute measure of landscape treatment effectiveness. However, effectiveness can be estimated for a given set of conditions. The use of actual wildfire environments produces estimates of the realised effects of human manipulations of fuel complexes. Although all treatments can theoretically alter the interaction of fire, fuels and weather on a landscape (Finney *et al.* 2007), the net benefits are seen in treatments that are actually burned, if we ignore changes in ignition risks.

Fuels treatments have a deterministic effect on modelled surface fire spread rates. They may either inhibit or enhance the rate at which fires pass through an area depending on how the surface fuels have been altered. For example, shortly after a prescribed fire, surface fuels may be lacking, such that a wildfire is denied sufficient fuel to allow rapid, if any, spread into a treated area. Conversely, in some forest types (e.g. *Pinus ponderosa*), opening of the canopy through thinning operations may re-establish a grass understorey that is exposed to sun and wind, accelerating the passage of any fire that enters the site. The net effect of such treatments, outside their respective boundaries, will be to alter the timing and potentially the direction and momentum of the fire as it arrives at different points on the landscape. Regardless of the changes, as long as they are known, the effects of fuels treatments on surface fire spread rates of any subsequent wildfire can be simulated as exactly as parameter inputs and modelled physics allow, with absolute repeatability. In principle, regions burned or prevented from burning owing to treatments could be attributed to the treatments and the resultant changes in fire size owing to treatments calculated.

However, treatments often change more than surface fire behaviour. They are ostensibly meant to protect from catastrophic wildfire (US Congress 2003). This objective often translates into treatments that are intended to reduce the likelihood of either passive or active crown fires by the removal of ladder fuels and thinning of the canopy such that continuity is reduced. Reducing canopy fires lowers fire severity at the site, but also reduces the likelihood of spot fires being spawned by lofted firebrands from these intense blazes. Severe fire weather characterised all of the fires studied here, and spot fires were a key component of fire growth, with multiple ignitions occurring hundreds to thousands of metres downwind of the spreading fires. Treatments can potentially retard fire growth by being both poor locations for spot fire ignitions and having low likelihoods of spawning additional firebrands to ignite fires further downwind. The landscape effect of this aspect of fuel treatments on fire spread is stochastic, with potentially large effects on fire spread and ultimate fire sizes. Although the magnitude of this effect can be estimated, spatial attribution of burning at any given location due to treatments can only be dealt with probabilistically.

The net effect of fuels treatments will be the combination of changed surface fire behaviour and crown fire potential. Treatments can often increase rates of surface fire spread, raising the average rate of burned area expansion while simultaneously reducing the probability of extreme spread rates and behaviour due to crown fires and associated spot fire-related growth.

The analysis of the separate and combined effects of previous wildfires (unplanned) and planned treatments (Table 3, Fig. 3) shows that individual treatment effects can interact to create landscape-level changes in fire risk that are greater than the sum of individual treatment area effects. This was seen in the Antelope and Moonlight fires, but not in the Borrego fire, where unplanned and planned treatment effects did not interact. Such potential for interaction has previously been shown for surface fires interacting with simulated treatments (Finney 2001; Finney *et al.* 2007). However, the results presented here are, in large part, because of stochastic changes in fire spread resulting from fuels treatments altering the spatiotemporal timing and intensity of extreme fire behaviour, primarily by limiting direction and rates of spot fire-related growth of the wildfires.

It is noteworthy that three of the studied wildfires experienced exacerbated fire spread because of their respective fuels treatments. This occurred in the Camp 32 fire owing to an accident of timing. The wildfire burned through an area that had been thinned and left with slash piles awaiting a prescribed burn under more favourable weather conditions. The uncharacteristic fire behaviour and spread rates within this fuel treatment were heavily weighted in the fire simulations because of the relatively small size of this fire (365 ha). Therefore, we do not consider this result to be characteristic of treatment effects in this forest type, which was dominated by Douglas fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). In contrast, the Kelsay and Boulder fires are from similar mixed-conifer forests in Oregon, with combinations of Douglas fir, ponderosa pine, lodgepole pine (*Pinus contorta*) and western hemlock (*Tsuga heterophylla*). Both were characterised by patchwork clearcuts, averaging ~5 ha in size, that had experienced mastication or prescribed burning and replanting, with most (90%) occurring 5–30 years before the fire. Simulated surface fire spread rates were likely overestimated, because LANDFIRE data do not have the resolution to accurately reflect the many logging roads and skid trails that disrupt fuel continuity at these sites, altering fire boundaries (Narayanaraj and Wimberly 2011). However, the simulated exacerbation of overall fire spread rates is still realistic owing to increased crown fire prevalence caused by the continuous, even-aged fuel complexes of the treated areas.

Conclusions

Fuels treatments directly affect wildfire spread and behaviour within their boundaries but also indirectly change fire behaviour across the untreated landscape by altering the probability and timing of burning, ultimately affecting final wildfire sizes. Although this study evaluates the performance of 1300 individual fuel treatments in 14 large wildfires, the results are not comprehensively conclusive about the effectiveness of fuels treatments. Treatment effectiveness varies by ecosystem type, treatment intensity, size, age and distribution on the landscape as well as the weather conditions at the time of a wildfire. Statistically robust inferences of site- and landscape-level effects of treatments will require much larger sample sizes and detailed analyses of changes in fire behaviour and burn severity to properly account for these factors. This study clearly shows that even modest quantities of landscape fuel treatment (5%) can affect the final size of wildfires. However, no simple relationships exist between changes in fire size and the treated percentage of the landscape. Furthermore, separate treatments can act synergistically to enhance overall landscape-level effectiveness, reducing area burned primarily through alteration of the stochastic chances of long-range spot fire occurrence. Fuels treatments substantially alter patterns of fire risk across landscapes during any given fire event. These forest-management activities represent a trade-off between formation of large areas with low probabilities of increased burning and increased certainty of substantially reduced fire risks in known portions of landscapes, combined with modestly reduced fire extents. This patterning holds promise for using fuels treatments to reduce fire risk in wildland–urban interfaces and other regions of perceived value, reinforcing calls for greater concentration of future fuels treatments in these inhabited areas (Schoennagel *et al.* 2009). It should be stressed, however, that the millions of hectares of fuels treatments, and the concomitant changes in fire effects when they burn, represent novel disturbance regimes that will have unknown effects on ecosystem composition, structure and processes, even if they do serve to mitigate fires of uncharacteristic size or severity.

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References

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83–96. doi:10.1016/J.FORECO.2005.01.034

Ager AA, Vaillant NM, Finney MA (2010) A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management* **259**, 1556–1570. doi:10.1016/J.FORECO.2010.01.032

Albini FA (1979) Spot fire distance from burning trees: a predictive model. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-56. (Ogden, UT)

Bessie WC, Johnson EA (1995) The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* **76**, 747–762. doi:10.2307/1939341

Bradshaw LS, McCormick E (2000) FireFamilyPlus user's guide, version 2.0. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-67WWW. (Ogden, UT)

Cram DS, Baker TT, Boren JC (2006) Wildland fire effects in silviculturally treated vs. untreated stands of New Mexico and Arizona. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-55. (Fort Collins, CO)

Cruz MG, Alexander ME (2010) Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. *International Journal of Wildland Fire* **19**, 377–398. doi:10.1071/WF08132

Eidenshink J, Schwind B, Brewer K, Zhu Z, Quayle B, Howard S (2007) A project for monitoring trends in burn severity. *Fire Ecology* **3**, 3–21. doi:10.4996/FIREECOLOGY.0301003

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* **47**, 219–228

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, McHugh CW, Grenfell IC (2005) Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal of Forest Research* **35**, 1714–1722. doi:10.1139/X05-090

Finney MA, Seli RC, McHugh C, 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**, 712–727. doi:10.1071/WF06064

Graham RT, McCaffrey S, Jain TB (2004) Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-120. (Ogden, UT)

Hudak AT, Rickert I, Morgan P, Strand E, Lewis SA, Robichaud PR, Hoffman C, Holden ZA (2011) Review of fuel treatment effectiveness in forest and rangelands and a case study from the 2007 megafires in central Idaho, USA. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-252. (Fort Collins, CO)

Keane RE, Agee JA, Fulé P, Keeley JE, Key C, Kitchen SG, Miller R, Schulte LA (2008) Ecological effects of large fires on US landscapes: benefit or catastrophe? *International Journal of Wildland Fire* **17**, 696–712. doi:10.1071/WF07148

Key CH, Benson NC (2006) Landscape assessment: ground measure of severity, the Composite Burn Index, and remote sensing of severity, the Normalised Burn Ratio. In 'FIREMON: Fire Effects Monitoring and Inventory System'. (Eds DC Lutes, RE Keane, JF Caratti, CH Key, NC Benson, S Sutherland, LJ Gangi) pp. LA-1–LA-51. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-164-CD. (Ogden, UT)

Loehle C (2004) Applying landscape principles to fire hazard reduction. *Forest Ecology and Management* **198**, 261–267. doi:10.1016/J.FORECO.2004.04.010

Martinson EJ, Omi PN (2008) Assessing mitigation of wildfire severity by fuel treatments – an example from the Coastal Plain of Mississippi. *International Journal of Wildland Fire* **17**, 415–420. doi:10.1071/WF06067

Narayanaraj G, Wimberly MC (2011) Influences of forest roads on the spatial pattern of wildfire boundaries. *International Journal of Wildland Fire* **20**, 792–803. doi:10.1071/WF10032

National Wildfire Coordinating Group (2009) Quadrennial fire review 2009. (National Association of State Foresters, USDA Forest Service and USDI Bureau of Indian Affairs, Bureau of Land Management, National Park Service and US Fish and Wildlife Service) Available at http://www.iafc.org/files/wild_QFR2009Report.pdf [Verified 9 February 2012]

Pollet J, Omi P (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* **11**, 1–10. doi:10.1071/WF01045

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005) The wildland–urban interface in the United States. *Ecological Applications* **15**, 799–805. doi:10.1890/04-1413

Raymond CL, Peterson DL (2005) Fuel treatments alter the effects of wildfire in a mixed evergreen forest, Oregon, USA. *Canadian Journal of Forest Research* **35**, 2981–2995. doi:10.1139/X05-206

Rollins MG (2009) LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire* **18**, 235–249. doi:10.1071/WF08088

Rollins MG, Frame CK (2006) The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-175. (Fort Collins, CO)

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Rocky Mountain Research Station, Research Paper INT-115. (Ogden, UT)

Rothermel RC (1991) Predicting behavior and size of crown fires in the Northern Rocky Mountains. USDA Forest Service, Rocky Mountain Research Station, Research Paper INT-438. (Ogden, UT)

Ryu S, Chen C, Zheng D, LaCroix JJ (2007) Relating surface fire spread to a landscape structure: an application of FARSITE in a managed forest landscape. *Landscape and Urban Planning* **83**, 275–283. doi:10.1016/J.LANDURBPLAN.2007.05.002

Schoennagel T, Nelson CR, Theobald DM, Carnwath GC, Chapman TB (2009) Implementation of National Fire Plan treatments near the wildland–urban interface in the western United States. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 10706–10711. doi:10.1073/PNAS.0900991106

Scott JH, Burgan RE (2005) Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-153. (Fort Collins, CO)

Scott JH, Reinhardt ED (2001) Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-29. (Fort Collins, CO)

Scott JH, Reinhardt ED (2005) Stereo photo guide for estimating canopy fuel characteristics in conifer stands. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-145. (Fort Collins, CO)

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)

US Congress (2003) House Resolution 1904, Healthy Forests Restoration Act of 2003. 108th United States Congress, 1st Session, 7 January 2003. (National Archives: Washington DC)

US GAO (2007) Wildland management: a cohesive strategy and clear cost-containment goals are needed for Federal Agencies to manage wildland fire activities effectively. Government Accountability Office, Testimony GAO-07-1017T, 19 June 2007. (Washington, DC)

Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7**, 23–34. doi:10.1139/X77-004

Van Wagner CE (1993) Prediction of crown fire behavior in two stands of jack pine. *Canadian Journal of Forest Research* **23**, 442–449. doi:10.1139/X93-062

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834

Wimberly MC, Cochrane MA, Baer A, Pabst K (2009) Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. *Ecological Applications* **19**, 1377–1384. doi:10.1890/08-1685.1