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Examining alternative fuel management strategies and the relative contribution of National Forest System land to wildfire risk to adjacent homes – A pilot assessment on the Sierra National Forest, California, USA

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ABSTRACT

Determining the degree of risk that wildfires pose to homes, where across the landscape the risk originates, and who can best mitigate risk are integral elements of effective co-management of wildfire risk. Developing assessments and tools to help provide this information is a high priority for federal land management agencies such as the US Forest Service (USFS) that have limited resources to invest in hazardous fuel reduction and other mitigation activities. In this manuscript we investigate the degree to which fuel management practices on USFS land can reduce wildfire exposure to human communities. We leverage wildfire simulation with spatial risk analysis techniques and examine a range of hypothetical fuel treatment scenarios on a landscape encompassing the Sierra National Forest in California, USA. Results suggest that treating USFS land does little to reduce overall wildland urban interface (WUI) exposure across the landscape. A treatment scenario that focused on treating defensible space near homes was by far the most efficient at reducing WUI exposure, including exposure transmitted from USFS lands. Findings highlight potential tradeoffs and raise questions as to what other land management objectives fuel treatments on federal lands might be able to more cost-effectively achieve relative to WUI protection. Site-specific risk-based analyses can help elucidate these tradeoffs and opportunities.

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1. Introduction

Managing wildland vegetation and fuels to reduce potential threats to the wildland urban interface (WUI) remains a high priority for the US Forest Service (USFS) and other federal land management agencies in the United States. As a result, landscape assessments and budgetary allocation processes typically have a strong emphasis on WUI risk proximal to USFS land (e.g., Thompson et al., 2015a). However, the question of whether implementing fuel treatments on federal lands to protect the WUI is effective, efficient, or the most appropriate investment of taxpayer dollars remains unanswered (Calkin et al., 2014; Omi, 2015; Reinhardt et al., 2008).

Difficulties in answering this question stem from a limited empirical basis to evaluate fuel treatment effectiveness as well as uncertainty over the relative efficacy of alternative treatment strategies (Collins et al., 2010; Hudak et al., 2011). On some landscapes, where specific conditions align, modeling efforts suggest that strategically locating treatments in the wildlands may be an effective option for interrupting fire spread pathways and mitigating WUI risk (Ager et al., 2010). Other analyses however suggest that a shift in emphasis away from broad-scale fuel treatments to intensive fuel management near homes is a more efficient way to mitigate wildfire impacts to human communities (Gibbons et al., 2012; Price and Bradstock, 2012, 2014; Syphard et al., 2014). Managing fuels directly within the interface, while costly, may require smaller areas of treatment to achieve comparable reductions in risk leading to higher overall cost-effectiveness relative to managing fuels in wildlands (Penman et al., 2014).

In the context of federal land management and the WUI, a requisite first step in mitigation planning is determining the relative contribution of federal lands to WUI risk. Wildfires often start outside of the WUI and can spread far from the ignition location to cause damage to other landowners and homeowners. This phenomenon has been termed “risk transmission,” and spatial fire spread models are increasingly used to characterize risk transmission potential and to identify potential sources of exposure and risk (Ager et al., 2014a, 2014b, 2015; Scott and Thompson, 2015; Scott et al., 2015; Thompson et al., 2015b). Haas et al. (2015), for

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instance, identified areas along the Front Range of Colorado, USA, where ignitions could result in the greatest population impacts, and further partitioned results according to whether ignitions occurred on federal or privately owned land.

While the attribution of potential fire impacts back to ignition locations is intuitive and relatively easy to accomplish for both historical and simulated wildfires, it may present an incomplete picture of risk transmission. Here we expand the transmission concept to consider how landscape-scale vegetation and fuel conditions contribute to fire spread and WUI exposure. Specifically, we focus on quantifying how fuel management practices on federal land could reduce transmission of risk to the WUI. We use stochastic wildfire simulation to characterize the exposure of human communities to wildfire using simulated fire perimeters and ignition locations, and apply these methods on a case study landscape encompassing the Sierra National Forest in California, USA. Related studies using the same simulation approach have been applied to characterize the exposure of human communities, municipal watersheds, and critical wildlife habitat to wildfire (Scott et al., 2012; Thompson et al., 2013a, 2015a, 2015b).

In this study we use simulated perimeters to further explore how WUI exposure levels vary under alternative "fuelscapes", i.e., hypothetically treated landscapes. Our treatment scenarios are based on the "ideal landscape" concept (Finney, 2002, 2006), and range in scope from strictly infeasible – designed to provide a benchmark against which to compare results – to plausibly feasible – grounded in realistic treatment rates and spatially identified treatment constraints (North et al., 2015). Relative to other WUI risk analyses that consider alternative fuelscapes and use spatial fire spread modeling (e.g., Ager et al., 2010), our simulation approach captures a broader range of fire weather conditions under which fuel treatments may be tested by wildfire, and explicitly incorporates the probability of large fire ignition rather than assuming large fire occurrence. We compare simulated exposure levels under current conditions with those from alternative fuelscapes, and attribute exposure according to fires that ignite within and outside of USFS ownership. In the subsequent sections we describe our fire modeling approach and generation of landscape fuel treatment alternatives, present exposure analysis results, and discuss policy and management implications of our findings.

2. Methods

Our modeling approach was built around four main elements, which are described in more detail in subsequent sub-sections. First, we describe how we mapped human communities (i.e., the WUI), which are the ultimate endpoint of our assessment. Stochastic wildfire simulation formed the backbone of our entire analysis, and is presented second. We describe our use of the fire modeling system FSim (Finney et al., 2011) to simulate the occurrence and spread of wildfire. Third, we describe how we generated landscape conditions under current and hypothetical post-treatment scenarios, all of which were used as inputs for simulations with FSim. We compare alternative scenarios in terms of the extent and location of treated areas. Fourth, we describe how we quantified WUI exposure to wildfire under the various treatment scenarios. To begin, we introduce the study area for our analysis.

2.1. Study area

The study area consisted of the Sierra National Forest and surrounding land ownerships, located on the western slope of the southern Sierra Nevada Mountains, California (Fig. 1). The analysis area was a 30-km buffer around the north, west and south sides of the Sierra NF. A buffer was not added to the east because the forest boundary at that location is the Sierra Crest, a high-elevation, sparsely vegetated area that fires do not historically cross from the east to the west. To account for fires that could affect the analysis area from an ignition outside of it, we also identified a fire occurrence area (FOA) and used that to simulate fire starts and summarize historical fire occurrence. The FOA included a 30-km buffer around to the north and south of the analysis area. The FOA did not extend to the west of the analysis area because that is primarily agricultural land with little potential to influence the analysis area.

Vegetation and topography varied widely across the FOA. At the foot of the mountains to the west, elevation is only 100 m above sea level; the vegetation there consists of orchards, row crops and grasslands. The eastern edge of the study area is the Sierra Crest at nearly 4000 m elevation.

2.2. Characterizing the human community

We used the West-wide Wildfire Risk Assessment Where People Live (WPL) raster—representing the density of residential structures (houses per km^2)—to characterize the human community across the study area (Fig. 1). WPL was based on the LandScan population database from the Oakridge National Laboratory. LandScan, and uses advanced modeling approaches to incorporate remotely sensed data such as nighttime lights and high-resolution imagery, along with local spatial data to spatially distribute 2010 U.S. Census population counts within census blocks polygons (Oregon Department of Forestry, 2013). The native WPL raster cell size is 30 m, so each cell covers 900 m^2, or 0.0009 km^2. We multiplied the WPL density value by 0.0009 to estimate the expected number of houses per pixel.

2.3. Wildfire simulations

We used the FSim large-fire simulator (Finney et al., 2011) to simulate 10,000 complete fire seasons. The result was an event set—a set of hundreds of thousands of simulated wildfire perimeters that collectively represent possible outcomes of the 10,000 simulated wildfire seasons; each simulated wildfire in the event set has a known probability of occurrence (Scott and Thompson, 2015). FSim is a comprehensive wildfire occurrence, growth and suppression simulation system that pairs a wildfire growth model (Finney, 1998, 2002) and spatial and temporal models of ignition probability with simulated weather streams in order to simulate wildfire ignition and growth for thousands of fire seasons. FSim's temporal ignition probability model is a logistic regression of historical large-fire occurrence in relation to the historical Energy Release Component (ERC) of the National Fire Danger Rating System for the period 1992–2013. The spatial ignition model is a raster representing the relative density of large-fire ignitions across the landscape.

FSim generates raster values of annual burn probability (*BP*) and conditional flame length probabilities. FSim also generates polygons, in ESRI Shapefile format, representing the final perimeter of each simulated wildfire. An attribute table specifying certain characteristics of each simulated wildfire—its start location and date, duration, final size, and other characteristics—is included with the shapefile.

After calibrating FSim for the current condition (Scott et al., 2015), we then ran FSim on each of the hypothetical fuelscapes (described below). We used the feature of FSim whereby these subsequent simulations on hypothetical fuelscapes use the same simulated fire occurrences (locations, dates, weather conditions, etc.) so that differences among the simulations can be attributed to the factors that changed between simulations rather than to stochasticity (see Thompson et al., 2013b). In this analysis, the only factor that we changed between runs was the fuelscape. More

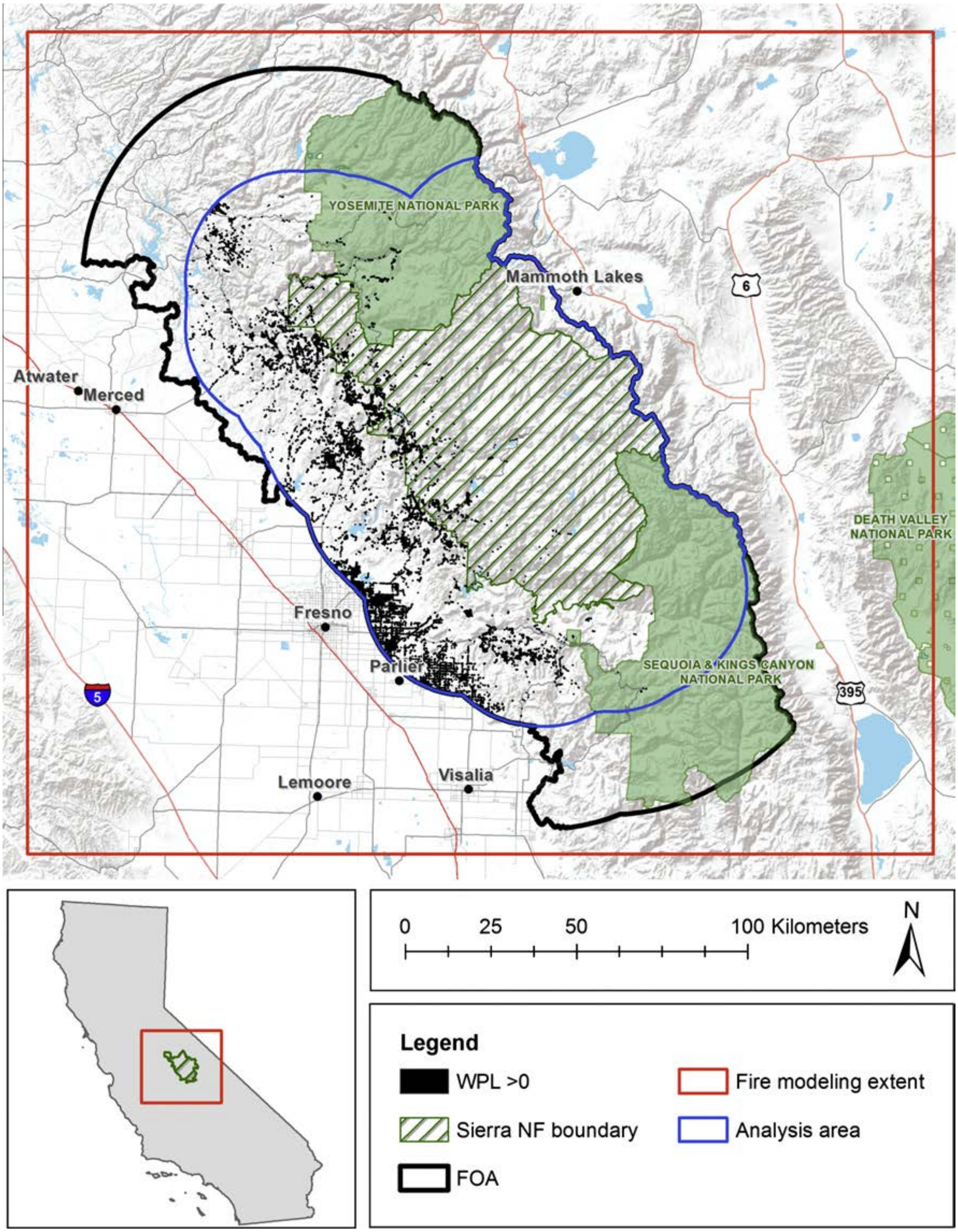

Fig. 1. The analysis area consists of a buffer around the Sierra National Forest. The fire occurrence area (FOA) is the area within which we simulated fire starts. The fire modeling extent includes a buffer around the analysis area so that simulated wildfires could spread without encountering the edge of the spatial data, which would artificially limit the fire's size. WPL = Where People Live (see Section 2.2).

information on FSim model structure and calibration can be found in Finney et al. (2011), Scott et al. (2013), and Thompson et al. (2015a, 2015b).

2.4. Current-condition fuelscape

Among FSim's spatial inputs is the fire modeling landscape file (LCP)—a raster representation of fuel, vegetation and topography across the fire simulation area. We used LANDFIRE version 1.3.0 (also known as "LANDFIRE 2012") as the source for the current-condition LCP (Ryan and Opperman, 2013). LANDFIRE is a vegetation and fuels database that provides consistent, wall-to-wall geospatial data generated for fire and fuels modeling activities. We downloaded the fuel, vegetation and topography rasters, in ESRI grid format, in NAD83 UTM11N geographic projection, for which grid north deviates from true north by only 0.7° to 2.2°

across the FOA. We used a final resolution of 180-m in FSim, so we downloaded the LANDFIRE data in their native 30-m grid cell resolution, resampled to a 180-m cell size using the nearest neighbor method, then assembled a 180-m cell size LCP file from the resampled grids.

Even at its native 30-m cell size, LANDFIRE data to not attempt to characterize homes as a fuel type for use in fire growth simulation. Instead, LANDFIRE fuel data represent the dominant land cover as observed in satellite imagery. Thus, fuel types where homes are located vary considerably across the landscape. In urban areas, homes are mapped as nonburnable land cover. In more remote areas, homes are mapped as whatever the surrounding vegetation suggests, whether grass, shrub or timber fuel types. After resampling to 180-m resolution, which is necessary to avoid undue computation times, the fuelscape raster is too coarse to resolve the actual fuel conditions around individual houses.

2.5. Post-treatment landscape conditions: biophysical suitability and treatment prescriptions

To support the generation of alternative hypothetical fuelscapes (see next section), we first generated a biophysically ideal fuelscape following the “ideal landscape” concept proposed for use in the Treatment Optimization Model of FlamMap (Finney, 2002, 2006). This concept is premised on the idea of identifying fuel conditions everywhere on the landscape where treatments are possible and would lead to meaningful changes in post-treatment fire behavior. This portion of our analysis centered around two main steps: identifying areas that would be biophysically suitable for treatment, and defining prescriptions and post-treatment conditions following basic principles of fuel treatments (Agee and Skinner, 2005).

To generate the biophysically ideal fuelscape, we established simple rules for updating surface and canopy fuel characteristics from the current condition to a condition representing what an ideal treatment could produce. We designed these fuel treatment rules to conform to biophysical limitations on the potential effects of a fuel treatment. For example, we did not consider grass-dominated vegetation types to be biophysically treatable because the post-treatment fuel model tends to be identical to the pre-treatment fuel model after a very short period of time. In addition, we did not consider as biophysically treatable any land identified in the LANDFIRE data as having been already treated or disturbed by wildfire. Areas disturbed by insects or disease were considered treatable.

To begin creation of the ideal fuelscape, we reviewed the characteristics of the Scott and Burgan (2005) standard fire behavior fuel models and the LANDFIRE fuel model mapping ruleset for LANDFIRE mapping zone 6—the dominant mapping zone in the study area. Informed by the LANDFIRE ruleset, we used our own judgement to generate a simple fuel-model crosswalk (Table 1). Canopy fuel characteristics are handled separately from surface fuel model (described below), so simulated fire behavior under the biophysically ideal fuelscape can change considerably from the current condition even if the surface fuel model does not change.

Raising the canopy base height is a primary objective of fuel treatments in conifer forests (Agee and Skinner, 2005). We assumed that any intentional fuel treatment would raise canopy base height to at least 2 m through a combination of thinning, pruning and crown scorch (in a prescribed fire). Our ruleset raised canopy base height to a value 1.5 times the current-condition value, but not less than 2 m. Coupled with a change in fuel model (Table 1), this canopy base height rule nearly eliminates the potential for passive and active crown fire on the ideal fuelscape.

In the portion of the study area considered biophysically treatable, we reduced canopy bulk density to 0.75 of the current-condition value to reflect a desired reduction in canopy fuel as a result of thinning, pruning and mortality from prescribed fire. Canopy height was not changed from the current-condition to the ideal condition on the assumption that thinning would be from below, meaning that the largest trees would be favored for retention.

Table 1
Fuel model crosswalk for identifying the post-treatment fuel model from the current condition fuel model. Only fuel models highlighted in bold changed between the current condition and the hypothetically treated condition.

Current condition Fire behavior fuel model		Treated condition Fire behavior fuel model	
Code	Name	Code	Name
GR1	Short, sparse dry climate grass	GR1	Short, sparse dry climate grass
GR2	Low load, dry climate grass	GR2	Low load, dry climate grass
GS1	Low load, dry climate grass–shrub	GS1	Low load, dry climate grass–shrub
GS2	**Moderate load, dry climate grass–shrub**	**GS1**	**Low load, dry climate grass–shrub**
SH1	Low load dry climate shrub	SH1	Low load dry climate shrub
SH2	**Moderate load dry climate shrub**	**SH1**	**Low load dry climate shrub**
SH4	**Low load, humid climate timber–shrub**	**GS2**	**Moderate load, dry climate grass–shrub**
SH5	**High load, dry climate shrub**	**GS2**	**Moderate load, dry climate grass–shrub**
SH7	**Very high load, dry climate shrub**	**SH2**	**Moderate load dry climate shrub**
TU1	Low load dry climate timber–grass–shrub	TU1	Low load dry climate timber–grass–shrub
TU2	**Moderate load, humid climate timber–shrub**	**TU1**	Low load dry climate timber–grass–shrub
TU5	**Very high load, dry climate timber–shrub**	**TU2**	**Moderate load, humid climate timber–shrub**
TL2	Low load broadleaf litter	TL2	Low load broadleaf litter
TL3	**Moderate load conifer litter**	**TL2**	**Low load broadleaf litter**
TL4	**Small downed logs**	**TL3**	**Moderate load conifer litter**
TL5	**High load conifer litter**	**TL4**	**Small downed logs**
TL6	**Moderate load broadleaf litter**	**TL5**	**High load conifer litter**
TL7	**Large downed logs**	**TL4**	**Small downed logs**
TL8	**Long-needle litter**	**TL5**	**High load conifer litter**
TL9	**Very high load broadleaf litter**	**TL8**	**Long-needle litter**

Canopy cover affects the wind reduction capability of the forest canopy. Lower canopy cover values result in higher mid-flame wind speeds, therefore higher spread rate and intensity. From this standpoint alone, a fuel treatment should not strive to reduce canopy cover. However, in order to mitigate potential for active crown fire, a fuel treatment should reduce canopy bulk density, and any fuel treatment that reduces canopy bulk density can result in lower canopy cover. Rather than set a strict post-treatment target for canopy cover, we instead applied mild reductions where the current condition canopy cover is already moderate, and moderate reductions where the current-condition canopy cover is high (Table 2), which is generally consistent with the canopy bulk density reduction described above.

This biophysically ideal fuelscape is indifferent about the specific mechanism of fuel treatment—prescribed fire, mechanical, etc.—but instead focuses on the biophysically achievable outcome of an appropriate treatment for the biophysical setting. We applied the rules described above to all lands in the study area to generate a biophysically ideal fuelscape. We then used that ideal fuelscape and the current-condition fuelscape, along with other information, to generate hypothetical fuelscapes as described below.

2.6. Post-treatment landscape scenarios: treatment extent and placement

Based in part on this biophysically ideal fuelscape, we generated a set of hypothetical fuelscapes representing alternative fuel

Table 2
Canopy cover crosswalk for identifying the post-treatment condition from the current condition. Only canopy cover values highlighted in bold changed between the current condition and the hypothetically treated condition.

Current condition canopy cover (%)	Treated condition canopy cover (%)
0	0
15	15
25	25
35	35
45	**40**
55	**45**
65	**50**
75	**55**
85	**65**
95	**75**

conditions across the study area. We summarized house exposure only within the analysis area (see Section 2.7), but, in order to avoid edge effects, we applied the hypothetical treatments across the entire fire modeling landscape. Some of these hypothetical fuelscapes are not realistic or achievable in their intensity or extent. They are nonetheless included to provide a baseline for comparing the effects of the achievable fuelscapes to the current condition.

2.6.1. Non-burnable National Forest

For this hypothetical fuelscape we simply set all land in USFS ownership in the fire modeling landscape (according to the Automated Lands Program, Basic Ownership dataset for USDA Forest Service lands (USDA, 2015)) to a non-burnable fuel model. As such, no fires could originate on USFS land, and no fire originating outside of USFS land could spread through USFS land. In wildfire simulation modeling, embers could still, in theory, travel across the nonburnable USFS land and ignite adjacent fuel. This is not meant to be thought of as a realistic fuelscape, but captures the lack of transmission potential from USFS land. This fuelscape is designed to serve as a benchmark to find the absolute greatest effect on homes exposed that could arise from "treating" all USFS land.

2.6.2. Biophysical Optimum and Constrained Biophysical Optimum

For the Biophysical Optimum hypothetical fuelscape we set all treatable USFS land within the fire modeling landscape to its biophysically ideal condition, but left all other land ownerships in their current condition. The Constrained Biophysical Optimum hypothetical fuelscape is similar to the Biophysical Optimum fuelscape, but we limited the application of the biophysically ideal condition to the most "operable" land as defined by North et al. (2015). According to North et al. (2015), after first accounting for biological (forested or non-forested land, etc.) and legal constraints on roadless and wilderness lands, a set of four alternative operational/administrative scenarios were developed with consideration of factors like slope, distance from existing road, and commercial value of the forest. The first scenario (Scenario A) constrained mechanical treatments to the greatest degree, closely following current standards restricting mechanical treatments to slopes <35% and within 305 m (1000 ft) of existing roads (North et al., 2015). Scenario B allows greater access, with road building up to 610 m (2000 ft) to reach more valuable timber, offsetting the additional expenses. Scenario C is slightly less constrained with access to timber on slopes of 50% or less and within 152 m (500 ft) of a road to reach timber of higher value. Finally, we selected Scenario D, which describes the loosest constraints on mechanical treatments, allowing access to all timber, regardless of value within 610 m (2000 ft) of existing roads and slopes <35% and all forest within 305 m (1000 ft) of existing roads on slopes of 50% or less (North et al., 2015).

2.6.3. The Five-percent Solution

Not all of the land in the Constrained Biophysical Optimum fuelscape could be treated in a reasonable length of time. The Five-percent Solution fuelscape is similar to the Constrained Biophysical Optimum fuelscape, but is limited to a treated land area equal to five percent of the total USFS land base in the fire modeling landscape. In the Five-percent Solution fuelscape, we selected for treatment the pixels treated in the Constrained Biophysical Optimum alternative that were closest in distance to non-zero WPL pixels (i.e., pixels with homes).

2.6.4. Defensible Space

In all of the previous fuelscapes, all treated pixels occurred on USFS ownership; the Defensible Space fuelscape is the only one that alters fuels beyond USFS ownership. Our objective for the Defensible Space fuelscape was to treat as many biophysically treatable WPL pixels as possible, up to the total extent treated in the Five-percent Solution fuelscape, with a priority of treating pixels on or close to the USFS ownership. To accomplish this, we selected for treatment pixels that were biophysically treatable and located where the WPL raster indicated that houses existed on or within 2160 m (12 pixels) of the USFS boundary. A buffer distance of even one more 180-m pixel would result in treating more land area than the Five-percent Solution fuelscape, so we opted for this slightly less extensive design.

2.6.5. Comparing fuel treatment scenarios

Fig. 2 illustrates the location of all treatments in each of the fuel treatment scenarios. The four treatment scenarios that entail treating only USFS land spatially overlap with the relationship Non-burnable National Forest > Biophysical Optimum > Constrained Biophysical Optimum > Five-percent Solution. Table 3 summarizes the spatial extent of the five hypothetical treatment scenarios, and identifies whether the operability constraints of North et al. (2015) were included. The Non-burnable National Forest fuelscape resulted in 592,233 ha treated, or 42% of the burnable fuelscape in the analysis area. The Biophysical Optimum fuelscape was similar to the Non-burnable National Forest fuelscape, and resulted in 528,972 ha treated, or 37% of the land area in the analysis area. Thus only a small portion (5%) of the current conditions on the Sierra National Forest is in its biophysically ideal condition. The Constrained Biophysical Optimum fuelscape resulted in 134,865 ha treated, representing 9% of the analysis area, and the Five-percent Solution fuelscape amounted to 39,136 ha treated, representing 3% of the analysis area. Lastly, the Defensible Space fuelscape treated 31,075 ha (2% of the analysis area) 24,086 ha of which was outside of USFS lands.

2.7. Exposure analysis

From the simulation results for each fuelscape we calculated the mean annual number of homes exposed to wildfire. First we summed the WPL raster values (number of homes) that fell within each perimeter and then associated that sum—the number of homes exposed to that particular fire—with the location of the ignition location. Dividing by the total number of simulated fire seasons yielded the mean annual exposure level. The final exposure values calculated this way will be nearly identical to the expected annual number of homes exposed to wildfire calculated as the sum-product of the number of houses and *BP* across all pixels in the FOA (see Thompson et al., 2013a); the small differences are due to how perimeter polygons and raster burn probabilities are spatially resolved.[1] Analyzing the perimeters is a more computationally intensive process, but as described above allows us to link each individual fire to its ignition location and other characteristics.

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[1] In fact we performed calculations both ways and verified that results are quite similar; we only present results from the perimeter analysis for economy of presentation.

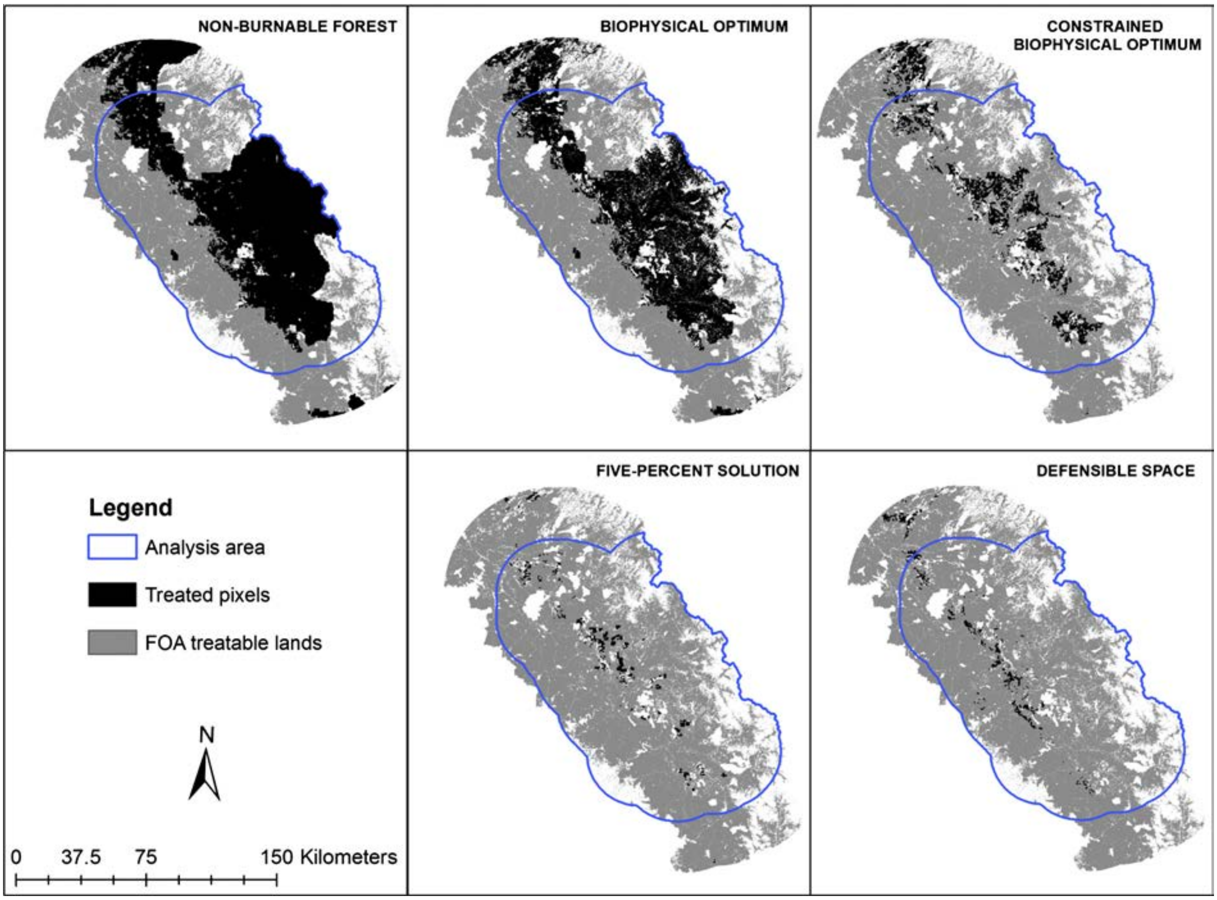

Fig. 2. Treatment masks showing the locations of each of the five hypothetical treatment scenario implementations. The Non-burnable Forest, Biophysical Optimum, Constrained Biophysical Optimum, and Five-percent Solution treat locations within USFS lands only (all of which are treated in the NF scenario, and subsequent fuelscapes treat smaller amounts). The Defensible Space treatment scenario includes treatments both within and outside of USFS lands. Treatments outside of the analysis area are modeled to avoid artificial edge effects.

Table 3
Summary of land area treated (ha) for each hypothetical fuelscape. Operability constraint is based on North et al. (2015).

Scenario	Hectares treated			Operability constraint?
	USFS	Other	% of analysis area (burnable only)	
Non-burnable National Forest	592,233	0	42%	No
Biophysical Optimum	528,972	0	37%	No
Constrained Biophysical Optimum	134,865	0	9%	Yes
Five-percent Solution	39,136	0	3%	Yes
Defensible Space	6989	24,086	2%	No

Using the perimeters we calculated a landscape measure of exposure source—the percentage of total exposure originating within Forest Service ownership.

3. Results

3.1. Summary

Results suggest that treating USFS land can significantly reduce the USFS land as a *source* of damaging fires while doing relatively little to reduce overall WUI exposure across the landscape. Fires that started on USFS lands comprised a relatively small share of overall transmitted exposure to the WUI. Key findings include: (1) the Non-burnable National Forest fuelscape minimized overall home exposure; (2) the Biophysical Optimum fuelscape minimized home exposure associated with fires that started on USFS lands; (3) the Five-percent Solution and Defensible Space fuelscapes were most efficient at reducing area burned and home exposure, respectively; and (4) the Defensible Space fuelscape was by far the most efficient at reducing home exposure. The percentage of WUI exposure from fires starting on USFS land ranged from 0.00% (Non-burnable National Forest fuelscape) to 16.20% (Current Condition fuelscape). In terms of feasible treatment scenarios, treating USFS land near where people live (Five-percent Solution) was not nearly as effective as treating the same amount of area where people live with a focus on land closest to the national forest (Defensible Space). Interestingly, the Defensible Space fuelscape even outperformed the Five-percent Solution fuelscape in terms of reducing the USFS land as a source of exposure to homes. These results are at least partially explained by the alignment of topography and predominant wind direction to promote spread fire away from rather than towards the WUI. It might also be the case that the Defensible

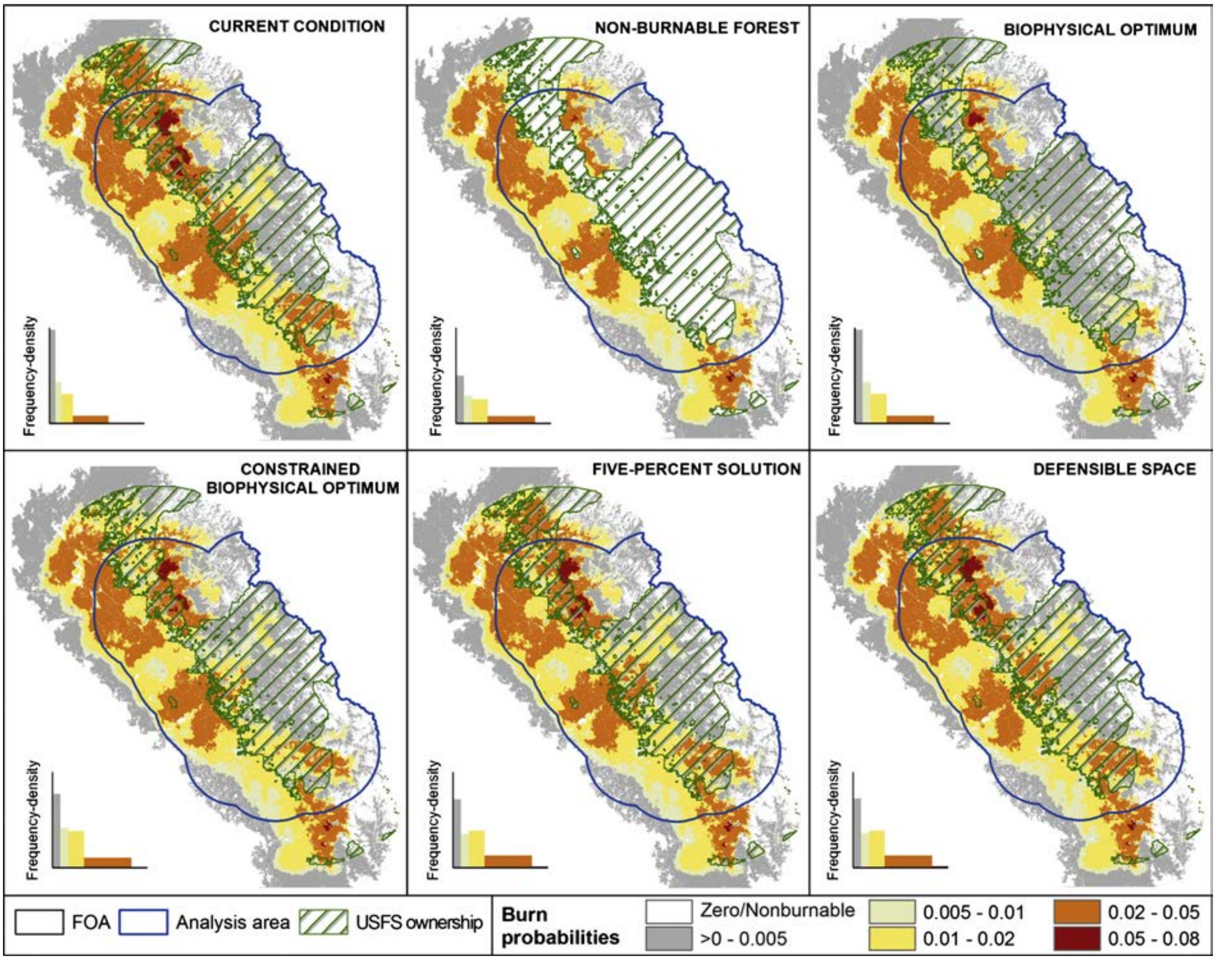

Fig. 3. Simulated annual burn probability (*BP*) for the current condition and five hypothetical fuelscapes. The inset frequency-density histograms show the width of each class as well as the frequency of observations per unit class width. The area of each bar in the histogram is proportional to the number of pixels in the class.

Space treatment scenario left less gaps for fires to spread around and through into the WUI.

3.2. Wildfire simulations

Fig. 3 displays simulated *BP* values among the current condition and the five hypothetical fuelscapes. At a whole-landscape scale, it is difficult to discern differences in *BP* among the hypothetical fuelscapes. The Non-burnable National Forest fuelscape, which made all USFS land in the FOA nonburnable, shows the greatest change from the initial condition—all USFS land is now zero *BP*. The greatest changes in *BP* values generally occur within rather than outside of USFS land.

Although the differences in simulation results are subtle when displayed on a map, they become much more apparent in tabular form (Table 4). The Non-burnable National Forest fuelscape reduced mean annual area burned within the analysis area by 51%. In contrast, the Biophysical Optimum fuelscape, which treats almost as much area, but to within biophysical limitations instead of to outright non-burnability, reduced mean annual area burned by 36%, which is more than 70% of the Non-burnable National Forest effect. Adding the operability constraint in the Constrained Biophysical Optimum alternative resulted in an overall reduction in area burned of just 16% compared to the current condition. The Five-percent Solution alternative, which treats a reasonable fraction of the landscape, results in a 7% reduction in annual area burned. Finally, the Defensible Space fuelscape, despite treating a similar area to the Five-percent Solution fuelscape, results in only a 5% reduction in area burned.

As a measure of treatment efficiency at reducing area burned, we calculated the reduction in mean annual area burned as a fraction of the total land area treated for each fuelscape (Table 4). The least efficient was the Biophysical Optimum fuelscape, which treated all possible treatable land on USFS ownership. By contrast, the Non-burnable National Forest fuelscape, which treated more acres to a nonburnable condition, was more efficient per unit area treated. Somewhat surprisingly, the Five-percent Solution fuelscape was the most efficient, followed by the Defensible Space fuelscape. These two fuelscapes seem to have treated the land most amenable to a reduction in *BP*; this result could also reflect diminishing marginal returns associated with larger treatment extents.

The values in Table 4 (and Fig. 3) are annualized, i.e., they represent a single fire season. These fuel treatments would have an effective duration of more than one year, so the absolute ratio of burned-area avoided to acres treated could be much larger than those listed in Table 4. Nonetheless, these values provide a useful measure of the relative efficiency of each fuelscape at reducing area burned.

3.3. Exposure analysis

While informative, area burned reductions presented in Table 4 are insufficient to describe treatment effects on mitigating the exposure of homes to wildfire. Table 5 instead summarizes how

Table 4
Summary of mean annual area burned within the analysis area for the current condition and for each hypothetical fuelscape.

Scenario	Mean annual area burned (ha)	Absolute reduction in mean annual area burned from CC (ha)	Percentage reduction in mean annual area burned from CC (%)	Reduction in mean annual area burned from CC per hectare treated
Current Condition (CC)	22,357	–		
Non-burnable National Forest	11,265	11,092	50	0.019
Biophysical Optimum	14,618	7739	35	0.015
Constrained Biophysical Optimum	18,857	3500	16	0.026
Five-percent Solution	20,828	1530	7	0.039
Defensible Space	21,291	1066	5	0.034

Table 5
Summary of mean annual homes exposed to wildfire for the current condition and for five hypothetical fuelscapes. CC = current condition.

Scenario	From fires starting on any land ownership		From fires starting on USFS land ownership	
	Annual homes exposed	% reduction from CC	Annual homes exposed	% reduction from CC
Current Condition (CC)	531	–	86	–
Non-burnable National Forest	404	24%	0	100%
Biophysical Optimum	458	14%	35	60%
Constrained Biophysical Optimum	500	6%	66	23%
Five-percent Solution	503	5%	68	21%
Defensible Space	437	18%	51	41%

the treatment scenarios reduce home exposure. In the current condition, we estimated a mean annual exposure of 531 homes per year, of which 86 were exposed to fires that originated on USFS land. The Non-burnable National Forest fuelscape reduced the overall exposure-source by 24% to 404 homes per year, and the exposure-source from USFS-originating fires to 0, because no fires could originate on USFS land with this fuelscape. The Biophysical Optimum fuelscape reduced the overall exposure-source to 458, a 14% reduction from the current condition, and reduced the exposure-source from fires starting on USFS land by 60% to 35 homes per year. The Constrained Biophysical Optimum fuelscape reduced the overall exposure-source to 500 homes per year, a reduction of just 6% from the initial condition. However, the exposure of homes to USFS-originating fires was reduced by 23% to 66 homes per year. The Five-percent Solution fuelscape reduced the overall exposure-source to 503 homes per year, almost identical to the Constrained Biophysical Optimum fuelscape that treated more than three times as many acres. The exposure of USFS-originating fires was reduced 21% over the current condition to 68 homes per year, again almost identical to the Constrained Biophysical Optimum fuelscape. Finally, the Defensible Space fuelscape reduced the overall exposure-source by 18%, which is even better than the 14% reduction for the Biophysical Optimum fuelscape that treated more than 10 times as much land area. However, as measured by USFS-originating fires, exposure was reduced by 41% to 51 homes per year.

Finally, as a measure of fuelscape efficiency at reducing home exposure to wildfire, we calculated the reduction in annual home exposure per 10,000 ha of fuel treatment (Table 6). The relative differences across fuelscapes and diminishing returns with large treatment extents are even starker in these terms, highlighting the Five-percent Solution and Defensible Space scenarios in particular as more efficient. These results are similar to Table 4, but whereas the Five-percent Solution scenario was more efficient in terms of reducing area burned, the Defensible space scenario was more efficient in terms of reducing home exposure.

4. Discussion

We used landscape-scale wildfire simulation and generated a range of fuelscape scenarios to explore the degree to which fuel treatments within or adjacent to USFS lands could reduce home exposure to wildfire. The fuelscape scenarios are not intended to be reflective of current policy or management priorities on the Sierra National Forest, but rather to help compare a range of treatment extents and locations. Results are specific to the analysis area and the spatial configuration of landscape conditions, WPL, and land ownership, and thus may not apply broadly. Results are also subject to uncertainties, assumptions, and limitations of contemporary fire modeling systems, which may not fully capture or accurately reflect fuel treatment and fire behavior dynamics (Finney et al., 2012; Omi, 2015). That is to say, simulation results do not equal reality. Nonetheless, the analysis suggests that mitigation of wildfire risk to homes through fuel treatment on some landscapes could be best accomplished by treating where the homes are, not on federal land further away. This finding cements the importance of landscape-scale assessment and evaluation of exposure and risk transmission as prerequisites for design of fuel treatment strategies to protect the WUI.

Our findings shed light on potential tradeoffs and raise questions as to what other land management objectives fuel treatments might be able to more cost-effectively achieve (Reinhardt et al., 2008). Where supported by similar analytical approaches, federal land management agencies may instead emphasize the protection, enhancement, or restoration of the resources and assets on the land it manages. Beyond addressing threat to the WUI, exposure and risk analyses can address a wide range of highly valued resources and assets including critical habitat, vegetation condition, and watershed health, and can further examine post-fire hazards such as debris flows (Ager et al., 2007; Scott et al., 2014; Thompson et al., 2013c, 2013d; Tillery et al., 2014).

Our findings also shed light on co-management of risk and how roles, responsibilities, and opportunities for efficient mitigation vary across homeowners and land management agencies (Calkin et al., 2014). Identifying where the scope of federal investments in WUI risk mitigation is limited may help identify opportunities for greater investments in community wildfire planning and engagement of state and private landowners. Again, these findings are not universal, and in some circumstances landscape conditions may align such that wildland fuel treatments can still protect the WUI while achieving other land management objectives (Ager et al., 2010). Site-specific risk-based analyses can help elucidate these tradeoffs and opportunities.

Future research could address some of the current work's limitations and extend the analysis. Two immediate next steps are to

Table 6
Reduction in annual number of homes exposure to wildfire per 10,000 ha of fuel treatment.

Scenario	From fires starting on any land ownership	From fires starting on USFS land ownership
	Reduction in annual number of homes exposed per 10,000 ha of fuel treatment	
Non-burnable National Forest	2.1	1.5
Biophysical Optimum	1.4	1.0
Constrained Biophysical Optimum	2.3	1.5
Five-percent Solution	7.2	4.6
Defensible Space	30.4	11.4

integrate treatment economics to more directly address the cost-effectiveness of alternative fuelscape scenarios, and to examine more concrete spatial treatment strategies with an eye on project-level implementation. As alluded to above, fuel treatment design and analysis could explore fire impacts to a broader set of resources and assets. Lastly, analysis efforts could also explore how past, current, and future fire management will influence landscape conditions and risk transmission potential (Calkin et al., 2015).

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