Final Report:
Can landscape fuel treatments enhance both protection and resource management objectives?

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Abstract

Actively treating fuels with prescribed fire or non-fire techniques is infeasible for a substantial portion of federal lands, and there is a need for increased use of wildland fires from unplanned ignitions to help manage fuels. The challenge is how to integrate active fuel management with the opportunistic use of wildland fire into an effective landscape-scale fuel treatment strategy that keeps people, property, and infrastructure safe and ecosystems healthy. This project aimed to improve our understanding of how fuels management can be designed at landscape scales to enhance both protection and resource management objectives.

Advances in fire modeling help quantify and map various components and characterizations of wildfire risk, and furthermore help evaluate the ability of fuel treatments to mitigate risk. However, a need remains for guidance in designing landscape-scale fuel treatments with protection objectives, resource management objectives, and wildfire response in mind. We build on these themes to illustrate an approach for examining whether, and how, fuels management can simultaneously minimize housing exposure while maximizing areas suitable for expansion of beneficial wildfire. We compare multiple hypothetical post-treatment conditions generated according to distinct treatment prioritization schemes (Housing Protection, Federal Risk Transmission, Random) and variable treatment extents, and illustrate how strategies compare. We used stochastic wildfire simulation and computations of exposure to wildfire to compare strategy performance across two very large (~2Mha) landscapes – the southern Sierra in California and northern New Mexico.

In general, we found that treating near housing units can provide the greatest level of protection relative to treating more remote wildlands to reduce transmission potential. Treating on federal lands to reduce federal transmission was highly effective at reducing exposure from federal fires and at expanding opportunities for beneficial fire but contributed comparatively little to reducing housing exposure from all fires. We find that treatment extents as low as 2.5-5% can yield significant benefits with spatially optimized strategies, whereas the random strategy didn't perform comparably until reaching 25% treatment extent. These general patterns held across two

landscapes with very different patterns of ownership, housing density, fire potential, and optimized treatment strategies. Treating to protect housing and expand managed fire opportunity are complementary, but not identical strategies, and there may be additional opportunities to enhance the latter by embedding treatment design more closely with operational response planning.

This work provides a contribution in terms of explicitly framing risk analysis and fuel treatment design around federal land and resource management objectives and adds to the knowledge necessary for designing effective landscape fuel treatment strategies that can protect communities and foster more beneficial wildfire on a fire-prone landscape. Successful operationalization of these themes requires embracing all pillars of the National Cohesive Wildland Fire Management Strategy, including coordinated management of fuels on various ownerships, home ignition zone mitigation, and cross-boundary fire response planning that can guide fire operations in reducing transmission and expand the decision space for response strategies. We were successful in leveraging recent advancements in spatial wildfire risk assessment to improve the state of knowledge about the source of exposure and risk to human communities, and to examine whether, and how, fuels management can foster more beneficial wildfire on a fire-prone landscape.

Objectives

Our goal was to investigate and evaluate landscape fuel treatment designs for their ability to enhance both protection and resource management objectives and determine if these two separate objectives could be achieved simultaneously. To accomplish this, we used advanced wildfire simulation— specifically the large fire simulator, FSim (Finney et al. 2011b)—and a risk analysis framework to evaluate a set of landscape fuel treatment designs that vary in the total area treated and in spatial distribution and arrangement of treatments.

Specific objectives were:

1. Develop an approach for evaluating landscape fuel treatment designs for their ability to decrease the exposure of houses to wildfire, and their ability to increase opportunities to use managed fire. We then used this approach to determine whether landscape fuel treatments can be designed to simultaneously meet protection objectives and resource management objectives.
2. Compare treatment intensities (i.e., total area treated) and spatial distributions of fuels treatments in terms of their ability to reduce home exposure and increase opportunities to use wildfire. In doing so, we determined if treatments are more effective when focused near homes or distributed strategically across the landscape.
3. Evaluate how the effectiveness of different landscape fuel treatment designs varies with proximity to homes, ownerships, fire potential, and treatment opportunities on two different study area landscapes. We compare these study areas according to a common set of performance measures.
4. Develop and use a metric based on the analysis of source-exposure that quantifies the opportunity to use wildfire. Specifically, we calculated an upper bound on area of opportunity for managing wildfire for benefits, based on spatial analysis of ignition locations of simulated perimeters that did not result in any housing exposure.

In accomplishing our objectives, we directly addressed the task statement FA-FON0017-0001 *Landscape fuel treatment strategies and wildfire management*. Our findings will inform the planning and implementation of landscape fuel treatment strategies that allow for safe and effective management of wildfire to meet protection and resource management objectives. Objective 1—to determine whether landscape fuel treatments can be designed to simultaneously meet protection and resource management objectives—directly supports the vision of the National Cohesive Strategy, a vision where fire is accepted as a natural and necessary process while conflicts between fire-prone landscapes and people are reduced. Objective 2—to compare treatment intensities and different spatial distributions of fuels treatments—met a specific research need articulated in the task statement: "to identify characteristics of effective landscape fuel treatment strategies." Objective 3—evaluate the effectiveness of landscape fuel treatment designs—met the specific research need from the task statement: "to evaluate how effectiveness is constrained by social and ecological factors." Finally, the task statement sought projects that would consider "the interaction between landscape fuel treatment strategies and subsequent wildfire management actions." Objective 4 allowed us to do exactly that, by developing a metric that describes the effectiveness of fuel treatment designs in terms of the area where a strategy of managed wildfire can be employed.

Background

Wildfires are a major concern across the globe as they threaten and cause damage to human communities. At the same time, there is recognition that fire is an inevitable and necessary natural change agent in fire-prone ecosystems, and evidence suggests fire can confer resilience and ecosystem benefits (Hagmann et al., 2021; Johnston et al., 2021; Stephens et al., 2021). In the United States, federal policy promotes actively managing the landscape with fuel treatments to protect human populations and infrastructure while acknowledging the important role that wildland fire can play to maintain natural ecosystems; operationalizing strategies to navigate these tensions has proven challenging (Schultz et al., 2019). Because actively treating fuels with prescribed fire or non-fire techniques is infeasible for a substantial portion of federal lands, many have argued for increased use of wildland fires from unplanned ignitions to help manage fuels (Miller, 2003; North et al., 2015a; Schoennagel et al., 2017) and there is some evidence of a shift in fire management response away from full suppression (Young et al., 2020). The notion that wildland fire can be an effective fuel treatment, particularly in dry conifer forests, is supported by several studies (Collins et al., 2009; Teske et al., 2012; Parks et al., 2015; Prichard et al., 2021), and paradigms are being proposed to increase managed fire and modify fuel treatment strategies to optimize for future fire (Ingalsbee, 2017; North et al., 2021). The challenge is how to integrate active fuel management with the opportunistic use of wildland fire into an effective landscape-scale fuel treatment strategy that keeps people, property, and infrastructure safe and ecosystems healthy.

Advances in fire simulation (Finney, 2002; Sullivan, 2009; Finney et al., 2011), have created a capacity to quantify and spatially map various components and characterizations of risk (Haas et al., 2013; Scott et al., 2013; Parisien et al., 2019; McEvoy et al., 2021), information which in turn can inform fire and fuels management planning. Typically, the procedure is to simulate the spread and intensity of many individual wildfires across a landscape and use the simulated fire information to compute metrics describing the likelihood, intensity, and effects of fire (Thompson et al., 2015). When simulation outputs are overlaid on maps of houses and other highly valued resources or assets (HVRAs), estimates of in situ-risk, which is the expected net value change (either positive or negative) to HVRAs on-site, can be computed and mapped. These procedures also allow for the characterization of risk transmission in terms of where the risk originates on the landscape (Ager et al., 2012b; Ager et al., 2017a). For example, Scott et al. (2012) evaluated the likelihood that fires starting on Forest Service land will reach community protection zones, Barnett et al. (2016) explored the potential for unplanned ignitions inside of wilderness boundaries to spread outside the wilderness boundary, and Alcasena et al. (2017) explored risk transmission and the scale of community firesheds in Spain. So-called source-risk, the risk that gets transmitted off-site when a fire ignites in one location and subsequently spreads to another location, is especially important to understand as unplanned ignitions are managed for longer durations across larger landscapes.

Quantitative estimates of risk have informed fuels management planning. The risk analysis framework has been used to evaluate and assess the ability of fuel treatments to mitigate risk to different values or resources of concern (e.g., Ager et al., 2010; Salis et al., 2016). By appropriately modifying the spatial fuel data that a fire simulator uses, alternative landscape fuel treatment configurations – so-called "fuelscapes" – can be evaluated and different prioritization schemes can be compared to determine where it is best or most cost-effective to locate fuel treatments (e.g., Barros et al., 2019; Kreitler et al., 2019). Some studies have quantified the advantages of mitigating the source-risk, in particular the risk that is transmitted from federal lands (Ager et al., 2019). For example, when fuel treatments are located across a landscape such that they interrupt pathways of fire spread, they can reduce burn probability and intensity (Finney, 2007; Ager et al., 2010), and in some cases enhance suppression capabilities (Moghaddas and Craggs, 2007). Other studies suggest that it is more effective to focus on mitigating the in situ-risk by locating fuel treatments close to the values of concern that need protection (Penman et al., 2015; Scott et al., 2016; Florec et al., 2019). However, the exposure and potential loss of a highly valued resource or asset to wildfire may depend on the clustering or dispersion of the HVRAs (Muller and Yin, 2010; Syphard et al., 2012; Ager et al., 2013; Alexandre et al., 2015; Evers et al., 2019). Consequently, the optimal strategy for the protection of HVRAs may depend as heavily on the spatial arrangement of HVRAs as on factors affecting fire occurrence and spread.

Risk analysis has also been used to inform planning that supports operational fire management decisions (O'Connor et al., 2016; O'Connor et al., 2017; Schultz et al., 2019; Greiner et al., 2020; Calkin et al., 2021). Quantitative estimates of the potential fire-related losses and benefits to HVRAs can be used to spatially classify the landscape into wildfire response zones. For example, Thompson et al. (2016a) presented an approach for determining wildfire response zones based on quantitative estimates of in situ- and source-risks. Where the in situ-risk and source-risk are both a net loss, aggressive suppression may be very appropriate and necessary, but where the in situ- and source-risk are both a net benefit, the most appropriate response may be to manage fire to meet resource objectives. Where in situ- and source-risk are mixed in terms of net loss or benefit, it is less clear cut on how best to approach fuel management and respond to wildfires. Such risk-based response zones have been combined with information on landscape features and locations likely to serve as fire control lines to create pre-determined zones known as PODs (Thompson et al., 2016a; Dunn et al., 2017; Dunn et al., 2020; Stratton, 2020; Thompson et al., 2020), which in practice have been used to support incident response decisions including management of fire to meet resource objectives (O'Connor and Calkin, 2019; Caggiano et al., 2020). PODs and their component potential control locations have also been used to design and evaluate fuel treatment strategies (Thompson et al., 2017; Hogland et al., 2021), and with the passage of the Infrastructure Investment and Job Act in the US will serve as the basis for the design of strategic fuel break networks (see H.R. 3684 §40803).

Despite the recent progress represented by these examples, a need remains for guidance for designing and prospectively evaluating landscape-scale fuel treatments with protection objectives, resource management objectives, and wildfire response in mind. We build on these themes to illustrate an approach for examining whether, and how, fuels management can foster the expansion of beneficial wildfire. In other words, an analytical approach is needed to help answer: Can landscape fuel treatments be designed to enhance both protection and resource management objectives?

To address this question, we designed a set of landscape-scale fuel treatment strategies that vary systematically in total area treated and in the spatial distribution and arrangement of treatments. We used wildfire simulation and a risk analysis framework to evaluate these treatment designs for their ability to enhance both protection and resource management objectives. In a separate deliverable, we illustrate how quantitative risk assessment results and estimates of net value change can help guide the development of optimal fuel treatment projects to optimize for protection and resource objectives. For the bulk of this report, we deemphasize fire effects and focus instead on two salient aspects of risk – exposure and transmission – recognizing their influence on wildfire response decision making as well as current policy and strategic prioritization initiatives.

To operationalize this prioritization framework, we consider two objectives: minimizing housing exposure and maximizing area suitable for expansion of beneficial wildfire. We ran the simulations on two different landscapes in California and New Mexico and compare/contrast the results. In the remainder of this report, we describe our modeling approach, present salient results, discuss novel insights and relations to existing literature, and offer suggestions for how future work could better integrate with wildfire response planning.

Materials and Methods

Study Design

We utilized a simulation modeling approach where the FSim large-fire simulator (Finney et al., 2011) was calibrated to current fuel and weather conditions and replayed with multiple hypothetical post-treatment conditions generated according to distinct treatment prioritization schemes and variable treatment extents. Our modeling approach was built around five main elements which are described in more detail in the following sub-sections. First, we calibrated FSim to current conditions to develop base model parameters and measures of contemporary wildfire likelihood. Next, we developed estimates of wildfire intensity and rate of spread utilizing deterministic simulation modeling. Third, we mapped both current housing exposure and areas that transmit fire from federal lands onto private land where they subsequently expose homes. Fourth, we developed priority landscapes to either reduce home exposure or reduce risk transmission from federal lands. Stand level treatments were selected by their relative ability to meet objective values and each of the developed fuelscapes was replayed with the FSim large-fire simulator. Finally, we analyzed the simulations to quantify the treatment effect on both reducing home exposure and increasing opportunities for managed fire, including various approaches to quantify risk tolerance for home exposure levels.

Study Areas

We conducted our simulations and analyses for two distinct study areas. The first was in north-central New Mexico (8,500,000 ha). The area was selected because it contains a complex mix of ownerships, vegetation, and fire regimes, including substantial wildland-urban interface (WUI), juxtaposed with wildland areas (Figure 1). Approximately 3.45 million hectares or 40% of the study area are in Federal ownership. This includes lands managed by the Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, and the USDA Forest Service. Elevations vary greatly across the analysis area from 1280m southeast of Las Vegas New Mexico to 4260m in the Culebra Range of the Sangre de Christo mountains. Vegetation predominantly follows elevation bands with grasslands and pinjon-juniper woodlands at lower elevations transitioning into Ponderosa Pine and wet mixed conifer forests at higher elevations. The primary fire management objectives for the region include a mix of resource and asset protection and resource management. Information on contemporary landscape conditions as well as fuels management and incident response concerns can be found in recent reports by Day et al. (2021) and Caggiano et al. (2020).

The second study area was in the central Sierra Mountain Range within California (11,443,954 ha). The area was selected because it also contains a complex mix of ownerships, vegetation, and fire regimes, including substantial wildland-urban interface (WUI), juxtaposed with wildland areas (Figure 2). Approximately 7.03 million hectares or 61% of the study area are in Federal ownership. This includes lands managed by the Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, and the USDA Forest Service. Elevations vary greatly across the analysis area from sea level west of Lodi California to 4421m on top of Mount Whitney in the Siera mountain range. Vegetation predominantly follows elevation bands with grasslands and pinjon-juniper woodlands at lower elevations transitioning into Ponderosa Pine and wet mixed conifer forests at higher elevations. The area has been the subject of related fire simulation, fuel treatment, and response planning work; see (Scott et al. 2016; Thompson et al. 2016).

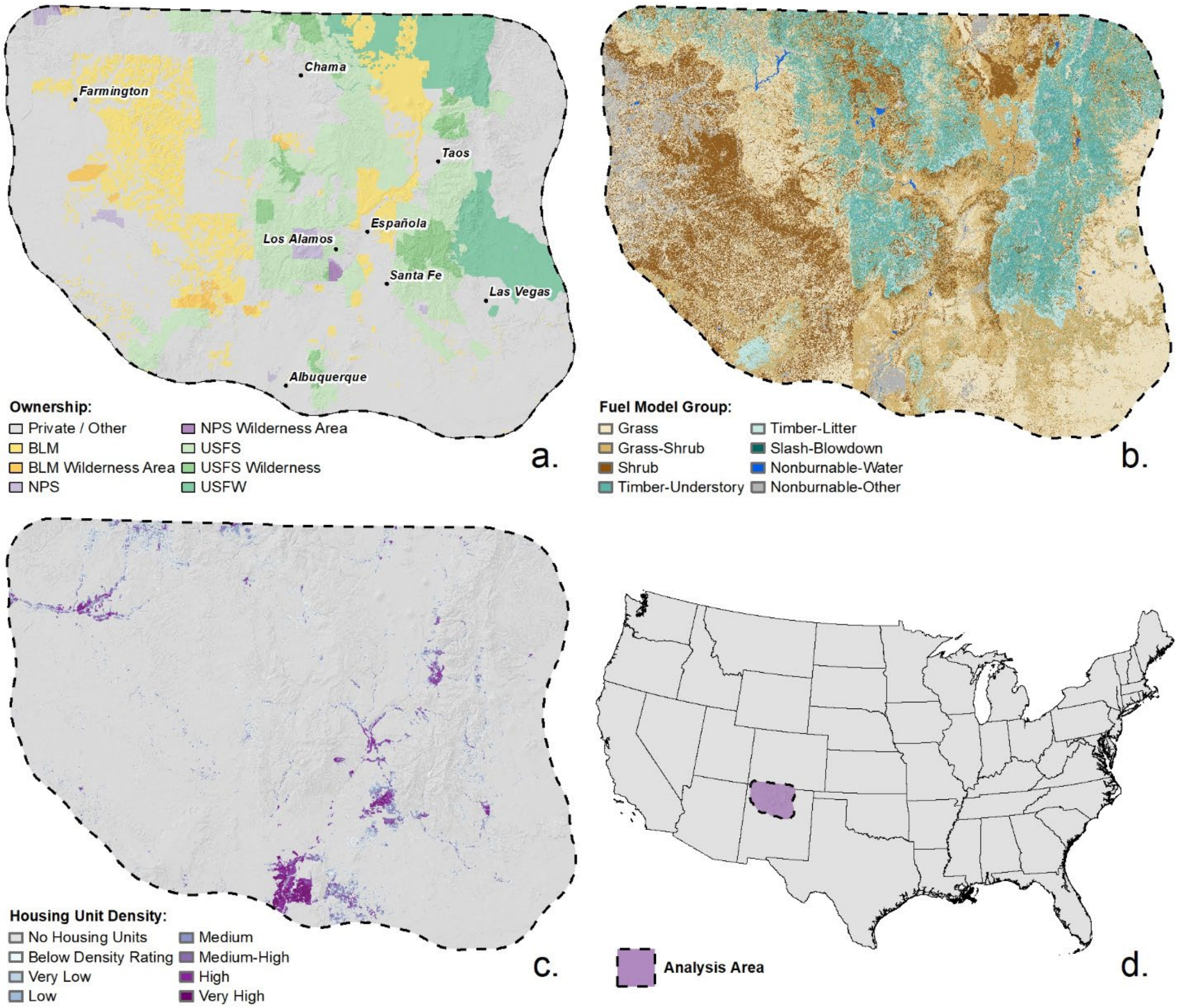

Figure 1. Maps of the distribution of land ownerships for the New Mexico study area (a), Wildland Fuel distribution (b), Housing Unit Density (c), and location of the project analysis area (d).

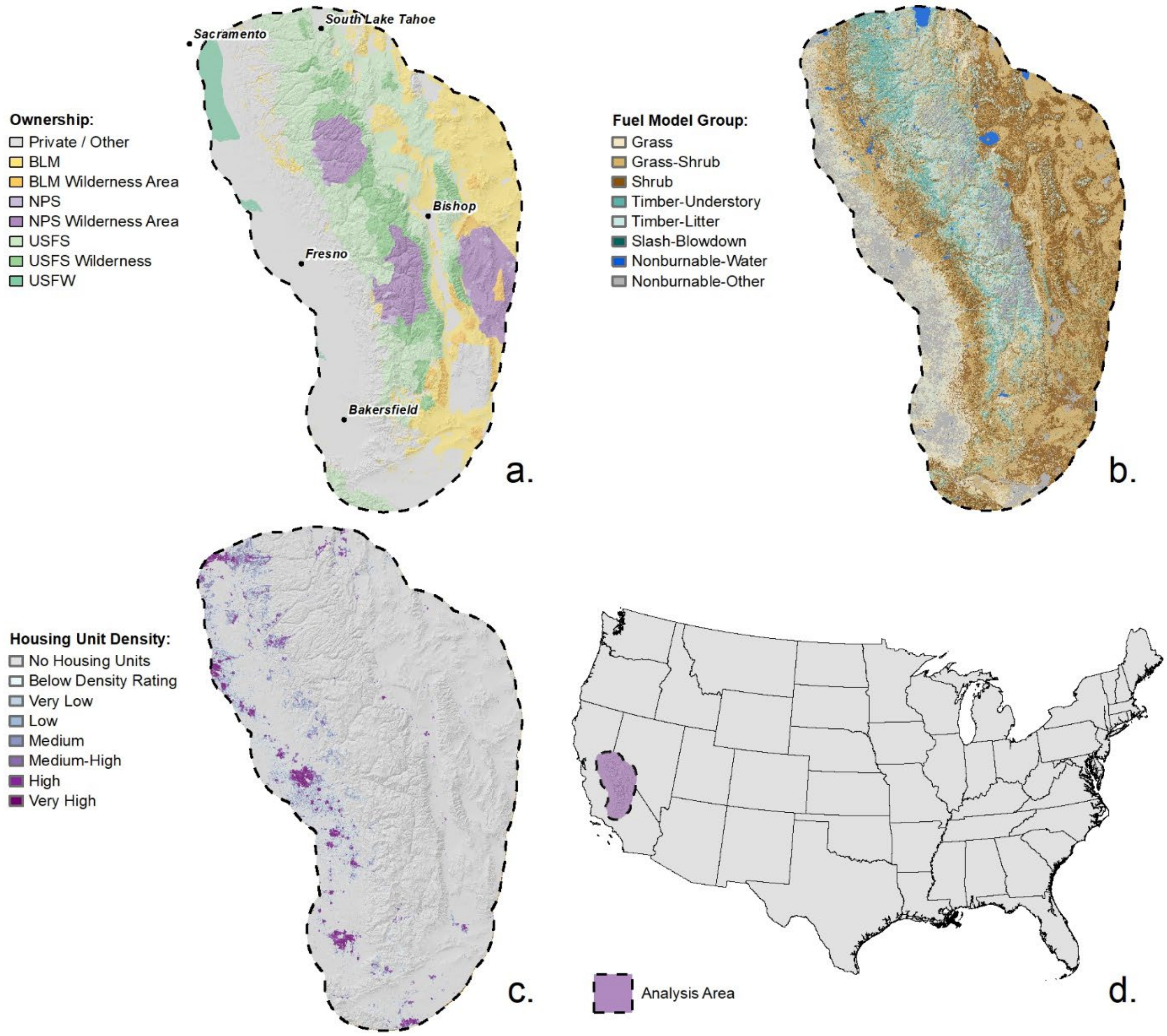

Figure 2. Maps of the distribution of land ownerships for the California study area (a), Wildland Fuel distribution (b), Housing Unit Density (c), and location of the project analysis area (d).

FSim Model & Calibration to Current Conditions

The FSim large-fire simulator was used to simulate 20,000 complete fire seasons. FSim is a comprehensive fire occurrence, growth, behavior, and suppression simulation system that uses locally relevant fuel, weather, topography, and historical fire occurrence information to make a spatially resolved estimate of the contemporary likelihood and intensity of wildfire across the landscape (Finney et al., 2011). The FSim model is described in detail in prior publications (Thompson et al., 2013; Scott et al., 2016) and is widely used for applications including hazard and risk assessment, fuel treatment design and evaluation, and, increasingly, incident response planning (Barnett et al., 2016; Thompson et al., 2016a; Riley et al., 2018; Thompson et al., 2020). In brief, FSim pairs the minimum travel time fire growth model (MTT, Finney, 1998, 2002) and spatial and temporal models of ignition probability with simulated weather streams to simulate wildfire ignition and growth for thousands of fire seasons. FSim simulations were completed at 120-m resolution using the LANDFIRE 14 fuelscape (www.landfire.gov). 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 1992–2016. The spatial ignition model is a raster representing the relative density of large-fire ignitions across the landscape. Fire containment is modeled with a logistic regression that predicts containment probability as a function of high versus low spread periods (Finney et al., 2009). Additionally, FSim simulates progressive suppression actions that limit wildfire growth on the flanks of modeled perimeters under low fuel and weather conditions.

FSim generates an event set—a set of simulated wildfire perimeters that collectively are integrated into a probabilistic result of wildfire likelihood (624,710 fires for the New Mexico study area; 3,331,315 in the California study area). Individually, simulated perimeters represent a known probability of occurrence and can be analyzed to estimate asset exposure and risk transmission. The event set is exported 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.

FSim simulations were calibrated to historical measures of large fire occurrence (mean large fire size, and the mean number of large fires per million hectares) derived from the 1992 – 2016 USDA Forest Service Fire Occurrence Database (Short, 2017). After calibrating FSim for the current condition, we ran FSim on each of the hypothetical fuelscapes (described below). More information on FSim model structure and calibration can be found in Finney et al. (2011), Scott et al. (2016, 2017), and (USDA Forest Service, 2021).

Deterministic Wildfire Modeling - FLEPGen

To estimate wildfire characteristics across the Analysis Area we used a scripted geospatial modeling process called the Flame-Length Exceedance Probability Generator (FLEPgen, Scott, 2020). FLEPgen performs multiple deterministic FLAMMAP simulations (Finney, 2006) under a range of weather types (wind speed, wind direction, and fuel moisture content), then integrates those simulations by weighting them according to their weather type probabilities, which weighs high-spread weather conditions that will be expressed to a greater degree across the landscape. The FLEPgen process was applied to both the Current Condition fuelscape and the Treated fuelscape at 120-m resolution.

The Treated fuelscape was developed previously for a national-scale risk assessment. The dataset represents a modified version of the LANDFIRE 14 fuelscape where a set of hypothetical treatments were implemented across the United States. Forested fuels received a moderate severity ‘mechanical remove’ treatment. Shrub fuels received a moderate severity ‘prescribed fire’ treatment. Grass and sagebrush fuel types were excluded from treatment because treatments would be ineffective at meaningful time scales or ecologically inappropriate given the risk of invasive annual grass introduction. All treatments were aged to the LANDFIRE 5 years post-disturbance period.

The national scale Treated fuelscape was not specifically calibrated to the local fuels within the two project Analysis Areas. To prevent model effects where fuel reduction treatments inadvertently exacerbate fire behavior, we removed fuel treatments from the analysis that were ineffective. To be considered effective a fuel treatment had to reduce wildfire behavior by at least 0.15m and not increase the rate of spread by more than 20%. Masking out these areas for the New Mexico study area (185,346 ha) left 3.0 million hectares treatable or 35.8 % of the total

Analysis Area. Masking out these areas for the California study area (4,506,511 ha) left 6.9 million hectares treatable or 60.6 % of the total Analysis Area.

FLEPgen was run with the same weather inputs as the FSim model. Utilizing FLEPgen allows for analysis of fire behavior at the pixel/stand-level without the influence of adjacent fuels. The FLEPgen-derived fire intensity results were used to model treatment effect and in the development of the priority fuelscapes described in further detail below. While the FLEPgen tool was used in the development of priority fuelscapes the stochastic FSim tool was used to measure treatment effects across the landscape.

Mapping Local and Transmitted Exposure

Housing units were mapped using the national Housing-unit density (HuDen) dataset (Scott et al., 2020). HuDen was generated using population and housing-unit count data from the U.S. Census Bureau, building footprint data from Microsoft, and land cover data from LANDFIRE. Building footprints were assigned population and housing-unit counts based on the population estimates of the Census block unit, then smoothed to create raster data at 30-m resolution. We converted housing-unit density values to housing-unit count and summed those values to 120m resolution using the ArcGIS Aggregate tool. Figure 1c and Figure 2c represent maps of the HuDEN data for the two Analysis Areas.

Our measure of local exposure evaluates the likelihood that housing units would be impacted by wildfire. We measured housing exposure by overlaying the annualized burn probability results from the FSim model with raster maps of housing unit counts to produce estimates of the annual number of homes exposed by wildfire. To map transmitted wildfire exposure, we selected all FSim fire perimeters that originated on federal lands (Figure 1a and Figure 2a) and calculated the number of Housing Units exposed from each by summing the total number of homes within each fire polygon shapefile with the ArcGIS Zonal Sum tool. Summarizing the number of homes exposed by simulation year provided an estimate of the annual number of homes exposed from fires that originate on federal lands. Maps of in situ and transmitted wildfire exposure were used in the generation of priority fuelscapes described below.

Figure 3 depicts how exposure and opportunity for beneficial fire are calculated, using actual simulated FSim fire perimeters and HuDen layers. Fire A originated on federal lands and resulted in no home exposure, making it a candidate for beneficial fire. Fire B similarly originated on federal lands and spread into populated areas, resulting in transmitted exposure from federal lands. These are the fires that treatments on the federal estate to reduce transmitted exposure target (described more below). Lastly, Fire C originates off the federal estate near populated areas and results in local exposure. These are the fires that treatments near housing to reduce local exposure target (described more below). Note these three example fires are not exhaustive in capturing all possibilities (for instance, had Fire A spread onto adjacent ownerships but resulted in no housing exposure it would still be a candidate for beneficial fire).

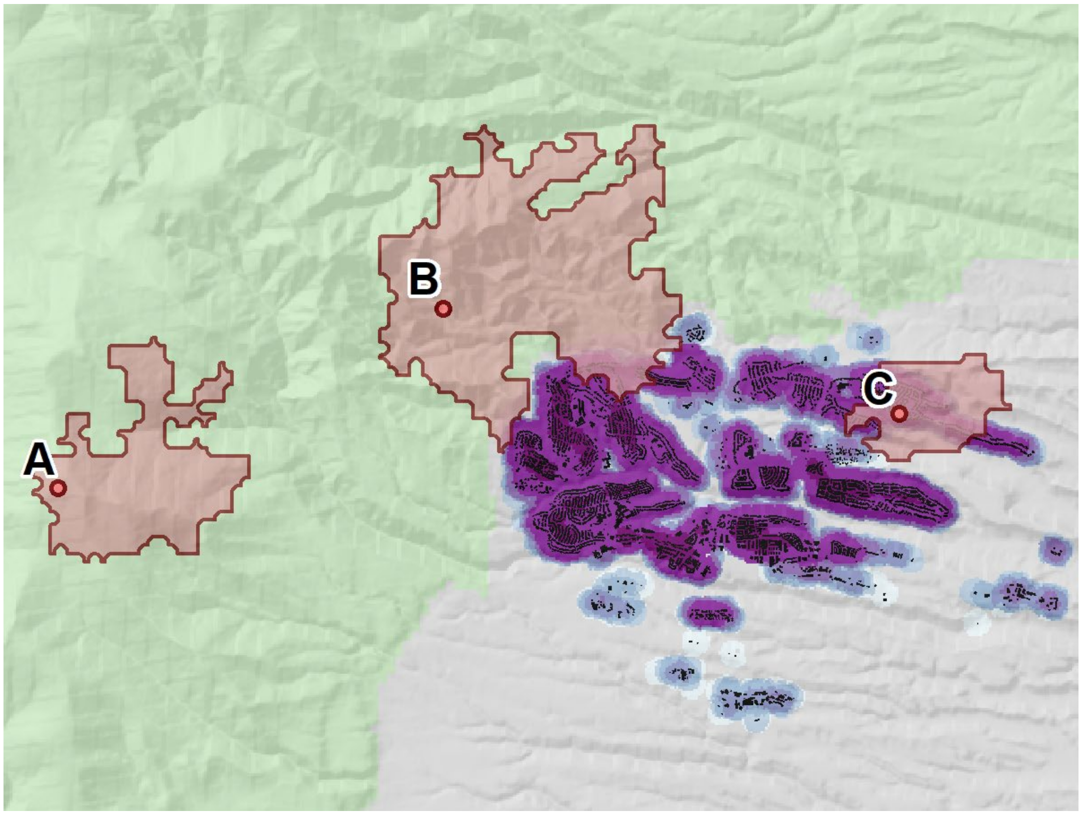

Figure 3. Stylized depiction of three simulated wildfires and corresponding implications for opportunity for beneficial fire (fire A), transmitted exposure (fire B), and local exposure (fire C).

Developing Priority Landscapes

To test the impact of fuel on in situ and transmitted exposure we developed a series of 20 hypothetical post-treatment fuelscapes for each study area. Each of the individual fuelscapes were generated from a combination of the current condition and the treated fuelscape where the entire landscape was treated with a hypothetical fuel reduction treatment as described above. Treatments were implemented at the stand level. Each of the objective values was attributed to a hexcel grid that covered the Analysis Area. The hexcel grid (n = 253,239 for NM; n = 475,467 for CA) was 33.5 ha in size and mimics the operational scale of treatments within the Analysis Areas. Given the broad scale of this analysis, additional site-specific variables that may impact the feasibility of treatments such as road access, slope steepness, treatment cost, etc. were not considered.

Individual stands were prioritized for management utilizing the Landscape Treatment Designer (LTD, Ager et al., 2012a). LTD has been widely used in the literature (Vogler et al., 2015; Ager et al., 2016; Ager et al., 2017b; Palaiologou et al., 2021) and is a straightforward optimization tool that maximizes for user-defined objectives given a set of constraints (treatment area). Treatments were weighted by their ability to address each of the prioritization metrics discussed below. We modeled scenarios where 1%, 2.5%, 5%, 7.5%, 10%, 25%, and 100% of the analysis area was treated. Note that the Federal Risk Transmision scenario was limited to only treating on federal lands where the maximum area treated scenario covered 18% of the NM study area (1,538,651 ha), and 40% of the CA study area (4,577,586 ha).

Reduce Housing Exposure – Protect Housing

Developing priority treatments to reduce housing exposure first required measuring the level of housing exposure under the current condition scenario. We used the calibrated current condition wildfire simulation outputs generated from FSim to quantify housing exposure by overlaying the annualized burn probability results from the FSim model with raster maps of housing unit counts to produce estimates of the annual number of housing units exposed by wildfire. Treatments were weighted by their ability to reduce flame lengths as measured by the FLEPgen tool. A 2.5 km Kernel Smoothing was iteratively implemented on the weighted Housing Unit exposure values and summarized to the stand level. Priority stands maximized the reduction of fire intensity in densely developed locations.

Expand Opportunities for Managed Fire - Reduce Federal Transmitted Exposure

Developing priority treatments to reduce transmission of wildfire exposure from federal lands relied on first mapping the locations of fire transmission under the current condition scenario. We used the calibrated current condition wildfire simulation outputs generated from FSim to quantify housing exposure using a method similar to that previously used in Ager et al. (2017a) & Ager et al. (2019). Ignitions were filtered for those occurring on federal lands and associated perimeters were intersected with the housing density to determine total home exposure per ignition. The resulting point data were smoothed using a kernel density tool with a 2.5 km fixed search radius at 120m resolution for the entire Analysis Area. Treatments were weighted by the ability to reduce transmission calculated as the change in rate of spread value developed in the FLEPgen simulations. Priority stands maximized the reduction of rate of spread in locations with the highest level of risk transmission.

Random Treatments

A random treatment scenario was developed to serve as a benchmark to assess the relative effectiveness of the other prioritization scenarios. Each analysis area stand was assigned a random number and stands were selected for treatment until the treatment intensity targets were met.

Modeling Alternative Strategies

After calibrating FSim for the current condition landscape, FSIm was rerun as a 'record off' run on the 19 additional fuelscape scenarios for the two project areas. Using the 'record off' functionality of FSim allows for the simulation of the same set of wildfire events where location, weather, and duration are held constant but the fuelscape is variable. This allowed us to attribute differences among the simulations to the fuelscapes that changed between simulations rather than to model stochasticity (see Scott et al. 2016). All simulations were run on 48-thread Windows machines using FSim version B1.22 (USDA Forest Service, 2021). Simulations are computationally intensive and took approximately 1,200 machine hours to complete for NM and 12,000 machine hours for CA.

Evaluation of Treatment Strategies

Each treatment strategy and treatment intensity level was evaluated on its ability to reduce landscape-level housing exposure and increase areas of opportunities for managed wildfire by reducing federally transmitted housing exposure. Treatments show the effect by altering the size of simulated wildfire perimeters (event set) that result in the exposure of housing units. There are two mechanisms within the FSim model for fuel treatments to alter the size of wildfire perimeters. First, treatments may alter the rate of spread within the minimum travel time growth algorithm (Finney, 2002). This would result both in a smaller overall fire size as well as a higher probability of the occurrence of simulated weather conditions that would extinguish a fire before it reaches housing units. Secondly, treatments may reduce simulated flame lengths which would lead to a smaller overall size as a result of the perimeter trimming function that mimics wildfire suppression actions. FSim uses a function to limit wildfire growth on the flanks of modeled perimeters under low flame length conditions.

Treatment Performance – Housing Exposure

To quantify housing exposure, we overlaid simulated fire perimeters on housing unit density layers. We report exposure in terms of the expected number of exposed housing units (HU) per year. Exposure was calculated for all simulated fires and for only those that originated on federal lands. It should be noted that suppression strategies such as point protection or positioning engines along roads that could reduce housing exposure are not specifically modeled here. Nor does the modeling consider potential home to home ignition in urban fuels, such that this measure is an estimated lower bound on exposure. Landscape housing exposure was calculated as:

$$eHUExp = \sum_h \sum_i BP_h * HUcount_h \qquad \text{(Equation 1)}$$

Treatment Performance – Expanded Opportunities for Managed Fire

To quantify the opportunity for resource benefit from managed fire, we quantify the area burned from fires that didn't expose homes. To compute this, we summed the number of housing units exposed to each simulated fire and added that attribute to the location of its ignition. Ignition points whose perimeters did not encounter any nonzero housing unit pixel were assigned a value of zero (e.g., zero housing units exposed). Points were converted to a raster and smoothed using a 2.5k search radius point density smoothing. The exposure raster was divided by a 2.5k smoothed point density raster of simulated large wildfires. The results generated a raster-based quantitative fireshed. We mapped opportunities assuming a risk tolerance of 0 homes exposed with a 90% probability of success (i.e., 90% is the proportion of simulated ignitions with the smoothed area resulting in the corresponding level of exposure). We characterize this as an upper bound on area of opportunity, recognizing that the presence of other fire-sensitive resources or assets on the landscape wouldn't necessarily support managed fire in all places, and furthermore recognizing that fires that burn onto non-federal jurisdictions may warrant a shift to more aggressive fire containment strategies. Opportunities for managed fire was calculated as:

$$Area\ of\ Opportunity = \sum\ Federal\ pixels\ where\ Exposure = 0 \qquad \text{(Equation 2)}$$

Results and Discussion

Fire Simulation Results & Prioritized Treatment Strategies

Figure 4 displays measures of wildfire hazard (likelihood and intensity) on the current condition NM landscape, specifically burn probability (across all flame length classes), conditional flame length and rate of spread. In NM, simulated probabilities and intensities are generally highest in areas to the west of Los Alamos and the east and northeast of Santa Fe and Taos. Figure 5 presents the same set of results for the CA landscape. In CA, simulated probabilities and intensities generally increase with elevation – up to a point - in the foothills of the Sierras areas to the east of Fresno and Bakersfield and to the south of Sacramento and South Lake Tahoe.

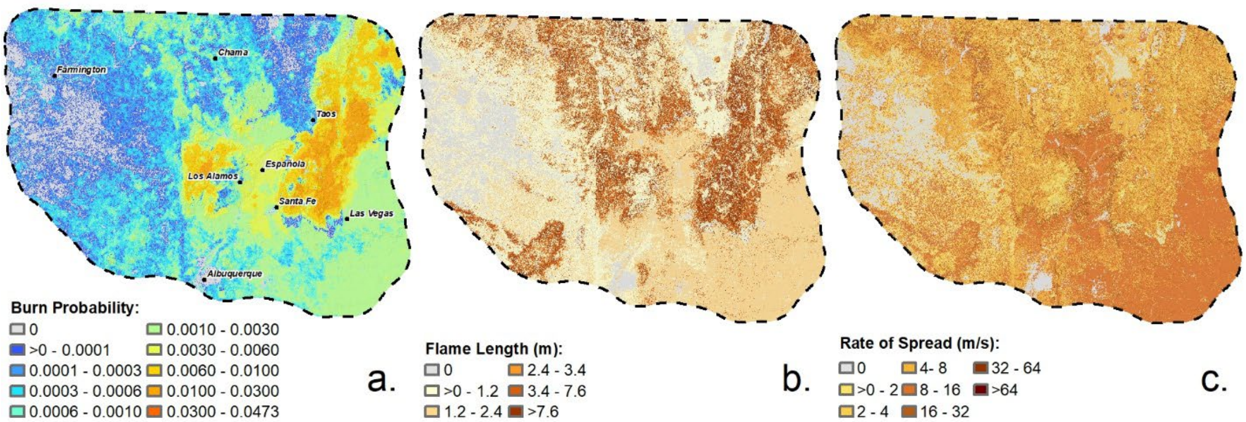

Figure 4. Maps of FSim simulated burn probability and FLEPgen generated (a) and Flame length (b) and Rate of Spread (c) for the NM current condition fuelscape.

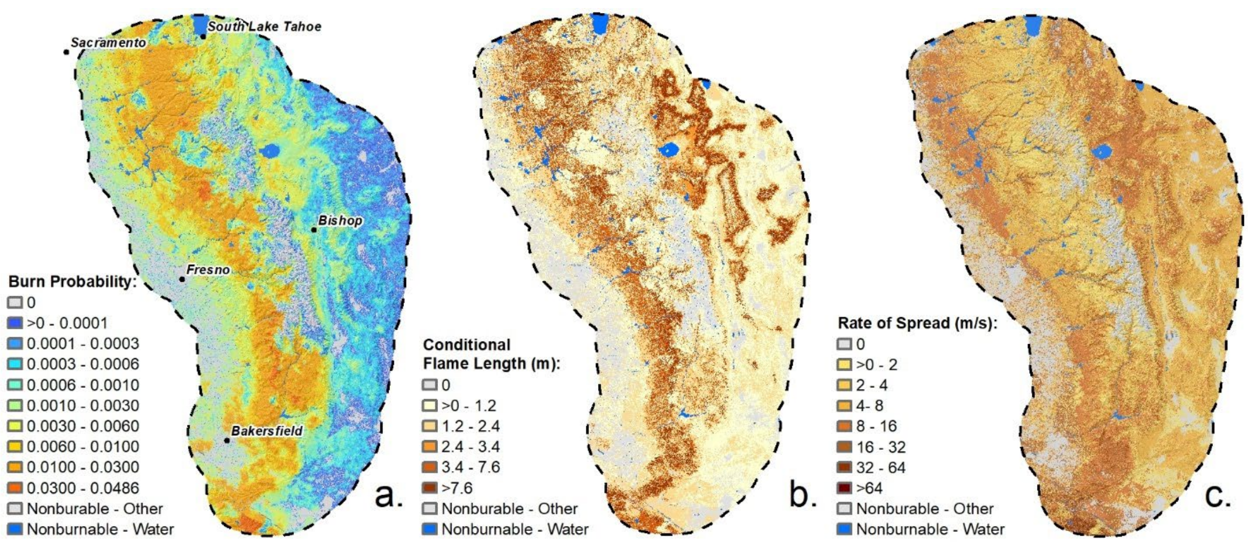

Figure 5. Maps of FSim simulated burn probability and FLEPgen generated (a) and Flame length (b) and Rate of Spread (c) for the CA current condition fuelscape.

Figure 6 displays spatial patterns of treatment for NM, across increasing treatment intensities/extents, for the two primary prioritization schemes (housing protection and federal transmission). In both cases, high priority treatment areas tend to be clustered near areas of higher housing density, and then emanate outward further and further into wildlands. Figure 7 displays the optimized treatments by increasing extents for CA, where the two prioritization schemes result in widely divergent treatment locations. Like NM, the high priority areas tend to be clustered near areas of higher housing density with treatable fuels, but with the housing protection theme priority areas tend to emanate outward into the valley towards population centers whereas the federal transmission theme emanates further into the wildlands.

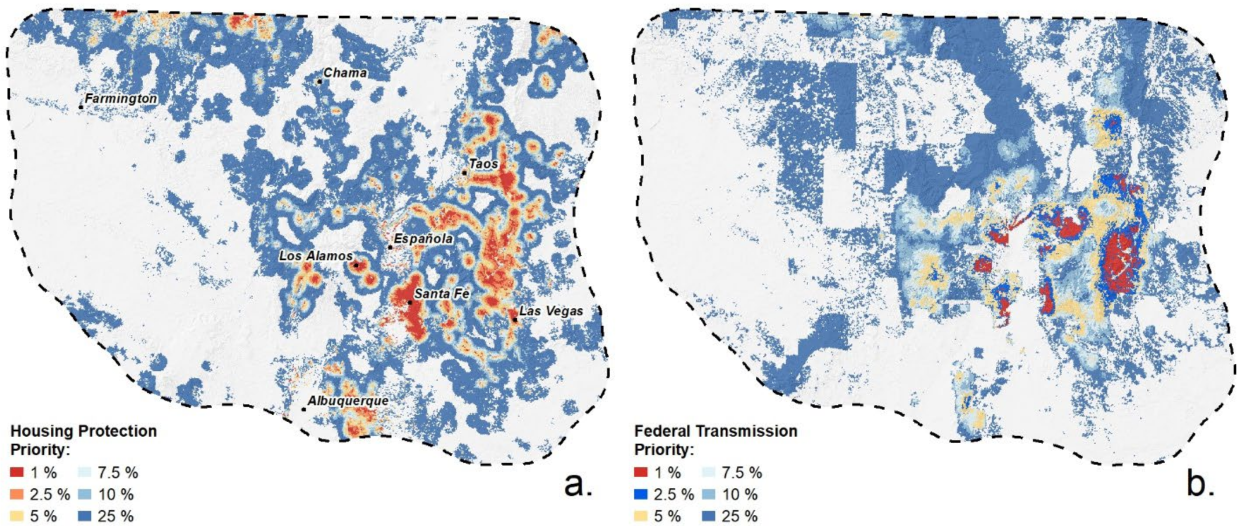

Figure 6. Optimal treatment strategies for NM, by treatment intensity, for prioritization themes focused on housing protection (a) and federal wildfire risk transmission (b).

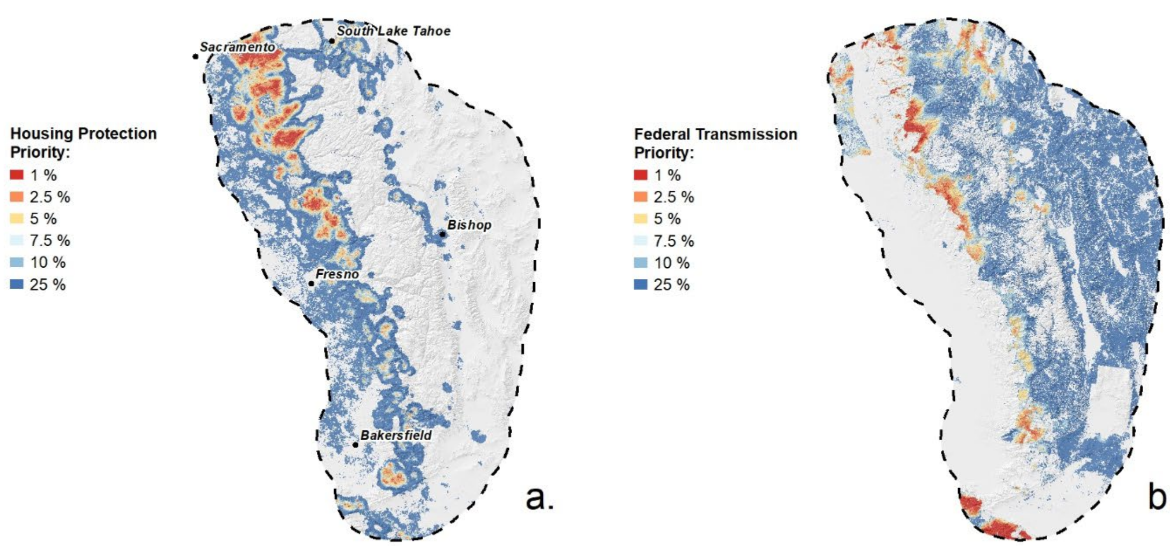

Figure 7. Optimal treatment strategies for CA, by treatment intensity, for prioritization themes focused on housing protection (a) and federal wildfire risk transmission (b).

Figure 8 and Figure 9 display areas of common and divergent treatment priority, for treatment extents up to 10%, for the NM and CA study areas. As treatment extent grows, so too does the area of overlap, or joint priority. However, there are fewer areas of joint overlap in CA, which are primarily concentrated along the western edge of federal lands, reflecting patterns of federal ownership (see Figure 2), fire spread, and transmission pathways.

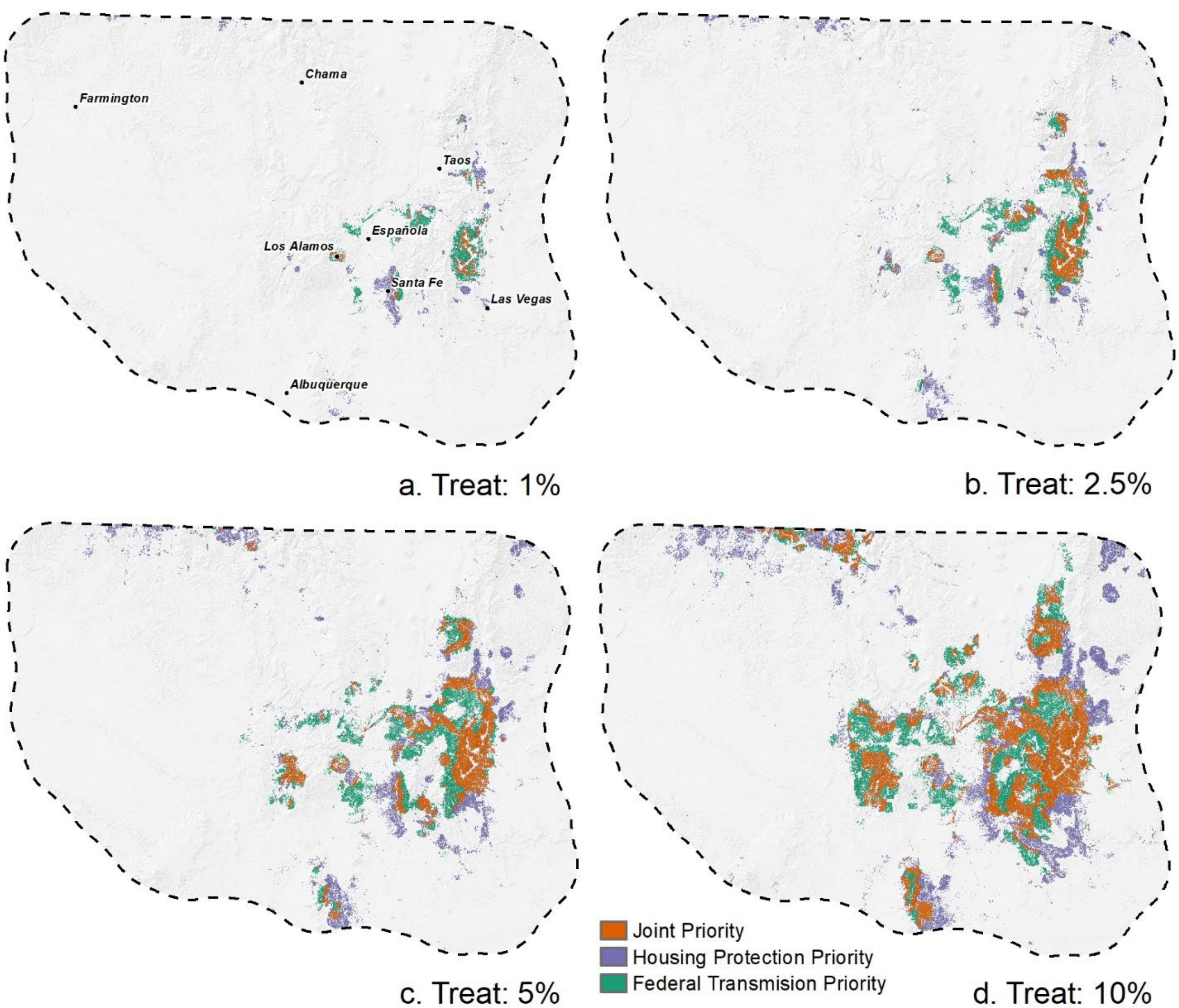

Figure 8. Optimal treatment strategies for NM, by treatment intensity, for prioritization themes focused on housing protection and federal wildfire risk transmission as well as the overlap between the two objectives.

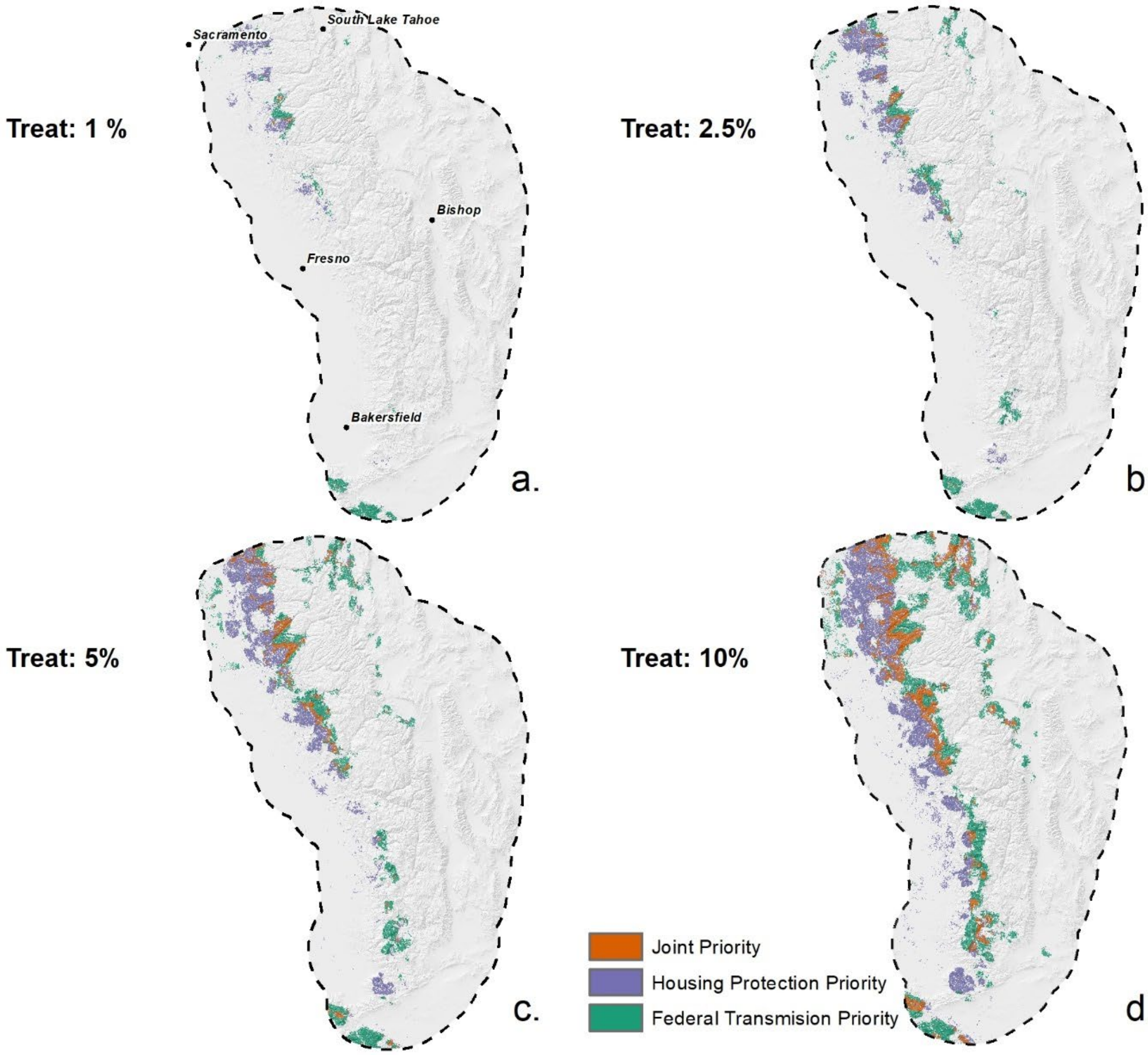

Figure 9. Optimal treatment strategies for CA, by treatment intensity, for prioritization themes focused on housing protection and federal wildfire risk transmission as well as the overlap between the two objectives.

Housing Exposure and Resource Benefit Opportunity

Figure 10 and Figure 11 compare treatment strategy performance for reduced housing unit exposure for NM and CA, differentiated by considering all simulated fires (panel a) and just simulated fires igniting on federal lands (panel b). Apart from scale differences (housing unit exposure is far greater in CA), both figures share many commonalities. First, housing exposure drops steeply with increasing treatment intensity and then begins to taper off at anywhere from 5-25% depending on theme. The housing protection strategy performs best at overall reductions in exposure, achieving significant reductions even at treatment intensities below 5%.

Notably, the performance of the Federal Transmission Priority theme looks very different comparing results across panels and origins of fires. In the case of the former, the Housing Protection theme clearly outperforms, and even the Random theme begins to outperform Federal Transmission once reaching around 10% treatment extent. In the case of the latter, on both landscapes the Federal Transmission theme performs nearly as well as the Housing Protection. Thus, although treating federal lands to reduce federal transmission can be highly effective at reducing exposure from federal fires, it contributes comparatively little to reducing exposure from all fires, due largely to where exposure-causing fires ignite. In the case of NM, the amount of exposure from non-federal fires is approximately twice that of federal fires. In the case of CA, that ratio increases up to approximately fourfold.

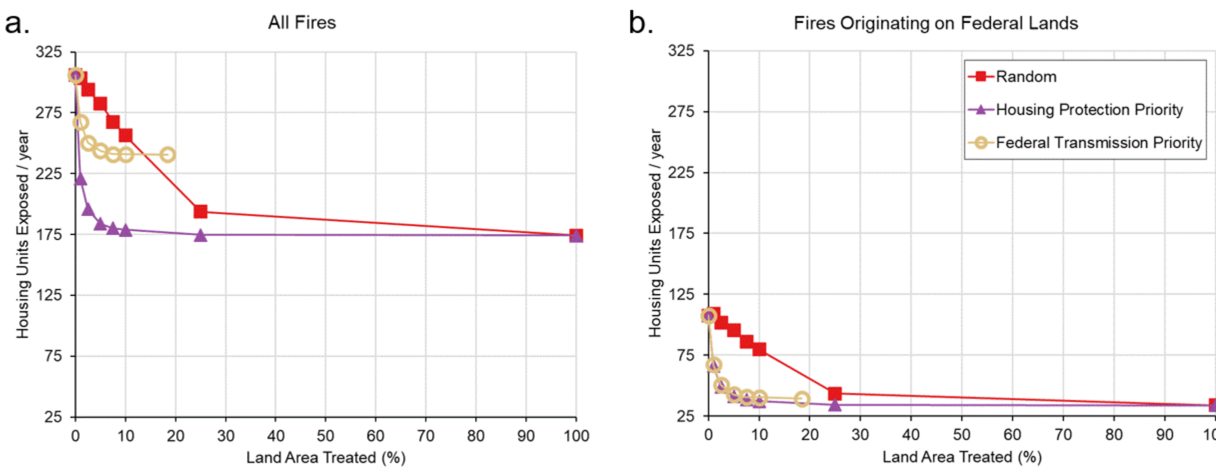

Figure 10. Reduction in housing unit exposure across prioritization themes and treatment intensities for NM, considering all simulated fires (a) and just fires ignited on federal lands (b). Note that the maximum available treatment intensity for the Federal Transmission theme in NM is 18%.

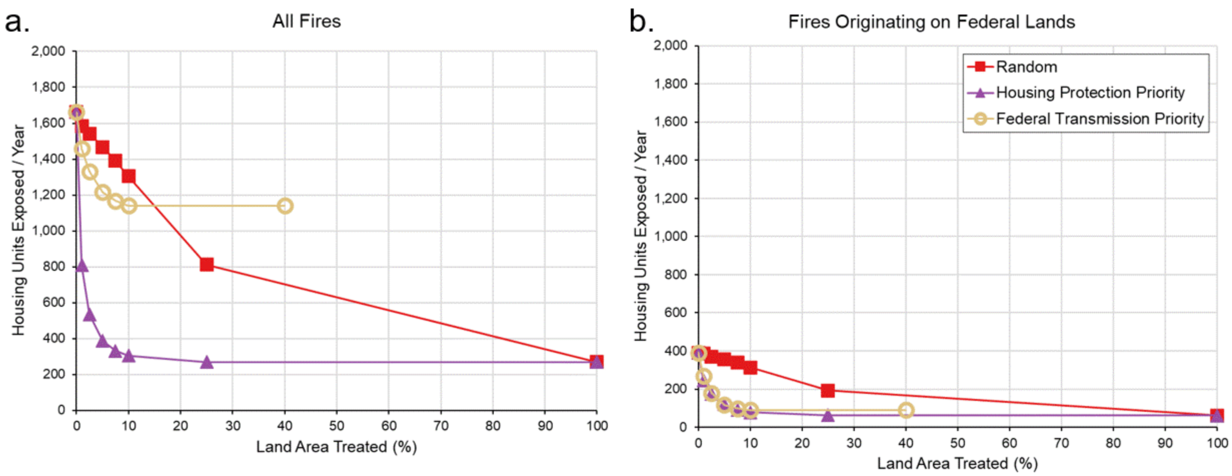

Figure 11. Reduction in housing unit exposure across prioritization themes and treatment intensities for CA, considering all simulated fires (a) and just fires ignited on federal lands (b). Note that the maximum available treatment intensity for the Federal Transmission theme in CA is 40%.

Next, Figure 12 and Figure 13 display treatment strategy performance for areas of opportunity where wildfires may be managed for benefits in NM and CA. In both cases, for a given treatment extent, the Federal Transmission theme outperforms the other themes. Results for NM generally share the similarity with Figure 10 of steep improvements that then taper, although here the slope of improvement is less steep. In NM, treatments can ultimately achieve a gain of over 600,000 ha of opportunity area. Results for CA by contrast do not appear to reach an asymptote and show continued expansion of opportunity area as treatment extent increases. Interestingly, the Random theme slightly outperforms the Housing Priority theme at treatment extents up to 10%, which could result from Housing Priority treatments placed largely off the federal estate whereas with the Random theme (not shown) some federal lands are treated with associated reductions in transmission potential. Treating the maximal extent of federal lands (40%) achieves nearly the same result as 100% for the other themes, achieving a gain of nearly 1 million ha of opportunity area.

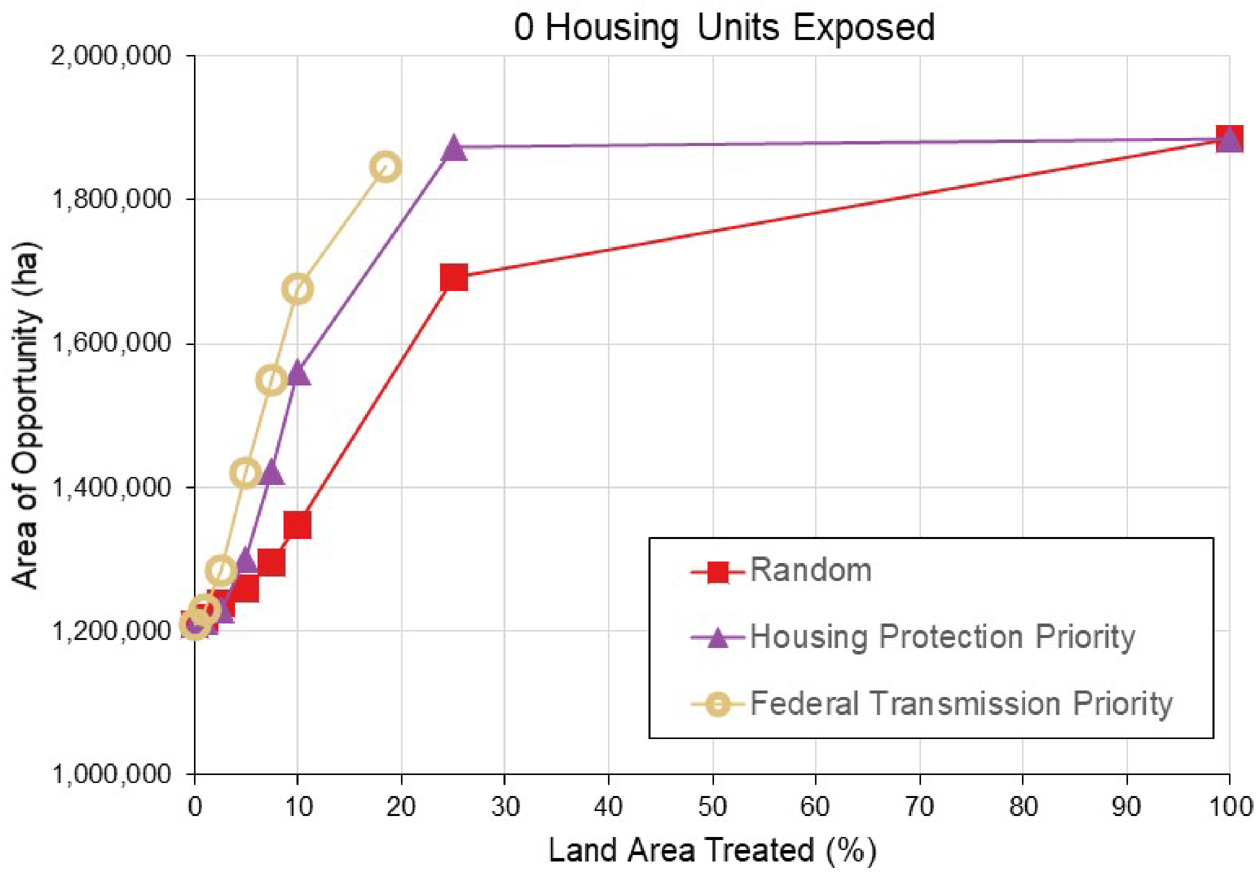

Figure 12. Increases in opportunities to manage wildfire in NM, across treatment themes and treatment intensities, considering only ignitions resulting in no exposure.

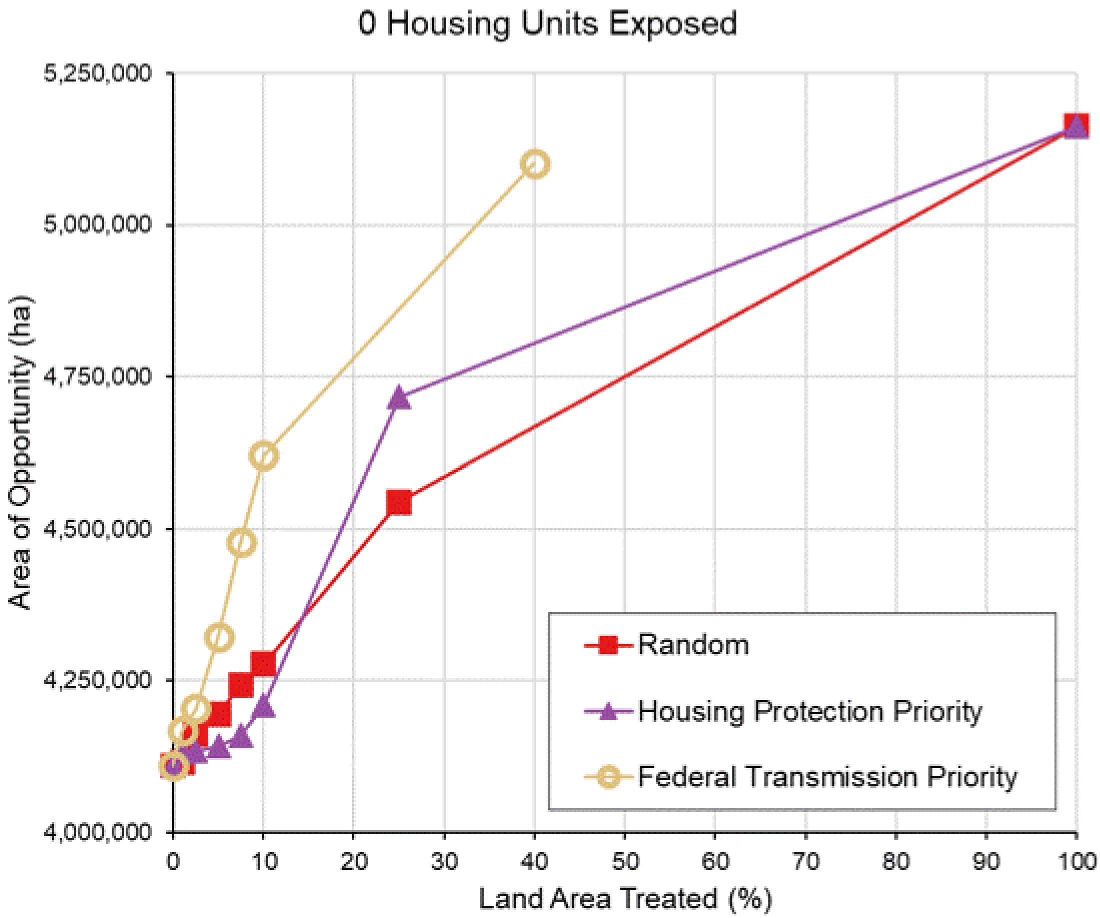

Figure 13. Increases in opportunities to manage wildfire in CA, across treatment themes and treatment intensities, considering only ignitions resulting in no exposure.

Lastly, Figure 14 and Figure 15 summarize treatment themes and extents across both performance measures for NM and CA. Results indicate complementarities across treatment themes, i.e., increasing levels of housing protection are associated with higher opportunities for managing wildfire with reduced exposure, and vice versa. To reiterate, for a given treatment extent the Housing Protection prioritization theme performs best in terms of housing units protected, whereas the Federal Transmission prioritization theme performs best in terms of increasing opportunity area. The Random prioritization theme performs worse than either strategy up to the 10% treatment extent (panel a), indicating the value of strategic treatment location.

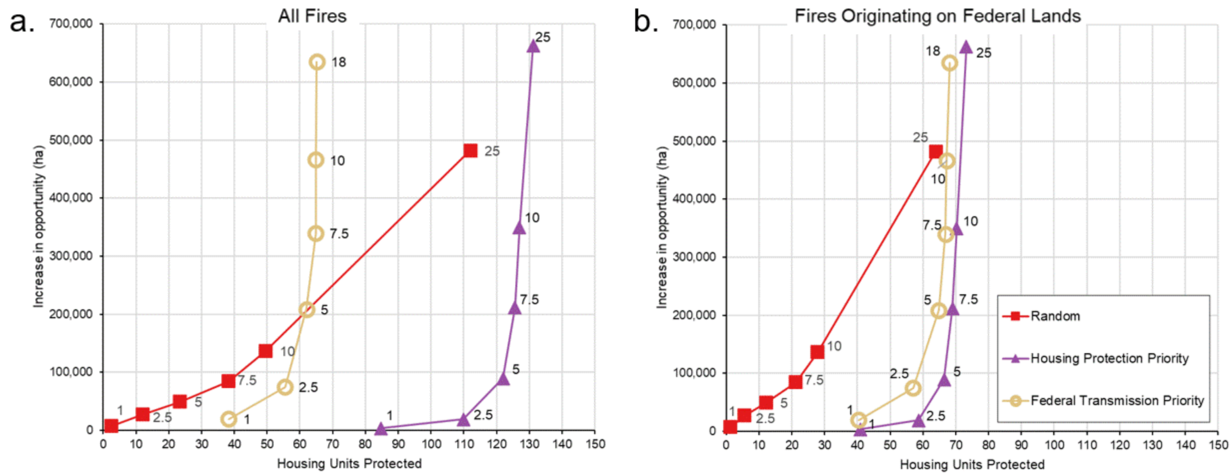

Figure 14. Joint evaluation of treatment strategy performance in NM in terms of housing units protected (x-axis) and increased area of opportunity for managed wildfire (y-axis), all relative to the baseline current conditions. Panel (a) represents all simulated fires and panel (b) represents only fires that originate on federal lands. The numbers associated with each point represent the treatment extent (in percentage).

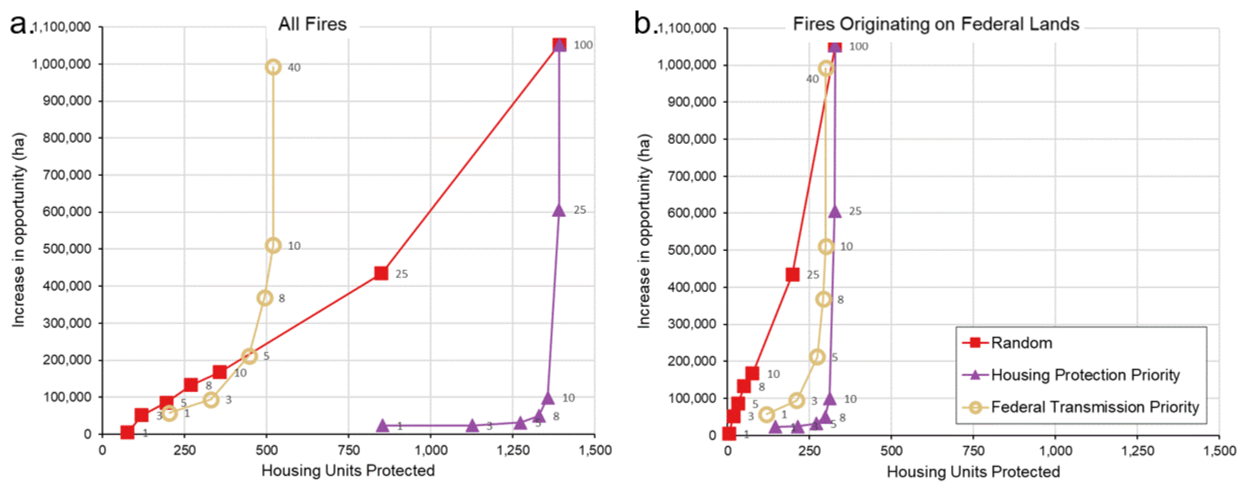

Figure 15. Joint evaluation of treatment strategy performance in CA in terms of housing units protected (x-axis) and increased area of opportunity for managed wildfire (y-axis), all relative to the baseline current conditions. Panel (a) represents all simulated fires and panel (b) represents only fires that originate on federal lands. The numbers associated with each point represent the treatment extent (in percentage).

One interesting finding is the common shape of the response curves and performance measures shown in Figures 10-15. These commonalities hold despite spatial differences in ownerships, housing density, and fire potential across the two study areas (Figures 1-2, 4-5). They also hold despite marked differences in spatial patterns of prioritized treatment themes (Figures 6-7). These findings suggest persistent insights regarding fuel treatment prioritization and how strategic location can align with treatment objectives.

Our findings demonstrate commonalities with other research on simulated fuel treatment effectiveness, notably that treating near housing units may provide the greatest risk reduction. Strategically locating treatments near at-risk assets can significantly reduce the area of treatment needed for a common level of protection. Treatment on the federal estate can be effective at reducing federal transmission, but this transmission may comprise only a comparatively small portion of total exposure and risk. In other words, focusing only on transmission reduction potential from the federal estate may present a narrow picture of broader risk mitigation opportunities.

In this sense, this work provides a contribution in terms of explicitly framing risk analysis and treatment design around federal land and resource management objectives in fire-prone systems. It highlights that reducing transmission from the federal estate and protecting human communities, while complementary, are not identical strategies. In fact, treatments prioritized to minimize housing exposure are more effective at that objective while effectively affording the same expansion in opportunity for managed fire. Conversely, expanding opportunities for fire use may better align with approaches that deemphasize transmission per se and instead emphasize the creation of strategic fuel breaks and containment opportunities that align with areas where land and resource objectives would benefit from managed fire disturbance. (North et al. 2021).

In addition to managing wildfire for landscape resilience, here is where synergy with broader elements of the National Cohesive Wildland Fire Management Strategy come into play. The focus on fire-adapted communities, in particular coordinated management of interface and intermix fuels on various ownerships combined with home ignition zone mitigation, can severely dampen the risks of fires that do burn into or near communities (irrespectively of whether they originate on the federal estate). The focus on safe and effective response, in particular POD-based planning that pre-identifies potential fire control locations, can guide fire operations in reducing transmission while gaining partner support and expanding the decision space. Combined, reduced potential for loss and enhanced potential for control can then further expand the land base available for managed fire, which can lead to further reinforcing feedbacks that benefit ecosystems and expand opportunities for even more fire (Parks et al., 2015; North et al., 2021).

As with any modeling study, there are limitations and extensions to address. As stated earlier, results are estimates of lower bounds (housing exposure) and upper bounds (area suitable for beneficial fire) of treatment benefit. This work did not consider a broader array of resources and assets and corresponding treatment priorities and tradeoffs, nor did it consider treatment costs, harvest revenue, or suppression expenditures. We did not explicitly consider time frames of treatment planning and implementation or vegetation-fire dynamics in the interim, instead focusing on comparisons with hypothetically optimized landscapes at a snapshot in time. We did not consider changes in smoke production and transport that could stem from expanded treatment and managed fire, although that too comes with tradeoffs in terms of delaying more intense smoke events. The FSim modeling system doesn't capture the formation of events so extreme they create their own weather and so could be underestimating the risk of extreme events from federal lands. Neither does FSim capture specific tactics and strategies that could result in different transmission pathways and exposure levels. Within these limitations in mind, this effort should be viewed as a framework for understanding the biophysical nature of wildfire and the implications of fuel conditions on risk exposure and fire growth, and not as a specific local solution or policy management recommendation. Future work could attempt to address many of these limitations, could consider hybrid strategies (e.g., 5% reduce fed transmission + 5% reduce housing exposure), and could expand to other landscapes where different patterns of fire spread potential and human development may lead to different findings.

Conclusions (Key Findings) and Implications for Management/Policy and Future Research

This project considered multiple aspects of risk, emphasizing exposure and transmission, and attempted to provide insights from simulation modeling and risk analysis to ongoing policy and management discussions. Findings largely share commonalities with existing literature, for instance the observation of a steep increase in fuel treatment benefits that taper as treatment extent increases (highlighting the importance of spatial optimization) and the observation that locating treatments near housing may be preferable to distant wildland treatments to optimally reduce housing exposure. Reducing federal transmission is complementary with, but not identical to, a strategy to protect housing, and these nuanced differences are important to highlight when developing strategies considering factors such as where and how risk can best be mitigated, and who has sufficient scope of control or the resources to mitigate that risk.

One relatively surprising aspect of our project was the consistency of thematic treatment performance across the two study areas despite their differences, suggesting a degree of durability of key findings. One important aspect with management and policy implications is the need for an all-lands, all-hands approach to manage fuels across ownerships to meaningfully reduce potential for housing loss; the companion point being that a focus on reducing federal transmission, while necessary in some locations, is not sufficient to meaningfully reduce WUI risk. To the extent that reducing transmission potential expands the decision space to manage unplanned ignitions for resource benefits, results suggest substantial opportunity to return fire to fire-adapted systems, which carries other types of risks but also catalyzes beneficial feedback loops.

As transmission and community exposure may influence national and regional investment priorities, the analytical framework presented here can help scale risk-based prioritization to the landscape level. Further, the framework can help daylight potential complementarities with federal management strategies that emphasize landscape resilience and restoring fire to fire-adapted systems. Future work here can proceed along three important directions – first by incorporating additional social and ecological variables to constrain spatiotemporal windows for managed fire more realistically, second by integrating treatment design with operational response planning to locate treatments to afford greater opportunities for control, and third by leveraging social science to understand how cross-boundary collaboration and coordination may set the stage for success to successfully implementing these themes on the ground.

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Appendix A

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Appendix B

List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Deliverable Type	**Description**	**Delivery Dates**
Datasets	USDA Forest Service Research Data Archive product providing geospatial layers on current conditions and treated fuelscapes, treatment prioritization themes, and FSim results for all hypothetical landscapes.	In process, expected publication date early spring 2022
Conference/symposia/ workshop	Oral presentation at professional society conference Vogler, KC, Scott, JH. 2019. Quantitative Fuel Treatment Prioritization: Using Big Data to Save Homes. Society of American	October 31, 2019

	Foresters National Convention. Louisville, KY, October 2019	
Conference/symposia/ workshop	Oral presentation at professional society conference Scott, JH, Vogler, K, Miller, C. 2019. Can landscape fuel treatments enhance both protection and resource management objectives? 8th International Fire Ecology and Management Congress. Tucson, AZ. November 18-22, 2019.	November 20, 2019
Conference/symposia/ workshop	Oral presentation at professional society conference Vogler, KC, Scott, JH, Thompson, MP, Miller, CL. 2021. Can landscape fuel treatments enhance both protection and resource management objectives? 16th International Wildland Fire Safety Summit & 6th Human Dimensions of Wildland Fire Conference. Virtual. May 24-27, 2021.	May 26, 2021
Refereed publication	Vogler, KC, Scott, JH. 2022.A risk-based fuel treatment prioritization strategy. In preparation.	In process, expected submission date January 2022
Refereed publication	Thompson, MP, Vogler, KC, Scott, JH, Miller, C. 2022. Comparing risk-based fuel treatment prioritization with alternative strategies for enhancing protection and resource management objectives. Submitted to Fire Ecology.	In review, expected publication date spring 2022
Training sessions	Webinar presentation Vogler, KC, Scott, JH, Thompson, MP, Miller, CL. 2021. Can landscape fuel treatments enhance both protection and resource management objectives? Southwest Fire Science Consortium.	May 26, 2021
Training sessions	Webinar presentation Vogler, KC, Scott, JH, Thompson, MP, Miller, CL. 2021. Can landscape fuel treatments enhance both protection and resource management objectives? California Fire Science Consortium	October 18, 2021

Appendix C

Metadata

Data Listing:

- **New Mexico Data** (1.53 GB): Currently located on the Pyrologix FTP site: www.pyrologix.com/ftp/Public/USFS_DataArchive_RJVA/NCNM_Data.zip

1. **NCNM_FuelData.gdb** – ArcGIS 10.3 geodatabase containing 120m rasters of current condition and treated fuel conditions for the north-central New Mexico study area.
   a. LF14trt_fm40_120m – 120m treated fuelscape raster
   b. LF14trt_ch_120m - 120m treated fuelscape raster
   c. LF14trt_cc_120m - 120m treated fuelscape raster
   d. LF14trt_cbh_120m - 120m treated fuelscape raster
   e. LF14trt_cbd_120m - 120m treated fuelscape raster
   f. LF4cc_fm40_120m - 120m current condition fuelscape raster
   g. LF14cc_ch_120m - 120m current condition fuelscape raster
   h. LF14cc_cc_120m - 120m current condition fuelscape raster
   i. LF14cc_cbh_120m - 120m current condition fuelscape raster
   j. LF14cc_cbd_120m - 120m current condition fuelscape raster
   k. LF14_slp_120m - 120m topography raster
   l. LF14_dem_120m - 120m topography raster
   m. LF14_asp_120m - 120m topography raster
2. **NCNM_FLPGen_Intensity.gdb** – ArcGIS 10.3 geodatabase containing 120m wildfire intensity rasters generated with the FLPGen fire model on the current condition and treated fuelscapes.
   i. *Citation*: Scott, Joe H. 2020. A deterministic method for generating flame-length probabilities. In: Hood, Sharon M.; Drury, Stacy; Steelman, Toddi; Steffens, Ron, [eds.]. Proceedings of the Fire Continuum-Preparing for the future of wildland fire; 2018 May 21-24; Missoula, MT. Proceedings RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 195-205.
   b. **FLEPGen_trt_ROS** – 120m Rate of Spread (ch/hr) raster for the treated fuelscape in the north-central New Mexico study area.
   c. **FLEPGen_trt_FL** – 120m Flame Length (ft.) raster for the treated fuelscape in the north-central New Mexico study area.
   d. **FLEPGen_cc_ROS** - 120m Rate of Spread (ch/hr) raster for the current condition fuelscape in the north-central New Mexico study area.
   e. **FLEPGen_cc_FL** - 120m Flame Length (ft.) raster for the current condition fuelscape in the north-central New Mexico study area.
3. **NCNM_Priority_Fuelscapes.gdb –** ArcGIS 10.3 geodatabase containing optimally generated fuelscape masks to address either home protection, federal risk transmission, or random treatment priorities.
   a. **NCNM_Hex_Stands** – Shapefile dataset of hypothetical hexagonal treatment stands for the north-central New Mexico study area. Shapefile attributed with average burn probability, delta rate of spread, delta flame length, home risk, and transmitted home risk.

b. **NCNM_Treatment_Mask** – 120m raster data set of where treatments could be implemented
c. **RAND1_Fuel_Mask** – 120m raster of priority treatment areas for the random – treat 1% scenario
d. **RAND2h_Fuel_Mask** - 120m raster of priority treatment areas for the random – treat 2.5% scenario
e. **RAND5_Fuel_Mask** - 120m raster of priority treatment areas for the random – treat 5% scenario
f. **RAND7h_Fuel_Mask -** 120m raster of priority treatment areas for the random – treat 7.5% scenario
g. **RAND10_Fuel_Mask** - 120m raster of priority treatment areas for the random – treat 10% scenario
h. **RAND25_Fuel_Mask** - 120m raster of priority treatment areas for the random – treat 25% scenario
i. **HuDEN1_Fuel_Mask** - 120m raster of priority treatment areas for the housing protection priority – treat 1% scenario
j. **HuDEN 2h_Fuel_Mask** - 120m raster of priority treatment areas for the housing protection priority – treat 2.5% scenario
k. **HuDEN 5_Fuel_Mask -** 120m raster of priority treatment areas for the housing protection priority – treat 5% scenario
l. **HuDEN 7h_Fuel_Mask** - 120m raster of priority treatment areas for the housing protection priority – treat 7.5% scenario
m. **HuDEN 10_Fuel_Mask** - 120m raster of priority treatment areas for the housing protection priority – treat 10% scenario
n. **HuDEN 25_Fuel_Mask -** 120m raster of priority treatment areas for the housing protection priority – treat 25% scenario
o. **FedTRSM1_Fuel_Mask** - 120m raster of priority treatment areas for the federal transmission priority – treat 1% scenario
p. **FedTRSM 2h_Fuel_Mask** - 120m raster of priority treatment areas for the federal transmission priority – treat 2.5% scenario
q. **FedTRSM 5_Fuel_Mask** - 120m raster of priority treatment areas for the federal transmission priority – treat 5% scenario
r. **FedTRSM 7h_Fuel_Mask** - 120m raster of priority treatment areas for the federal transmission priority – treat 7.5% scenario
s. **FedTRSM 10_Fuel_Mask -** 120m raster of priority treatment areas for the federal transmission priority – treat 10% scenario
t. **FedTrtAll_Fuel_Mask** - 120m raster of priority treatment areas for the treat all federal lands scenario

4. **NCNM_FSim_BurnProbability.gdb** – ArcGIS 10.3 geodatabase containing 120m wildfire likelihood (burn probability) rasters generated with the FSim model on each of the priority fuelscapes in the north-central New Mexico study area.
    i. Citation: Finney, M.A., McHugh, C., Grenfell, I.C., Riley, K.L., Short, K.C., 2011. A Simulation of Probabilistic Wildfire Risk Components for the Continental United States. Stochastic Environmental Research and Risk Assessment 25.7, 973-1000.

b. **FSim_IBP_CC** - 120m burn probability raster generated with the FSim model on the current condition scenario fuelscape

c. **FSim_iBP_TrtAll** - 120m burn probability raster generated with the FSim model on the treat all lands scenario fuelscape
d. **FSim_iBP_RAND1** - 120m burn probability raster generated with the FSim model on the random treat 1% scenario fuelscape
e. **FSim_iBP_RAND2h** - 120m burn probability raster generated with the FSim model on the random treat 2.5% scenario fuelscape
f. **FSim_iBP_RAND5** - 120m burn probability raster generated with the FSim model on the random treat 5% scenario fuelscape
g. **FSim_iBP_RAND7h** - 120m burn probability raster generated with the FSim model on the random treat 7.5% scenario fuelscape
h. **FSim_iBP_RAND10** - 120m burn probability raster generated with the FSim model on the random treat 10% scenario fuelscape
i. **FSim_iBP_RAND25** - 120m burn probability raster generated with the FSim model on the random treat 25% scenario fuelscape
j. **FSim_iBP_HuDEN1** - 120m burn probability raster generated with the FSim model on the housing protection priority treat 1% scenario fuelscape
k. **FSim_iBP_HuDEN2h** - 120m burn probability raster generated with the FSim model on the housing protection priority treat 2.5% scenario fuelscape
l. **FSim_iBP_HuDEN5** - 120m burn probability raster generated with the FSim model on the housing protection priority treat 5% scenario fuelscape
m. **FSim_iBP_HuDEN7h** - 120m burn probability raster generated with the FSim model on the housing protection priority treat 7.5% scenario fuelscape
n. **FSim_iBP_HuDEN10** - 120m burn probability raster generated with the FSim model on the housing protection priority treat 10% scenario fuelscape
o. **FSim_iBP_HuDEN25** - 120m burn probability raster generated with the FSim model on the housing protection priority treat 25% scenario fuelscape
p. **FSim_iBP_FedTRSM1** - 120m burn probability raster generated with the FSim model on the federal transmission priority treat 1% scenario fuelscape
q. **FSim_iBP_FedTRSM2h** - 120m burn probability raster generated with the FSim model on the federal transmission priority treat 2.5% scenario fuelscape
r. **FSim_iBP_FedTRSM5** - 120m burn probability raster generated with the FSim model on the federal transmission priority treat 5% scenario fuelscape
s. **FSim_iBP_FedTRSM7h** - 120m burn probability raster generated with the FSim model on the federal transmission priority treat 7.5% scenario fuelscape
t. **FSim_iBP_FedTRSM10** - 120m burn probability raster generated with the FSim model on the federal transmission priority treat 10% scenario fuelscape
u. **FSim_iBP_FedTrtAll** - 120m burn probability raster generated with the FSim model on the treat all federal lands scenario fuelscape

5. **NCNM_FSim_EventSet.gdb** – ArcGIS 10.3 geodatabase containing shapefiles of all simulated wildfire perimeters and ignition locations generated with the FSim model on each of the priority fuelscapes in the north-central New Mexico study area.
   a. **FSim_Ignitions** – Shapefile of FSim wildfire ignition start locations
   b. **FSim_Perims_CC** – Shapefile of FSim modeled wildfire perimeters for the current condition scenario
   c. **FSim_Perims _TrtAll** – Shapefile of FSim modeled wildfire perimeters for the treat all lands scenario

d. **FSim_Perims _RAND1** – Shapefile of FSim modeled wildfire perimeters for the random treat 1% scenario
e. **FSim_Perims _RAND2h** – Shapefile of FSim modeled wildfire perimeters for the random treat 2.5% scenario
f. **FSim_Perims _RAND5** – Shapefile of FSim modeled wildfire perimeters for the random treat 5% scenario
g. **FSim_Perims _RAND7h** – Shapefile of FSim modeled wildfire perimeters for the random treat 7.5% scenario
h. **FSim_Perims _RAND10** – Shapefile of FSim modeled wildfire perimeters for the random treat 10% scenario
i. **FSim_Perims _RAND25** – Shapefile of FSim modeled wildfire perimeters for the random treat 25% scenario
j. **FSim_Perims _HuDEN1** – Shapefile of FSim modeled wildfire perimeters for the housing protection treat 1% scenario
k. **FSim_Perims _HuDEN 2h** – Shapefile of FSim modeled wildfire perimeters for the housing protection treat 2.5% scenario
l. **FSim_Perims _HuDEN5** – Shapefile of FSim modeled wildfire perimeters for the housing protection treat 5% scenario
m. **FSim_Perims _HuDEN7h** – Shapefile of FSim modeled wildfire perimeters for the housing protection treat 7.5% scenario
n. **FSim_Perims _HuDEN10** – Shapefile of FSim modeled wildfire perimeters for the housing protection treat 10% scenario
o. **FSim_Perims _HuDEN25** – Shapefile of FSim modeled wildfire perimeters for the housing protection treat 25% scenario
p. **FSim_Perims _FedTRSM1** - Shapefile of FSim modeled wildfire perimeters for the federal transmission treat 1% scenario
q. **FSim_Perims _FedTRSM2h** - Shapefile of FSim modeled wildfire perimeters for the federal transmission treat 2.5% scenario
r. **FSim_Perims _FedTRSM5** - Shapefile of FSim modeled wildfire perimeters for the federal transmission treat 5% scenario
s. **FSim_Perims _FedTRSM7h** - Shapefile of FSim modeled wildfire perimeters for the federal transmission treat 7.5% scenario
t. **FSim_Perims _FedTRSM10** - Shapefile of FSim modeled wildfire perimeters for the federal transmission treat 10% scenario
u. **FSim_Perims _FedTrtAll** - Shapefile of FSim modeled wildfire perimeters for the treat all federal lands scenario

- **California Data** (5.45 GB): Currently located on the Pyrologix FTP site: www.pyrologix.com/ftp/Public/USFS_DataArchive_RJVA/Sierra_Data.zip
    - **Note –** Data is identical to above except for the California study area.

1. **Sierra_FuelData.gdb** – ArcGIS 10.3 geodatabase containing 120m rasters of current condition and treated fuel conditions for the California study area.

2. **Sierra_FLPGen_Intensity.gdb** – ArcGIS 10.3 geodatabase containing 120m wildfire intensity rasters generated with the FLPGen fire model on the current condition and treated fuelscapes.
    i. *Citation*: Scott, Joe H. 2020. A deterministic method for generating flame-length probabilities. In: Hood, Sharon M.; Drury, Stacy; Steelman, Toddi; Steffens, Ron, [eds.]. Proceedings of the Fire Continuum-Preparing for the future of wildland fire; 2018 May 21-24; Missoula, MT. Proceedings RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 195-205.
3. **Sierra_Priority_Fuelscapes.gdb –** ArcGIS 10.3 geodatabase containing optimally generated fuelscape masks to address either home protection, federal risk transmission, or random treatment priorities.

4. **Sierra_FSim_BurnProbability.gdb** – ArcGIS 10.3 geodatabase containing 120m wildfire likelihood (burn probability) rasters generated with the FSim model on each of the priority fuelscapes in the California study area.
    i. Citation: Finney, M.A., McHugh, C., Grenfell, I.C., Riley, K.L., Short, K.C., 2011. A Simulation of Probabilistic Wildfire Risk Components for the Continental United States. Stochastic Environmental Research and Risk Assessment 25.7, 973-1000.

5. **Sierra_FSim_EventSet.gdb** – ArcGIS 10.3 geodatabase containing shapefiles of all simulated wildfire perimeters and ignition locations generated with the FSim model on each of the priority fuelscapes in the California study area.