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Comparing risk-based fuel treatment prioritization with alternative strategies for enhancing protection and resource management objectives

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Abstract

Background: 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. It is also important to consider how human factors related to risk tolerance may affect opportunities to manage fire. We build on these themes to illustrate an approach for examining whether, and how, fuel management can simultaneously minimize housing exposure while maximizing area suitable for expansion of beneficial wildfire. We generate multiple hypothetical post-treatment conditions according to distinct treatment prioritization schemes (Housing Protection, Federal Transmission, Random) and variable treatment extents and compare performance across strategies for a 8.5 million ha case study landscape in north-central New Mexico, USA.

Results: In general, we find 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 did not perform comparably until reaching a much larger treatment extent. Increasing risk tolerance for housing exposure expanded the area suitable for managed fire, while decreasing risk tolerance for beneficial fire opportunity and flame length probability shrunk the area suitable for managed fire.

Conclusions: 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 base for designing effective landscape fuel treatment strategies that can protect communities and expand beneficial wildfire on a fire-prone landscape. Successful integration 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 response options.

Keywords: Wildland fire, Risk, Modeling, Planning, Cohesive strategy

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Resumen

Antecedentes: Los avances en el modelado del fuego ayudan a cuantificar y mapear varios componentes y características del riesgo de incendio, y también a evaluar la habilidad de los tratamientos para mitigar ese riesgo. Desde luego, queda todavía pendiente la necesidad de diseñar tratamientos de combustibles a escala de paisaje con objetivos de protección, de manejo de recursos y respuestas al fuego. Es también importante considerar cómo los factores humanos relacionados con la tolerancia al riesgo pueden afectar las oportunidades para manejar el fuego. Trabajamos sobre esos temas, para desarrollar una aproximación para examinar dónde y cómo, el manejo de los combustibles puede simultáneamente minimizar la exposición de las construcciones (viviendas) y maximizar, a su vez, el área adecuada para la expansión de incendios beneficiosos. Generamos múltiples condiciones hipotéticas post-tratamiento de acuerdo a diferentes esquemas de priorización (protección de residencias, azar, transmisión del fuego en tierras federales) y extensiones variables en los tratamientos, y comparamos la performance entre estrategias en un caso de estudio que involucró un paisaje de 8,5 millones de ha en el centro-norte de Nuevo México, EEUU.

Resultados: En general, encontramos que realizar tratamientos cerca de las viviendas pueden proveer el mayor nivel de protección en relación al tratamiento de lugares más remotos para reducir el potencial de transmisión del fuego. El tratamiento en tierras federales para reducir la transmisión del fuego fue altamente efectivo para reducir la exposición de estas tierras al fuego y expandir las oportunidades de fuegos beneficiosos, aunque contribuyeron comparativamente muy poco a reducir la exposición de las viviendas a todos los fuegos en general. Encontramos que la extensión de los tratamientos en bajos niveles (2,5 al 5%) pueden producir beneficios significativos si se usan estrategias optimizadas espacialmente, mientras que una estrategia realizada al azar no se comportó de la misma manera sino hasta alcanzar una expansión mucho mayor (> extensión) de estos tratamientos. El incremento de la tolerancia al riesgo en la exposición de viviendas expande el área posible de ser tratada con fuego manejado (i.e. quemas prescriptas), mientras que el decrecimiento de la tolerancia para realizar fuegos beneficiosos reduce la oportunidad de realizarlos, por incrementos a la altura de llama, contrayendo así el área adecuada para manejar los fuegos.

Conclusiones: Este trabajo provee una contribución en términos explícitos del encuadre de análisis de riesgo y diseños de tratamiento de combustible alrededor de tierras federales y objetivos de manejo de recursos, y aporta al conocimiento de base sobre el diseño de estrategias de tratamiento de combustible efectivos a nivel de paisaje que pueden proteger comunidades y expandir los efectos beneficiosos del fuego en lugares propensos al mismo. La integración exitosa de estos temas requiere incorporar todos los pilares de la Estrategia Nacional Cohesiva para el Manejo de Incendios Forestales, incluyendo el manejo coordinado de combustibles donde conviven varios propietarios, la mitigación de la ignición en áreas de vivienda, y la planificación de la respuesta al fuego en zonas con diferentes propietarios colindantes, que puedan guiar las operaciones de manejo y supresión del fuego y poder expandir las opciones de respuesta.

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 USA, 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 at reducing fire extent and severity, 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 wildfire into an effective landscape-scale fuel treatment strategy that keeps people and property safe and ecosystems healthy. Wildfires that are managed to achieve ecological benefits typically occur in remote areas distant from the wildland urban interface, involve a single management agency, and burn under conditions conducive to lower severity (Iniguez et al. 2022). A recent systematic review (Fillmore et al. 2021) identified six key thematic groups affecting decisions to manage wildfires using strategies other than full suppression: institutional influences (e.g., agency support), operational considerations (e.g., resource availability), fire outcomes (e.g., improved wildlife habitat), fire environment (e.g., previous fuel reduction work), perceived risk (e.g., risk to human life and infrastructure), and sociopolitical context (e.g., collaborative relationships and impacts to cooperators). Here, we build from some of these insights to explore how fire simulation and risk assessment can support landscape fire and fuel management scenario analyses, with the joint objectives of reducing community exposure and expanding areas of opportunity for beneficial fire. In particular, we focus on how landscape analysis can reduce uncertainty surrounding potential fire outcomes, the fire environment, and perceived risk, and leverage the insight that wildfires are more likely to be managed for benefit if they are unlikely to threaten human communities.

The work presented here builds off advances in fire simulation (Finney 2002; Sullivan 2009; Finney et al. 2011) that have created a capacity to quantify and spatially map various components and characterizations of risk (Haas et al. 2013; Scott et al. 2013; McEvoy et al. 2021), information which is hoped to inform and improve fire and fuel management planning. Simulation-based burn probability modeling is widely used in many operational and planning contexts (Parisien et al. 2019) and model results are increasingly made available for public viewing and policy analysis (e.g., Scott et al. 2020; Short et al. 2020). Often, 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 offsite when a fire ignites in one location and subsequently spreads to another location, is especially important to understand as wildfires burn for longer durations across larger landscape extents.

The use of quantitative risk analysis based on simulation and decision support models, though not without limitations and challenges, can inform fuel management planning and decision-making (Colavito 2021). Notable examples in the USA include national and regional fuel management prioritization (Ager et al. 2021; Thompson et al. 2015), incident decision support (Calkin et al. 2021; O'Connor and Calkin 2019; Noonan-Wright and Opperman 2015; Noonan-Wright and Opperman 2015), and project-level fuels reduction (Ager et al. 2007). 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; Plucinski 2019). 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 (HVRA) 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 and Thompson 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 as well as design of fuel management strategies (O'Connor and Calkin 2019; Caggiano et al. 2020; Thompson et al. 2017, 2022; Hogland et al. 2021; Beeton and Caggiano 2022a, 2022b, 2022c).

These analyses fit into a pattern of increasing global use of fire and risk modeling to diagnose landscape wildfire challenges and to prioritize and evaluate mitigation actions. Examples include comparable approaches in fire-prone regions of Australia (Furlaud et al. 2017; Gazzard et al. 2019), the Mediterranean (e.g., Alcasena et al. 2016; Jahdi et al. 2022; Sakellariou et al. 2022; Mitsopoulos et al. 2015), North America (e.g., McFayden et al. 2019; Metlen et al. 2021; Paveglio et al. 2018; Stockdale et al. 2019; Yemshanov et al. 2021; Pais et al. 2021), and South America (e.g., Molina et al. 2018; Castillo et al. 2017; Argañaraz et al. 2017). Other related approaches, such as Bayesian networks, similarly emphasize the importance of probabilistic analysis for proactively addressing wildfire management challenges (e.g., Price and Bedward 2019; Penman et al. 2020; Papakosta et al. 2017; Elia et al. 2020; Syphard et al. 2019; Elhami-Khorasani et al. 2022).

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. It is also important to consider how human factors related to risk perception and tolerance may affect decisions to manage fire (North et al. 2015b; Thompson et al. 2018; Fillmore et al. 2021). We build on these themes to illustrate an approach for examining whether, and how, fuel 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?

In this study, we designed a set of landscape fuel treatment strategies that vary systematically in total area treated and in 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, defined here as minimizing housing exposure and maximizing area suitable for beneficial wildfire. The analysis is presented for an 8.5 million ha case study landscape in north-central New Mexico, USA, and fire simulations are performed on alternative static fuelscape absent consideration of future growth, succession, or disturbance. Evaluation of expanded area of opportunity for beneficial fire is limited to fires igniting on federal lands and is considered an upper bound constrained by thresholds for simulated housing exposure and preexisting assessments of beneficial fire to specific HVRAs. In the subsequent sections, we describe our modeling approach, present salient results including attainment of treatment objectives and return on investment metrics, discuss novel insights and relations to existing literature, and offer suggestions for how future work could better integrate with wildfire response planning.

Methods

A generalized schematic of the modeling workflow is presented in Fig. 1, which is built around five main elements whose details are described in the following sub-sections. Starting in the upper left, a modeled fuelscape representative of current conditions (ca. 2015) is used to calibrate the fire modeling systems and develop estimates of fire likelihood, intensity, and rate of spread. Next, simulation results paired with exposure and risk analysis lead to the development of optimized priority fuelscapes. These fuelscapes are then run through the same fire modeling and exposure and risk analysis components to derive performance metrics for alternative treatment strategies.

Study area

We conducted our simulations and analyses for a study area 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 (Fig. 2). Approximately 3.45 million ha or 40% of the study area are in federal ownership. This includes lands managed by the Bureau of Land Management, National Park Service, US Fish and Wildlife Service, and the USDA Forest Service. Elevations vary greatly across the analysis area from 1280 m southeast of Las Vegas New Mexico to 4260 m in the Culebra Range of the Sangre de Christo mountains. Vegetation predominantly follows elevation bands with grasslands and pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.)

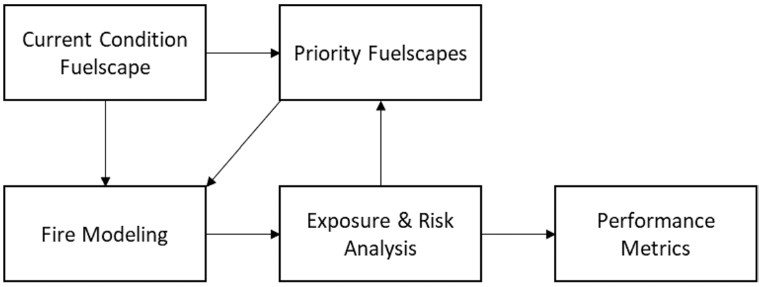

Fig. 1 Generalized modeling workflow for generating priority fuelscapes on the basis of exposure and risk analysis and deriving metrics to compare treatment strategy performance

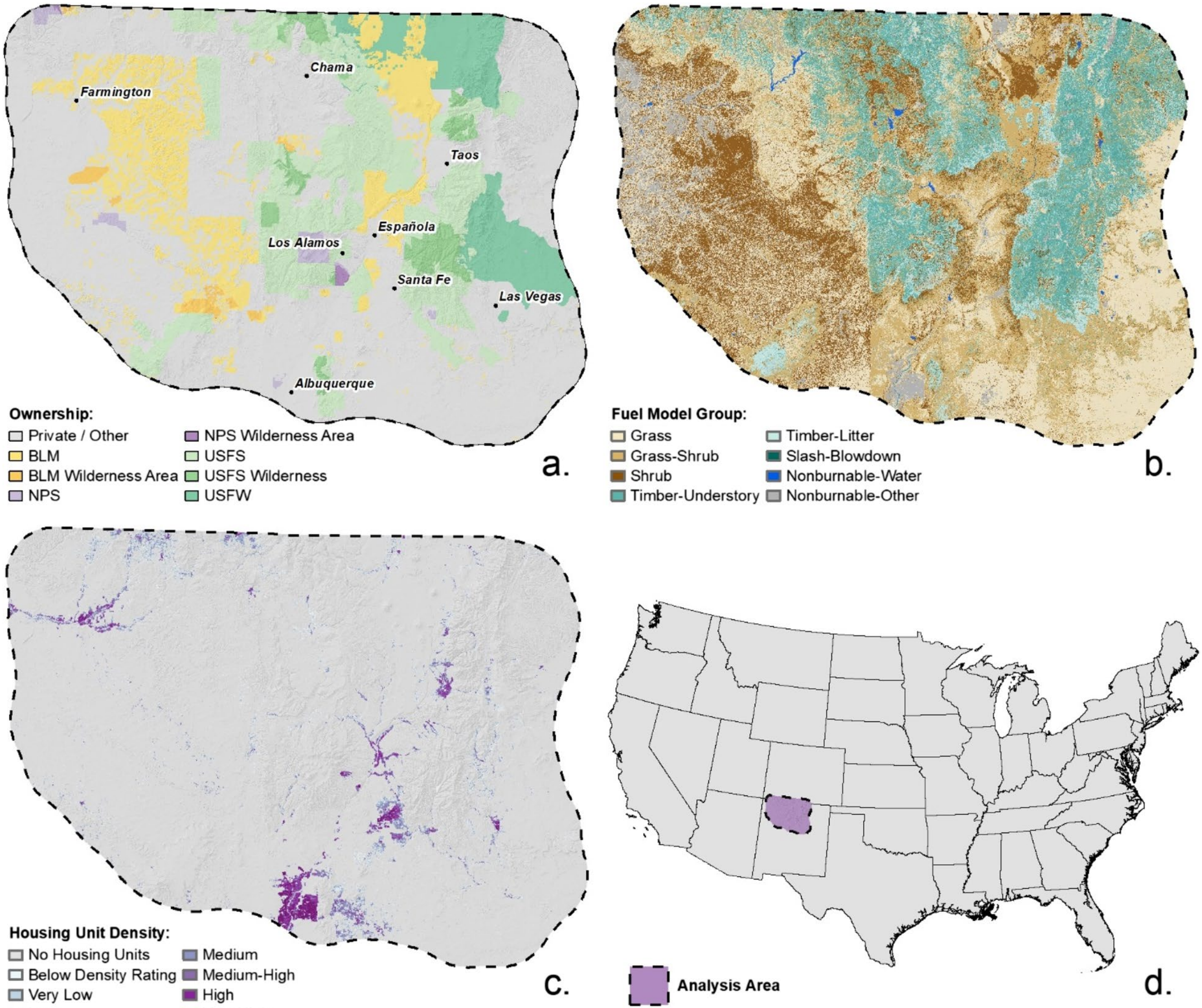

Fig. 2 Maps of the distribution of land ownerships (**a**), wildland fuel distribution (**b**), housing unit density (**c**), and location of the project analysis area (**d**). BLM, Bureau of Land Management; NPS, National Park Service; USFS, US Forest Service; USFW, US Fish and Wildlife Service. Fuel Model Groups represent the dominant fire-carrying fuel type. Housing unit density bins: 0 (no structures), > 0–6 (below density rating), 6–12 (very low), 12–24 (low), 24–49 (medium), 49–123 (medium-high), 123–741 (high), and > 741 (very high) structures per square kilometer

woodlands at lower elevations transitioning into Ponderosa Pine (*Pinus ponderosae scopulorum*) and wet mixed conifer forests at higher elevations. The predominant fire regime is 0–35 years, low severity (33% of the study area) followed by 35–100+ years, mixed severity (26% of the study area), and 35–100+ years, stand replacement severity (21%). Primary fire management objectives include a mix of resource and asset protection as well as resource management, and there is a history of managing wildfire for resource objectives in the region, in some cases leveraging some of the risk modeling tools described above (Caggiano et al. 2020; Davis et al. 2022). In 2022, two prescribed burns escaped and became wildfires (Calf Canyon Fire and Hermits Peak Fire) that merged and grew into the largest fire in New Mexico state history at approximately 138,295 ha. These fires were located in the eastern portion of the study area to the east of Santa Fe and south of Taos; the analysis presented here was performed before these fires occurred. Additional information on contemporary landscape conditions as well as fuel management and incident response concerns can be found in recent reports by Day et al. (2021) and Caggiano et al. (2020).

We leveraged information from a pre-existing quantitative wildfire risk assessment on federal lands in the study area to coarsely characterize the potential for beneficial fire and to constrain the maximum area suitable for expansion of beneficial fire (C. O'Connor and B. Gannon, personal communication). Key HVRAs in the area include human habitation, water for drinking and irrigation, infrastructure, wildlife habitat, cultural resources, and timber. Many of the HVRAs are modeled to experience benefits, which are listed in Table 1 along with their maximum beneficial flame length. For the Water HVRA category, irrigation and drinking water yields are both expected to benefit from flame lengths up to 1.8 m. In the Infrastructure category, ski areas (up to 2.4 m) and undeveloped recreation areas (up to 0.6 m) are expected to benefit. The Ecosystem Function category included more than ten sub-HVRAs, many of which benefit from a variety of fire intensities, with spruce-fir forest, high elevation grasslands, and aspen expected to benefit from flame lengths > 3.7 m. Five sub-categories of wildlife were identified, two of which benefit from flame lengths up to 1.8 m (Jemez Mountains salamander and Mexican spotted owl). Lastly, timber stands were expected to benefit from flame lengths up to 1.8 m.

Table 1 Highly valued resource and asset (HVRA) categories contained within the quantitative wildfire risk assessment along with maximum beneficial flame lengths considered for beneficial fire effects analysis

HVRA category	Maximum beneficial flame length (m)
Water	1.8
Infrastructure	2.4
Ecosystem function	> 3.7
Wildlife	2.4
Timber	1.8

FSim model and calibration to current conditions

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 likelihood and intensity of wildfire across the landscape (Finney et al. 2011). The FSim large-fire simulator was used to simulate 20,000 complete fire seasons. There is no temporal component to FSim beyond a single wildfire season, consisting of up to 365 days. FSim performs independent (and varying) iterations of 1 year, defined by the fuel, weather, topography, and wildfire occurrence inputs provided. Each year represents an independent realization of how fires might burn given the current fuelscape and historical weather conditions. FSim integrates all simulated iterations into a probabilistic result of wildfire likelihood.

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 utilizes probability modeling to identify when and where to simulate wildfire ignitions based on historical occurrence patterns. 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 temporal ignition probability model calibrates FSim to only start fires during the times of the year that have historically allowed for the development of large-fire disturbances. Additionally, the spatial ignition model is a raster representing the relative density of large-fire ignitions across the landscape. The entire landscape is saturated with wildfire over the

20,000 simulated citations but higher densities of fires are simulated in locations that have historically provided an ignition source, fuel, and weather conditions that support the development of large fires. 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 624,710 simulated wildfire perimeters that collectively are integrated into a probabilistic result of wildfire likelihood. Individually, simulated perimeters represent a 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 to 2016 USDA Forest Service Fire Occurrence Database (Short 2017). Additionally, care was taken to match simulated wildfire size distributions to the historical record and allow for the occurrence of simulated fires larger than any observed historically. While only large-fire sizes (> 247.1 acres) were considered in calibration, numerous small fires were also simulated. However, the impact of small fires on landscape-level burn probability is negligible. 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 gives higher weights to 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 USA. 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 modified to align in age with the LANDFIRE 5 years post-disturbance period.

The national-scale treated fuelscape was not specifically calibrated to the local fuels within the project analysis area. To prevent model effects where fuel reduction treatments inadvertently exacerbate fire behavior, we removed fuel treatments from the analysis that were ineffective from consideration in the prioritization themes. To be considered effective, a fuel treatment had to reduce flame length by at least 0.15m and not increase the rate of spread by more than 20%. Masking out these areas (185,346 ha) left 3.0 million hectares treatable or 35.8 % 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 120 m resolution using the ArcGIS Aggregate tool. Figure 2c represents a map of the HuDEN data for the analysis area.

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 (Fig. 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.

Developing priority landscapes

To test the impact of fuel on local (in situ) and transmitted exposure, we developed a series of 20 hypothetical post-treatment fuelscapes. Each of the individual fuelscapes was 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 ($n = 253{,}239$) was 33.5 ha in size and mimics the operational scale of treatments within the analysis area. Given the broad scale of this analysis, additional site-specific variables that may impact the feasibility of treatments such as road access, slope steepness, and treatment cost 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 user-defined objectives given a set of constraints (in this study, maximum treatment area). Treatments were weighted by their ability to address each of the prioritization metrics discussed below. We modeled scenarios where 1% (85,481 ha), 2.5% (213,702 ha), 5% (427,404 ha), 7.5% (641,106 ha), 10% (854,809 ha), 25% (2,137,017 ha), and 100% (8,548,085 ha) of the analysis area were treated. Note that the Federal Transmission scenario was limited to only treating on federal lands where the maximum area treated scenario covered 18% of the analysis Area or 1,538,651 ha. The 1% treatment scenario is roughly equivalent to a 5-year plan of work for the federal agencies within the analysis area.

Housing protection priority

Developing priority treatments to reduce housing exposure first required 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.

Federal transmission priority

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, 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 (Finney 2007). 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. 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 1200 machine hours to complete.

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 opportunity 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:

$$\text{eHUExp} = \sum_{h}\sum_{i}\text{BP}_{\text{h}} * \text{HUcount}_{\text{h}}$$

Treatment performance—expanded opportunities for managed fire

To quantify the opportunity for resource benefit from managed fire, we used a successive series of filters to constrain suitable area. First, we quantify the area burned from fires that did not 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 2.5-km search radius point density smoothing. The exposure raster was divided by a 2.5-km smoothed point density raster of large simulated 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 then filtered to only include ignitions from federal lands to prevent the model from identifying opportunities to manage ignitions on other ownerships. We characterize this as a theoretical upper bound on area of opportunity, referred to as high opportunity area. Recognizing that the presence of other fire-sensitive resources or assets on the landscape would not support managed fire in many locations, we next constrained the maximum area suitable for beneficial fire by quantifying the proportion of federal land where risk assessment results were neutral to positive (i.e., beneficial) and to capture managerial risk tolerance further filtered to intersect with locations where the probability of exceeding 1.8-m flame lengths was less than 25%. This amounted to approximately 43% of federal lands covered by the risk assessment, which we deploy in a coarse, non-spatial manner to create a practical upper bound called low opportunity area.

Opportunities for managed fire were calculated as:

$$\text{High opportunity area} = \sum \text{Federal pixels where exposure} = 0$$

$$\text{Low opportunity area} = \text{High opportunity area} \times 0.43$$

Return on investment

We calculated return on investment (ROI) metrics for various treatment strategies relating treatment benefit to treatment extent. Treatment benefits were calculated as a percentage of the maximum attainable benefit by treating 100% of the landscape. ROI metrics were then calculated as the ratio of the benefit percentage to landscape treatment percentage.

Results

Fire simulation results and prioritized treatment strategies

Figure 3 displays measures of wildfire hazard (likelihood and intensity) on the current condition landscape, specifically burn probability (across all flame length classes) and conditional fame length and rate of spread. Simulated probabilities and intensities are generally highest in areas to the west of Los Alamos and the east and

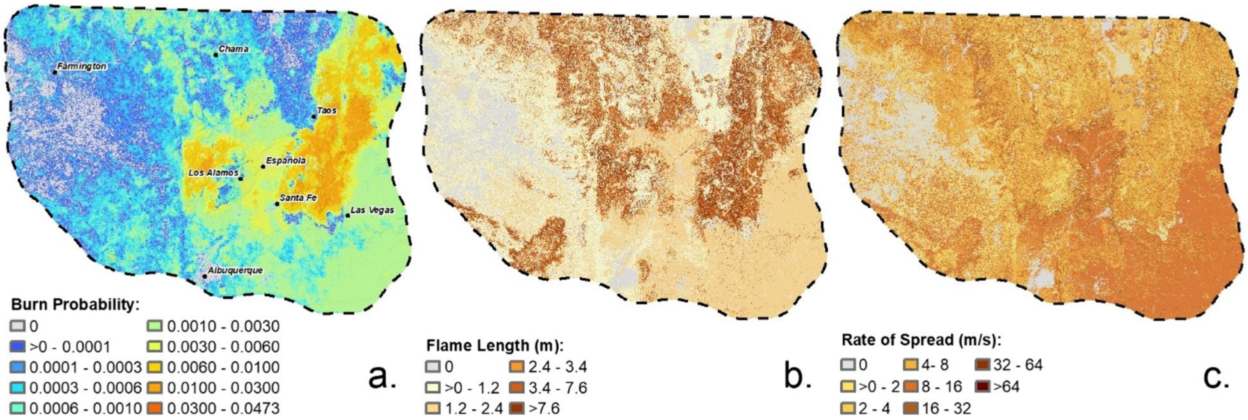

Fig. 3 Maps of FSim simulated burn probability and FLEPgen generated (**a**) and flame length (**b**) and rate of spread (**c**) for the current condition fuelscape

northeast of Santa Fe and Taos; these patterns are consistent with those of timber fire behavior fuel models targeted for treatment on the treated fuelscape (see 2).

Figure 4 displays spatial patterns of treatment, 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. High-priority areas also tend to be located near areas of greater fire likelihood and intensity, reflecting the joint effects of proximity to housing as well as fire spread patterns on the landscape. Figure 5 combines the findings of Fig. 4, displaying the spatial patterns of the two modeled treatment priorities including areas of overlap, for treatment extents up to 10%. As treatment extent grows, so too does the area of overlap, or joint priority.

Housing exposure and resource benefit opportunity

Figure 6 compares treatment strategy performance for reduced housing unit exposure, differentiated by considering all simulated fires (panel a) and just simulated fires igniting on federal lands (panel b). Starting with all fires, on the current condition landscape, the expected housing exposure is 306 units per year. At 100% treatment intensity, that number is reduced to 174 per year, i.e., extensive treatment can protect 132 housing units from exposure annually. Across all prioritization themes, housing

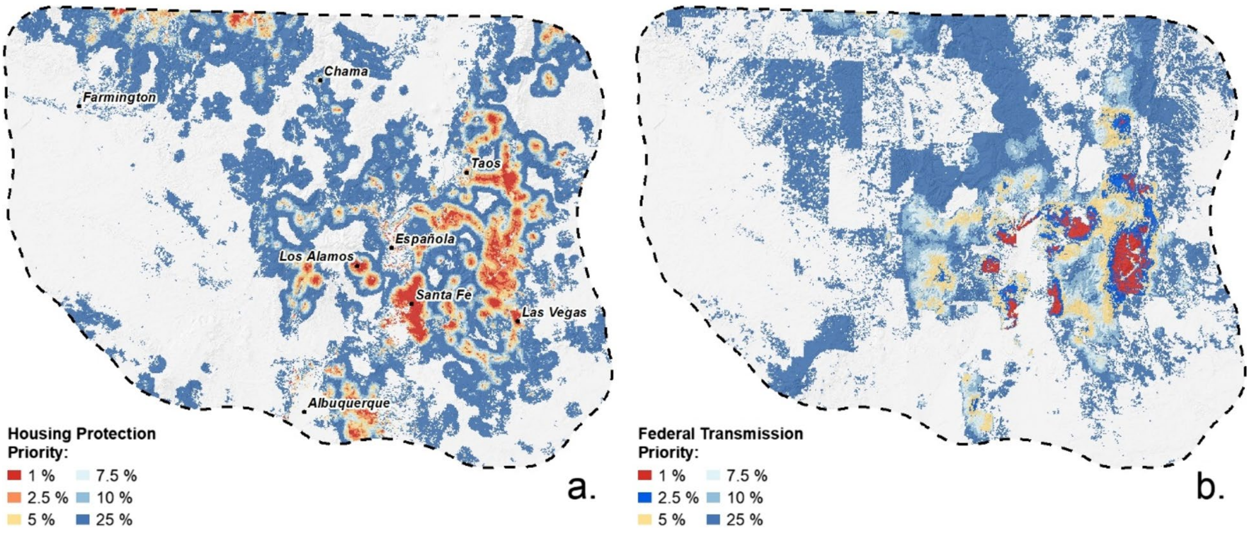

Fig. 4 Optimal treatment strategies, by treatment intensity, for prioritization themes focused on housing protection (**a**) and federal wildfire risk transmission (**b**)

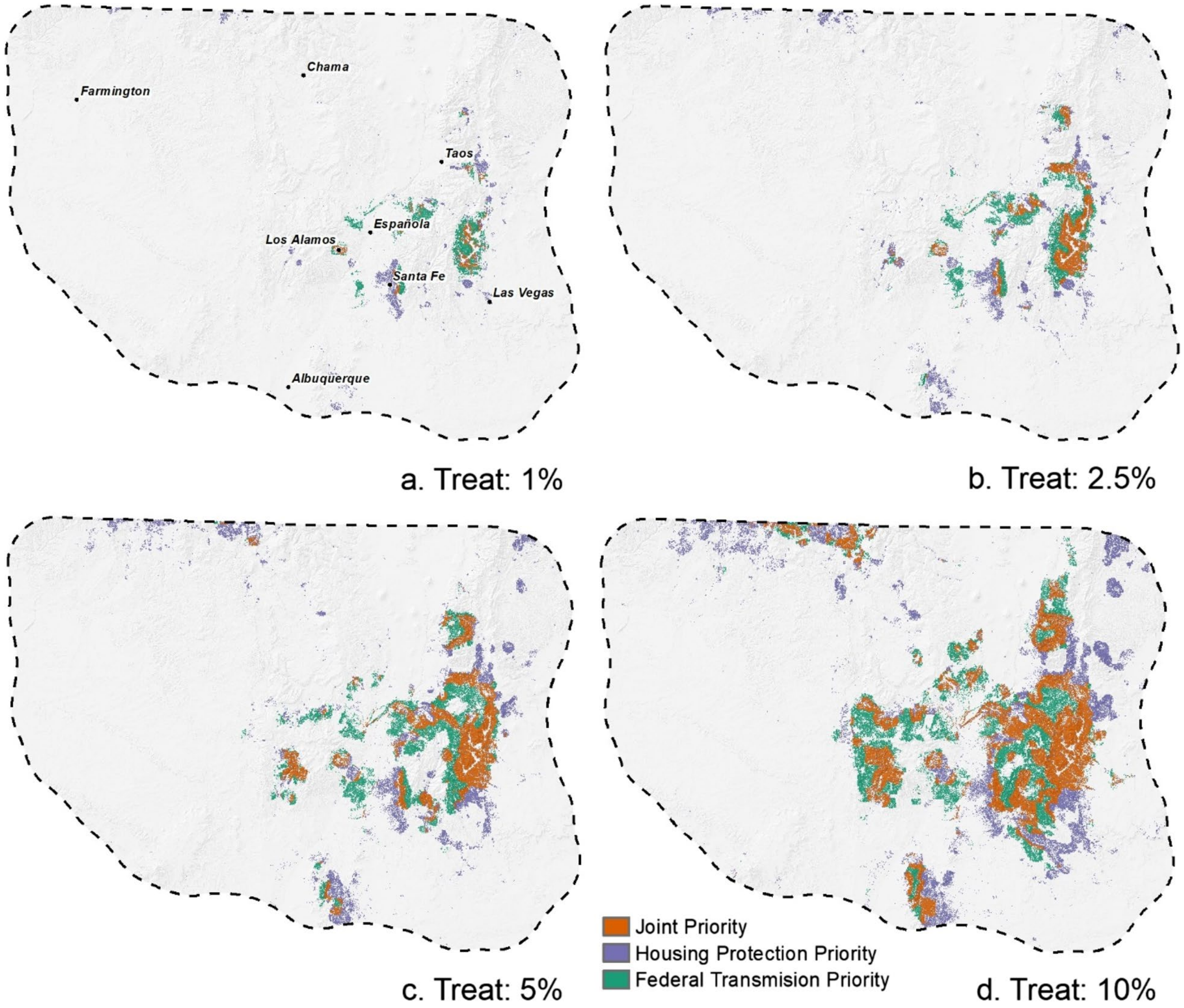

Fig. 5 Optimal treatment strategies, by treatment intensity, for prioritization themes focused on housing protection and federal wildfire risk transmission as well as the overlap between the two treatment priorities

exposure drops steeply with increasing treatment intensity and then begins to taper off at anywhere from 5–25% depending on theme. The Housing Protection Priority strategy performs best at overall reductions in exposure, achieving 83.3% of total possible reduction (110 home protected of 132 possible) at just the 2.5% treatment level, and 92.4% reduction (122/132) at the 5% treatment level.

Notably, in panel (a), the Federal Transmission theme performs comparatively worse than Housing Protection and asymptotes around 10% treated yielding no further benefit (at which point Random begins to outperform). By contrast, in panel (b) when looking only at federal fires, the Federal Transmission theme performs nearly as well as the Housing Protection theme. For the untreated landscapes, 108 housing units are exposed coming from federal fires per year, meaning 198 units are exposed from non-federal fires annually. In other words, housing exposure from non-federal fires is nearly twice that from the federal transmission. At 100% treatment intensity, exposure from federal fires can be reduced to 34 homes per year, i.e., extensive treatment can protect 74 housing units from exposure annually. Thus, although treating federal lands to reduce federal transmission can be highly effective at reducing exposure from federal fires (the 5% treatment level achieves 83.3% of total possible reduction from federal fires (65/74)), it contributes comparatively little to reducing exposure from all fires, due largely to where exposure-causing fires ignite.

Figure 7 displays treatment strategy performance for the objective of expanding the area of opportunity for

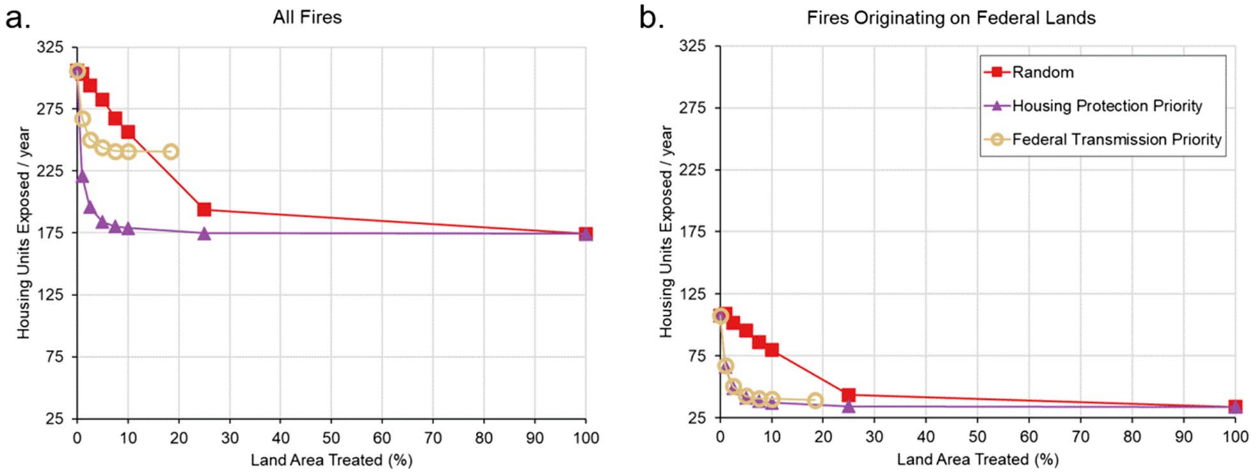

Fig. 6 Reduction in housing unit exposure across prioritization themes and treatment intensities, considering all simulated fires (**a**) and just fires ignited on federal lands (**b**). Note that the maximum available treatment intensity for the Federal Transmission theme is 18%

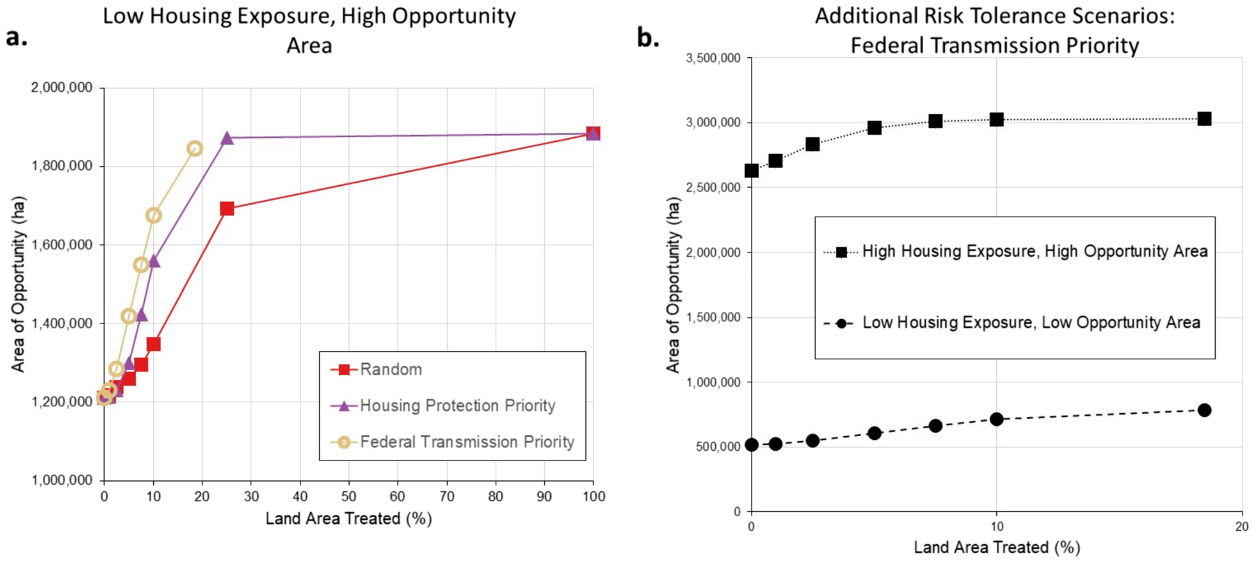

Fig. 7 Increases in opportunities to manage wildfire, across treatment themes treatment intensities, considering on ignitions resulting in no exposure (**a**) and comparison to other risk tolerance scenarios for housing exposure and opportunity area (**b**). Low housing exposure corresponds to 0 housing units exposed and high housing exposure corresponds to < 25 housing units exposed

managing wildfire, under various levels of risk tolerance. The left panel maintains the baseline tolerance of 0 homes exposed and uses the high opportunity area criteria for beneficial fire. Results generally share the similarity with Fig. 6 of steep improvements that then taper, although here the slope of improvement is less steep. At 100% treatment intensity, the area suitable for managing wildfire with 0 housing unit exposure increases from 1.21 million ha to 1.88 million ha, an increase of 673,410 ha. The Federal Transmission Priority strategy outperforms others for a given treatment extent, and 18% treatment extent achieves 98% of the maximum opportunity area (1.84/1.88 million ha). The right panel compares additional risk tolerance scenarios for just the Federal Transmission Priority strategy. In one case, when considering ignitions that expose < 25 housing units and retaining the high opportunity area criteria, the starting area available for managing fires is larger at 2.63 million ha, and reaches 3.03 million ha at the 18% treatment extent. By contrast, a stricter tolerance considering wildfires with 0 housing exposure and using the low opportunity area criteria reduces the suitable starting area by a factor of 5.15 to 516,456 ha, and at the 18% treatment extent the suitable area is reduced by a factor of 3.85 to 787,312 ha.

Figure 8 summarizes treatment themes and extents across both performance measures, presented for the low housing exposure, low opportunity area risk tolerance criteria. Results indicate complementarities across treatment themes, i.e., increasing levels of housing protection are associated with higher opportunities for managing wildfire due to reduced housing unit exposure, and vice versa. To reiterate, for a given treatment extent the Housing Protection Priority strategy performs best in terms of housing units protected, whereas the Federal Transmission Priority strategy 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. Consistent with Fig. 6, panel b illustrates the comparatively lower housing exposure associated with fires originating on federal lands.

Return on investment

Figure 9 compares treatment strategy performance in terms of ROI metrics that relate percent attainment of maximum achievable objective to percent of landscape treated. ROI metrics are presented for the low housing exposure, low opportunity area tolerance criteria. Unsurprisingly, the Federal Transmission Priority theme exhibits its higher ROI for increase in opportunity area, whereas the Housing Protection Priority exhibits a higher ROI for housing units protected. For the objective to protect housing, the highest ROI metrics occur at the 1% treatment rate, with an ROI of 64.38 for the Housing Protection Priority strategy, reflecting the pattern in Fig. 6 of a steep improvement that quickly tapers. By contrast, for the objective to expand opportunities for managed fire, the highest ROI metrics occurs at either the 7.5 or 10% treatment extent, reflecting the pattern observed in Fig. 8. For fires originating on federal lands, the Federal Transmission Priority strategy nearly dominates the Housing Protection Priority strategy for any given treatment extent, achieving nearly the same ROI for housing units protected with significant improvement in opportunity area ROI.

Lastly, Fig. 10 maps areas suitable for managed fire and how they vary according to housing exposure risk tolerance and treatment strategy at 10% treatment extent, using the high opportunity area risk tolerance criteria. Only federal lands are shown, for the narrower context of exploring opportunities for expanding managed fire on federal lands. Areas colored gray correspond to >25 homes exposed. Under the current condition, there are few opportunities to manage fires with 0 housing unit exposure, unsurprisingly largely located distant from population centers (panel a). Panel b illustrates the increase in opportunity areas for managed fire from the two prioritization scenarios and indicates substantial areas of overlap, although the overlap is attenuated for lower treatment extents (see Figs. 4 and 5). Panels c and d

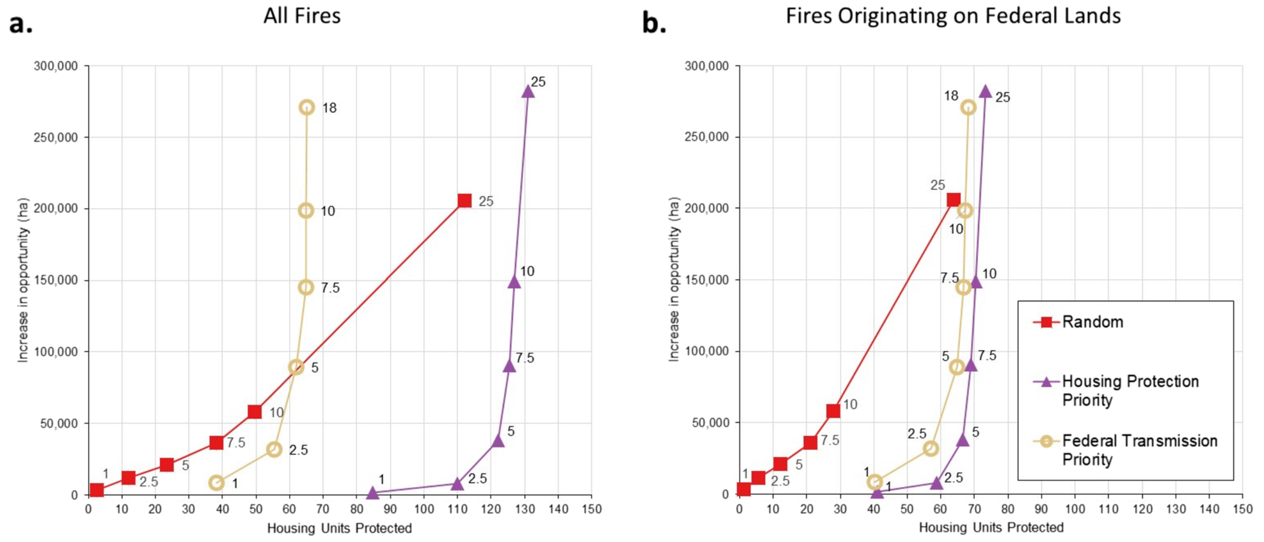

Fig. 8 Joint evaluation of treatment strategy performance in terms of housing units protected (*x*-axis) and increased area of opportunity for managed wildfire (*y*-axis), all relative to the baseline current conditions. a represents all simulated fires, and b represents only fires that originate on federal lands. Here, the results are presented for the low opportunity area criteria for beneficial fire. The numbers associated with each point represent the treatment extent (in percentage)

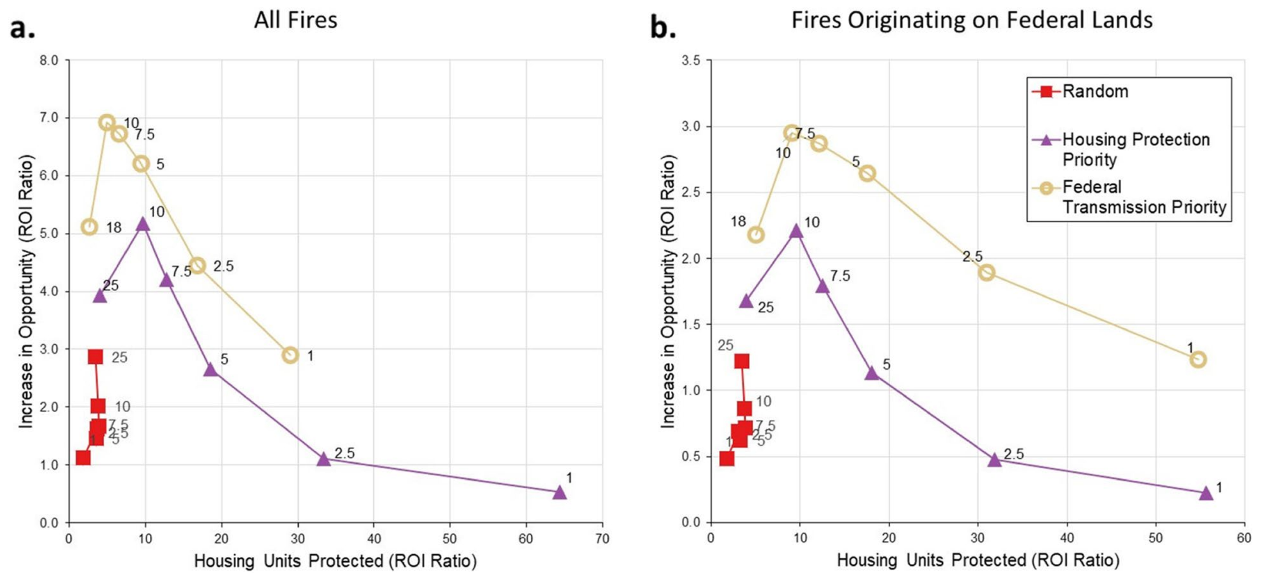

Fig. 9 Return on investment (ROI) metrics for treatment strategies, consider all fires (**a**) and fires originating on federal lands (**b**)

instead illustrate expanded opportunities for the different treatment strategies that are effectively the spatial union of panels a and b. Clearly, the treatment strategy offers substantial opportunity for managed fire with reduced likelihood of transmission to communities, especially in areas to the east of Santa Fe and southeast of Taos. Interestingly, this is approximately where the Calf Canyon Fire and Hermits Peak Fire burned, consistent with a need for large-scale treatment in those areas to reduce risks of large fire transmission and housing exposure.

Discussion

This study adds to the knowledge base regarding design of landscape fuel treatment strategies and shows whether, and how, fuel management can expand opportunities for beneficial wildfire on a fire-prone landscape. Most applications of the risk analysis framework—whether they support fuel management planning or operational fire management decisions—have been largely framed around purposes of meeting protection objectives. Our simulation-based results demonstrate how fuel management may expand opportunities for managing wildfires for resource objectives. This study expands on findings from recent work that combines stochastic wildfire simulation with risk analysis (Barnett et al. 2016; Scott et al. 2016; Thompson et al. 2016b) in at least two important ways. First, while others have evaluated the effectiveness of treatment strategies in terms of home exposure, we have evaluated effectiveness in terms of creating opportunities for using wildfire. Second, while previous research (Thompson et al. 2016a) has used risk analysis to determine where wildfires might be managed for resource objectives, our results suggest how landscape fuel treatments might be designed to expand those areas.

Our work demonstrates some commonalities with other research on simulated fuel treatment effectiveness. First, results indicated a steep increase in treatment benefits that then taper off at various treatment extents that vary with theme. Second, the importance of treatment strategy diminishes as treatment extent increases, in cases where extensive treatment is feasible. Third, treating near housing units may provide the greatest overall housing exposure, and strategically locating treatments near at-risk assets can significantly reduce the area of treatment needed for a common level of protection. ROI metrics for housing protection were highest at 1% treatment extents, reflecting the value of strategic and precise location of treatments that protect assets from a multitude of ignition sources across the landscape. ROI metrics for expanded opportunity area by contrast peaked at 7.5–10% treatment extents, suggesting a need for larger scale of treatment to create opportunity to reduce transmission from ignition on federal lands.

Treatment on the federal estate was modeled to 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. However, the Federal Transmission Priority scheme did substantially increase the area

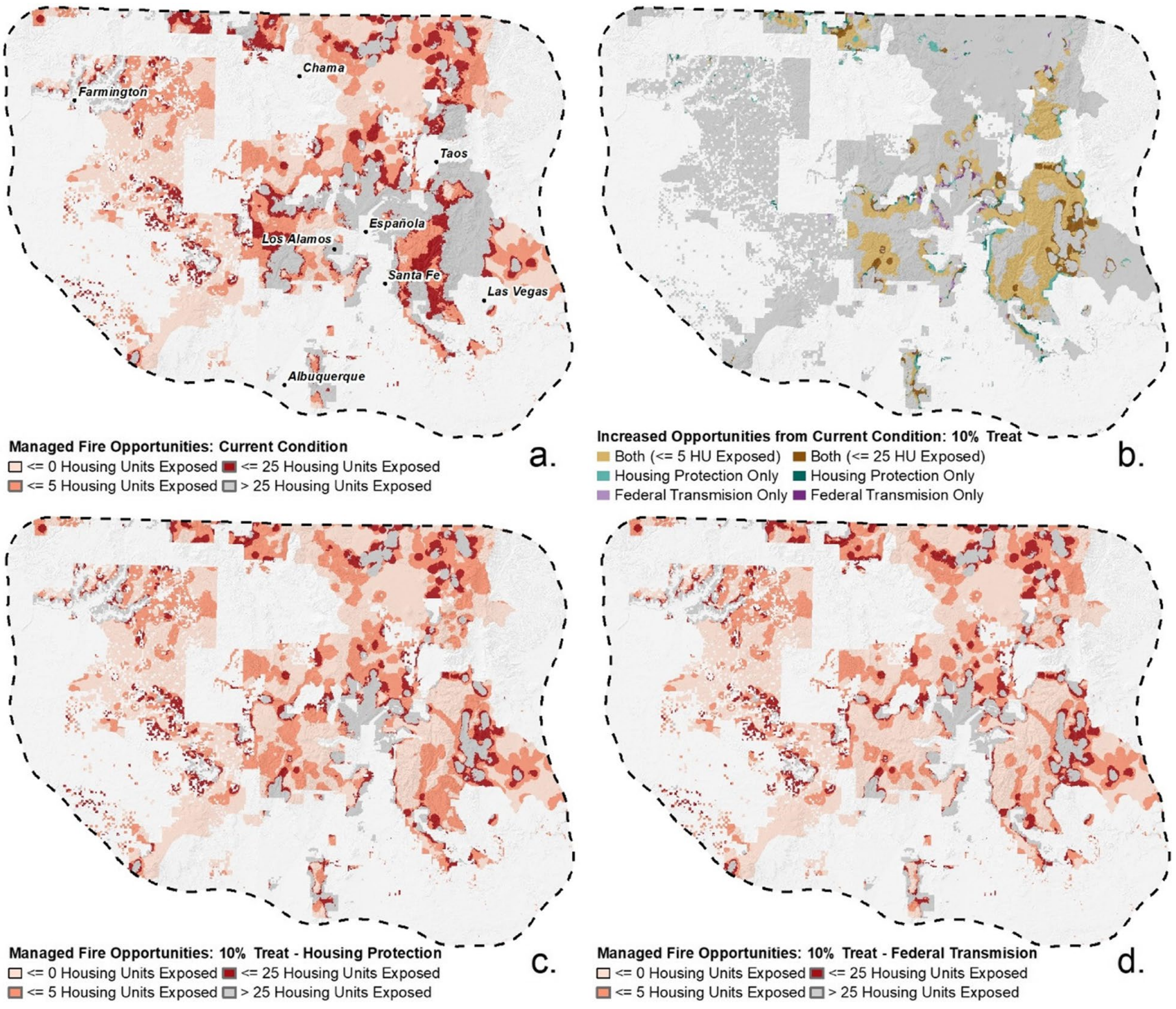

Fig. 10 Comparison of spatial patterns of ignition transmission and home exposure across the current condition landscape (**a**), increase in in areas of opportunity and spatial overlap from different treatment strategies (**b**), increase in managed fire opportunities from the Housing Protection strategy (**c**) and increase in managed fire opportunities from the Federal Transmission strategy (**d**)

suitable for managed fire while exhibiting positive ROI metrics for housing protection, suggesting possible synergies to reduce transmission risk while expanding options to meet federal land and resource management objectives in fire-prone systems. At the same time, the inclusion of risk tolerance criteria based on beneficial fire assessment and flame length probabilities substantially reduced the area suitable for managed fire. Recognizing the myriad other factors that can constrain the application of managed fire (Fillmore et al. 2021; Davis et al. 2022), these results suggest the need for expansion of prescribed burning as well to restore fire to fire-adapted systems.

Modeling results indicate 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 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 aspirational synergy with broader elements of the National Cohesive Wildland Fire Management Strategy comes 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). Relating to risk tolerance, the hypothetical choice of being more comfortable with exposure would be more feasible if exposed housing units were more fire resistant. 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 response options. Combined, reduced potential for loss and enhanced potential for control can increase managerial risk tolerance. This 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 when designing treatment priorities and assessing 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 does not 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 suppression tactics and strategies that could result in different transmission pathways and exposure levels. Additionally, there are modeling assumptions, uncertainties that can propagate, methodological issues over how to best validate burn probability models, and a need for continuous improvement in fire behavior modeling (Beverly and McLoughlin 2019; Parisien et al. 2020; Duff et al. 2012; Liu et al. 2015; Cruz et al. 2018). 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

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 base for designing effective landscape fuel treatment strategies that can protect communities and expand opportunities for beneficial wildfire on a fire-prone landscape. Successful integration 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 expanding response options.

Reducing federal transmission is complementary with, but not identical to, a strategy to protect housing. These nuanced differences are important to highlight when developing strategies considering factors such as where and how risk can best be mitigated and who can best mitigate that risk. The work presented here provides insights into how alternative treatment priorities differ in overall performance as well as in ROI metrics and can provide guidance for future mitigation investments with limited resources. Further, the framework can help identify complementarities with federal management strategies that emphasize landscape resilience and restoring fire to fire-adapted systems. Future work here can proceed along four important directions—first by expanding sensitivity analysis and application to other study areas to explore whether findings regarding treatment performance and ROI are robust, second by incorporating additional social and ecological variables into the analysis of managed fire opportunities, third by integrating treatment design with operational response planning to locate treatments to afford greater opportunities for control, and lastly 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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Authors' contributions

MPT helped conceive the study design and led the writing of the manuscript. KCV and JHS helped conceive the study design, led the data analysis and modeling efforts, and helped write the manuscript. CM helped conceive the study design and contributed to writing the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

Wildfire simulation data is available on the USDA Forest Service Research Data Archive (https://www.fs.usda.gov/rds/archive/catalog/RDS-2022-0026).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare they have no competing interests.

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