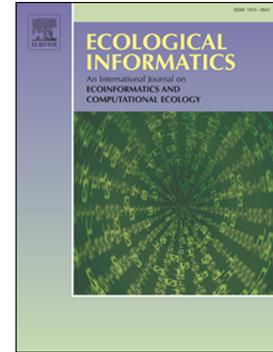


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Configurations of fuel break networks influence landscape-level fire-risk in Southern  
California

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## Abstract

Linear fuel treatments, Fuel Break Networks, are widely implemented in California, USA fuel types to improve firefighter safety and facilitate fire containment. Despite frequent construction, landscape scale evaluations of their effectiveness with fire modeling remain limited in this region. This study presents a framework to assess how fuel break configuration, arrangement, and firefighter tactics influence fire control opportunities using a customized spatial metric for Uncontrollable Wildfire Risk (UWR). UWR combines outputs from fire modeling software widely available to fire and land management practitioners with suppression difficulty weights derived from previous literature. Fire spread simulations were conducted across four case study fuel break configurations in Southern California: Single Segment, Branching Network, Enclosed Network, and Multiple Segment Network. Three leverage scenarios (unstaffed, firebreak, and firing operations) were applied to each landscape. Linear mixed effects models and spatial analysis quantified the effects of distance from treatment, wind alignment, topography, treatment width, length, sinuosity, and proximity to other treatments on UWR. Results showed that increased leverage intensity consistently reduced UWR, while treatment geometry and spatial arrangement influenced risk reduction in some models. Notably, in some instances unstaffed fuel breaks increased burned area due to changes in fuel characteristics and subsequent fire behavior. This research highlights the importance of selecting appropriate outcomes for wildfire modeling evaluations of fuel break placement and operational utilization.

*Keywords:* firefighter safety, fire ecology, fire risk, hazard, suppression leverage, spatial configuration

## 1. Introduction

In Southern California's diverse landscapes, contemporary wildfire regimes threaten the recovery of extant vegetation, creating a positive feedback loop where altered ecosystems burn more frequently and at higher severity (Keeley and Brennan, 2012; Mallek *et al.*, 2013; Stevens *et al.*, 2017). The region's historically frequent fire forested systems may be restored through the strategic use of fuel treatments and wildfire (Agee and Skinner, 2005; Tubbesing *et al.*, 2019; Furniss *et al.*, 2024; Boerigter *et al.*, 2024). Conversely, Southern California's chaparral-dominated ecosystems were shaped by less frequent (30-130 yr intervals), high-severity fire. Here, scientifically informed management practices involve limiting burned area and reducing the human ignitions that cause the largest wildfires, allowing these ecosystems to recover (Keeley and Brennan 2012; Keeley and Syphard 2018; Syphard *et al.*, 2018). Throughout the region, social, economic, and physical constraints challenge best management practices, reinforcing fire prevention and suppression as the dominant solution (Collins *et al.*, 2010; Miller *et al.*, 2020; Fillmore *et al.*, 2024; Halsey and Syphard, 2024; Furniss *et al.*, 2024).

To achieve fire management objectives, practitioners pre-emptively construct strategically placed linear fuel treatments, hereafter Fuel Break Networks (FBNs), in locations where firefighters are likely to place containment lines (Green 1977; Agee *et al.*, 2000). Fuel breaks are constructed and maintained along natural and anthropogenic features that moderate fire behavior and provide access and holding locations for firefighters, such as ridges, valleys, and road systems. (Green 1977; Syphard *et al.*, 2011; Gannon *et al.*, 2023). In shrub systems, construction involves fuel type conversion by partially or completely removing or rearranging dense surface and canopy fuels (Green 1977). Construction methods include mechanized equipment (crushing and mastication of vegetation), or hand tools, and prescribed fire. Initial

treatment is sometimes followed by seeding of less flammable herbaceous species (Green and Schimke, 1971; Green, 1977). Maintenance schedules vary by location and are influenced by local vegetation productivity (Green, 1977; Aubard *et al.*, 2020). Establishment methods depend on site conditions and objectives but may promote erosion, fragmented wildlife habitat, or invasive species spread (Merriam *et al.*, 2006; Shinneman *et al.*, 2019). These ecological consequences must be weighed against the benefits of a reduction in wildfire risk afforded by a well-designed and effectively used FBN (Shinneman *et al.*, 2019).

Generally, Southern California fuel breaks are effectively leveraged to contain wildfires in 22-47% of cases (Syphard *et al.*, 2011; Gannon *et al.*, 2023). Effectiveness is dependent upon treatment placement, maintenance, intensity, width, the presence and type of firefighting resources, fire behavior and weather (Omi 1977; Green, 1977; Agee *et al.*, 2000; Syphard *et al.*, 2011; Gannon *et al.*, 2023; Ortega *et al.*, 2024; Young *et al.*, 2024; Johnson, *in prep*). Firefighters using linear treatments may conduct direct (constructing fireline on the burning edge) and indirect suppression tactics (allowing fire to reach a distant fireline or firing operations) (Plucinski, 2019). When firefighters are present to conduct fire control or “leverage” the reduced fuel profiles and fireline intensities in FBNs, fuel break effectiveness, or the likelihood of successful containment and improved firefighter safety, increases (Green 1977; Syphard *et al.*, 2011; Gannon 2023; Young 2024). The concept of fuel treatment “leverage” originates from comparisons of ratios of fuel treatment area to avoided burned area, damages, and suppression costs (Loehle 2004; Boer *et al.*, 2009; Price *et al.*, 2015; Thompson *et al.*, 2017). Leverage uniquely suits the objectives of fuel break construction and is used hereafter to describe various wildland firefighting tactical FBN uses (Young *et al.*, 2024). Fuel breaks left unleveraged are “unstaffed” by firefighters during treatment-fire intersections. In southern

California unstaffed treatments are almost always ineffective in limiting fire size, however, additional consequences of this phenomenon are poorly understood (Syphard *et al.*, 2011).

Fire spread modeling has been used to evaluate the influence of planned and existing FBN extent, connectivity, placement, and prescription on various simulated outcomes (Oliviera *et al.*, 2016; Ott *et al.*, 2023; Nguyen *et al.*, 2024). Assessments in the USA, Portugal, and China have presented optimal fuel break construction scenarios by evaluating fire interception rates, reductions in area burned, exposure to buildings, cross-boundary transmission, and failure rates (Van Wagendonk *et al.*, 1996; Finney, 2001; Oliveira *et al.*, 2016; Zong *et al.*, 2021; Aparício *et al.*, 2022; Belavenutti *et al.*, 2023; Ager *et al.*, 2023; Nguyen *et al.*, 2024). Simulating fire spread through linear treatments requires field sampling to create custom fuel models (Collins *et al.*, 2013), the assignment of homogenous fuel structures (Gray and Dickinson, 2016), or the assumption that wildfires will not burn through linear treatments (Oliveira *et al.*, 2016). After selecting treatment assumptions, researchers must choose to focus on single outcomes (Oliveira *et al.*, 2016; Ager *et al.*, 2023; Zong *et al.*, 2021), or aggregated measures of multi-dimensional risk, such as towards ecological values or the built environment (Aparício *et al.*, 2022; Belavenutti *et al.*, 2023; Nguyen *et al.*, 2024). Previous simulation studies have had limited consideration of varying levels of suppression effort in the context of FBNs, creating a need for flexible prospective evaluation tools that explicitly consider the impact of fire contagion and intensity on containment opportunities and firefighter safety (y Silva *et al.*, 2014).

In operational wildland fire research, the agreed upon definition of risk generally includes fire likelihood, fireline intensity, and effects on social, ecological, or economic systems at varying levels (Scott, 2006; Miller and Ager, 2012). Wildfire effects are wide ranging and variable. Impacts on ecosystems may be positive or negative depending on ecological history and

current conditions (Stephens *et al.*, 2013). Conversely, impacts on the built environments and human safety are generally considered to be negative (Plucinski, 2019). Accounting for every variable may increase workflow complexity, decreasing the flexibility of applications (Thompson and Calkin 2011). Previous examples focusing on firefighter safety and fuels hazard include Integrated Hazard (IH) and Wildfire Hazard Potential (WHP) (Scott *et al.*, 2012; Dillon *et al.*, 2015). IH is the product of fire likelihood and fireline intensity. Wildfire Hazard Potential (WHP) advances this concept by combining fire likelihood, and fire intensity weighted line production rate derived control difficulty (Dillon *et al.*, 2015). Due to the complexity of analysis, managers using WHP rely upon experts to update the nationally mapped version of the product periodically at 270m spatial resolution (Dillon *et al.*, 2023). Consequently, WHP cannot be used for fine-scale sensitivity testing of planned fuel treatment effects on fuel hazard. While a version of IH is available for managers conducting counterfactual analysis using the Interagency Fuel Treatment Decision Support System (IFTDSS) (Drury *et al.*, 2016), a need exists for managers assessing the influence of planned treatments on the intersection of risk and explicit risks to fire control likelihood and firefighter safety.

Recent research has focused on landscape level evaluations, which includes outside of treatment area effects. These relationships often lack rigorous empirical evaluation due to the challenges associated with data collection and analysis. The lack of data-driven analysis of landscape treatments, like FBNs, is a critical gap in our knowledge regarding fuel treatment effectiveness (McKinney *et al.*, 2022; Ott *et al.*, 2023; Urza *et al.*, 2023). The evaluation of landscape level fuel break effectiveness is pressing considering increased investments in fuel treatments on private and public lands in the United States (Knight *et al.*, 2022). Additionally, the incorporation of fuel breaks within comprehensive land management frameworks such as

Potential Operational Delineations (PODs), which segment landscapes by fire response objectives, make landscape level fuel break effectiveness an important subject for further investigation (North *et al.*, 2021; Thompson *et al.*, 2022). The strategic placement of linear treatments may aid managers by reducing local and landscape risk, which may be leveraged to increase the effectiveness of control efforts. However, questions persist regarding their effectiveness under extreme weather conditions, in different configurations, and under various conditions of suppression leverage (Gannon *et al.*, 2023; Young *et al.*, 2024; Nguyen *et al.*, 2024).

We developed a framework to assess how planned and installed linear fuel break configurations alter across landscape opportunities for fire control and firefighter safety using a customized risk metric (Uncontrollable Wildfire Risk, details below) inspired by WHP (Dillon *et al.*, 2023). FBN spatial data was grouped into categories by arrangement characteristics, and case study examples were selected in Southern California. Case study examples under multiple suppression leverages were used as inputs in fire spread modeling and the outputs were used to develop our risk metric and to construct an FBN evaluation framework answering the following questions:

- 1) What are common configurations of constructed fuel breaks in California?
- 2) What is the landscape impact of fuel break leverage on Uncontrollable Wildfire Risk?
- 3) How does fuel break arrangement, configuration, and geometry influence Uncontrollable Wildfire Risk across landscapes?

## **2. Materials and Methods**

## 2.1 Study System

Southern California's variable topography, elevation, and climate support diverse vegetation communities including mixed conifer forest, shrublands, and grasslands (Van De Water and Safford, 2011). Except for the Sonoran and Mojave deserts, which are beyond the scope of this study, the region's vegetation is shaped by its Mediterranean climate, elevation gradients, and associated fire regimes (Stephenson and Calcarone 1999; Keeley and Syphard 2018). At low and mid elevations, the region's expansive wildland urban interface frequently borders crown-fire adapted chaparral communities dominated by flammable chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylos* sp.) and ceanothus (*Ceanothus* sp.) (Van De Water and Safford, 2011). At higher elevations, fire suppressed pine dominated forests historically shaped by frequent and low severity fire persist (Stephenson and Calcarone 1999). The area is bounded by the Pacific Ocean to the west and the Mojave and Sonoran Deserts to the east (Figure 1). Average annual precipitation in the region varies from 15 - 44cm fueled by periods of heavy rain during the winter. Average temperatures during the May to October fire season range from 19- 23C (NOAA, 2024). Anthropogenic sources provide 95% of the region's ignitions and can fuel fires occurring during Santa Ana winds in the fall and winter, accounting for the majority of the region's burned area (Keeley and Syphard, 2018)

## 2.2 Fuel Break Network Categories

Data on thirty fuel breaks were collected from a survey of California fire managers distributed during Spring 2021 (Johnson, *in prep*). Snowball sampling, a purposive chain-referral method where subjects recruit additional participants through their networks, was used to distribute the survey (Parker *et al.*, 2019). Survey data represents treatments throughout

California, with twenty-five treatments in the shrub, grass and oak woodland dominated Central California Foothills and Coastal Mountains, Southern California Mountains, and Southern California/Northern Baja Coast ecoregions (Supplementary Figure 6; Supplementary Table 12) (Omernik and Griffith 2014). The other five fuel breaks were in conifer systems and did not represent meaningfully different configurations from the rest of the data. Linear treatment data was provided directly by respondents or mined from the USDA Forest Service, Forest Activity Tracking System (FACTS) Hazardous Fuel Treatment Reduction dataset (USFS, 2020) and the California Department of Forestry and Fire Protection's (CAL FIRE) treatment database CalMAPPER (CAL FIRE, 2021). FACTS polygons were identified through project names and general locations collected through the survey. We also collected information on nearby treatments, which served two purposes: increasing certainty of association with survey responses and including adjacent treatments intended for simultaneous use during incident management.

Treatment designs were examined relative to topography, roads, and communities using ArcGIS Pro basemaps (ESRI, 2024). Design characteristics were recorded and non-exclusive treatment categories were established to group the dataset into four configurations: Single Segments, Branching Networks, Enclosed Networks, and Multiple Segment Networks (Figure 2). Branching Networks feature segments branching from primary ridge systems down sub-ridges or valleys (Omi 1977). Enclosed Networks surround high risk or strategic areas such as highways or continuous expanses of vegetation (Oliveira *et al.*, 2016). Multiple Segment Networks feature multiple discontinuous segments of varying shapes distributed across a landscape. Single Segments are individual, non-sinuuous treatments. We selected case study examples from each category for evaluation in a fire modeling environment: Limestone Ridge (Segment), Boundary Ridge (Branching), Mount Lowe (Enclosed), and North Mountain

(Multiple Segment). Treatment categories are not mutually exclusive; therefore one treatment might belong to multiple groups. For example, a treatment featuring characteristics of a Branching Network could be classified as a Multiple Segment Network.

Southern California is a crucial location for fuel break research (Syphard *et al.*, 2011; Gannon *et al.*, 2023; Young *et al.*, 2024; Nguyen *et al.*, 2024). Case study fuel breaks were selected exclusively from this region to facilitate treatment performance comparisons. The case study examples represent the EPA Level III Ecoregions most representative of the categorized fuel break data set described above – Southern California Mountains (Boundary Ridge and North Mountain), Southern California/Northern Baja Coast (Limestone Ridge), Central California Foothills and Coastal Mountains (Mount Lowe) (Omernik and Griffith 2014) (Figure 1). These ecoregions feature similar Mediterranean climates, a preponderance of chaparral shrub communities, and fire regimes (Stephenson and Calcarone 1999). However, key vegetation differences exist, such as concentrations of oak woodlands in the case studies in the Southern California Mountains and Central California Foothills and Coastal Mountains and coastal sage scrub in the Southern California Coast landscape (Griffith *et al.*, 2016).

The Boundary Ridge, Mount Lowe, and North Mountain polygons were collected from FACTS using a combination of respondent-provided documents and locations. The Boundary Ridge respondent submitted a post-fire assessment of the 2009 Sheep Fire including images of treatments. The Mount Lowe fuel breaks were located using respondent-provided aerial imagery. The North Mountain respondent provided an approximate location (North Mountain System near Beaumont, CA), which was used to identify linear treatments near Beaumont with North Mountain in the project name. All FBNs were implemented or maintained between 2015 and 2020. Treatment data for Limestone Ridge was provided as a line shapefile, which was buffered

according to the survey-reported width. A construction date for Limestone Ridge was not provided, but the treatment was successfully used in 2020 on the Silverado Fire. Below, we describe locations and adjacent vegetation using LANDFIRE Existing Vegetation Type (LANDFIRE, 2016).

The Limestone Ridge Single Segment fuel break (Figure 2A) was constructed across Limestone Ridge Road, which runs along a northeast angled ridge located east of Limestone Canyon in Limestone Canyon Regional Park. The treatment extends from the intersection with Santiago Canyon Road, west of the Williams Canyon community. The treatment covers 18ha, is 3.9km long, and approximately 46m wide. The primary pre-treatment vegetation type inside and surrounding the treatment is California coastal scrub. The fuel break was used to defend nearby communities during the 2020 Silverado Fire.

The Boundary Ridge Branching FBN (Figure 2B) consists of two separate treatments totaling 28km in length with an average width of 100m on the San Bernardino National Forest. One treatment, constructed in Southern California Dry-Mesic Chaparral, is on a primary ridge, with three lateral treatments following east angled sub-ridges. The North Fork of Lytle Creek is to the southwest and Lone Pine Canyon lies to the northeast. The second treatment separates Lone Pine Canyon to the southeast and the town of Wrightwood to the northwest, extending across a ridge and crossing Lone Pine Canyon road. Adjacent and interior vegetation is Mesic Mixed Conifer Forest and Woodland and Southern California Dry-Mesic Chaparral. The FBN was used during containment operations on the 2009 Sheep Fire.

The Mount Lowe Enclosed FBN (Figure 2C) consists of 4 separate segments northeast of San Luis Obispo, surrounding part of Highway 101 in the Santa Lucia Mountains. The

treatments are constructed primarily on northwest to southeast angled ridges around Highway 101 and the community of Thyle in the Los Padres National Forest. Surrounding and interior vegetation is primarily Northern and Central California Dry-Mesic Chaparral and Coastal Live Oak (*Quercus agrifolia*) Woodland and Savannah. Total treatment length covers 43km with an average width of 35m, although widths are variable between treatments. Survey results indicate the fuel break was unsuccessfully used during the 2015 Cuesta fire.

The North Mountain Multiple Segment FBN (Figure 2D) consists of 6 segments totaling 35.4km in length with an average width of 35.7m. The FBN is constructed in Southern California Dry-Mesic Chaparral and lies west of Highway 243 and east of Hemet, CA. The fuel breaks partially surround the community of Poppett Flats on public land managed by the San Bernardino National Forest and Bureau of Land Management. Managers reported the FBN has been used for wildfire management, but did not include the incident name(s). Please see Supplementary Tables 10 and 11 for additional description of case study fuel breaks characteristics (Scott and Burgan 2005).

### **2.3 Wildfire Simulations**

Fuel break assessments were conducted using Flammap 6.2, which allows users to simulate fire behavior and growth across landscapes for thousands of fires under static wind and fuel moisture conditions (Finney, 2006). First, we modified treatment polygons using ArcGIS Pro to represent three fuel break leverage scenarios, ordered by increasing intensity: unstaffed (treatments in place, but no barrier to fire spread), firebreak (unburnable linear surface through

treatment impedes fire growth but is susceptible to spot fires), and firing operation (200m wide unburnable surface from fuel break center impedes fire spread and limits spot fires).

Treatment polygons were used to modify LANDFIRE 2020 gridded fire modeling fuel profile inputs in the Interagency Fuel Treatment Decision Support System's (IFTDSS) Workspace Editor, which were exported for use in Flammap 6.2 (Drury *et al.*, 2016; LANDFIRE, 2020; Finney *et al.*, 2023). We delineated modeling landscapes using the IFTDSS Map Viewer by centering treatments and examining fires larger than 40.5 ha in study regions to determine dimensions (Parisien *et al.*, 2019). Four versions of each landscape were created including a control and the three leverage scenarios. Unstaffed and recently type-converted treatments were modeled by masking areas under polygons to fire behavior fuel model GR1 (Gray and Dickson, 2016). GR1 is an arid to semiarid climate short grass fuel model exhibiting minimal fire behavior compared to other grass fuel models (Scott and Burgan, 2005). Simulated firebreaks were implemented by converting a 30m polygon centerline to a non-burnable fuel model (NB 98). Approximated firing operation used a 200-meter one-sided buffer from centerlines masked to NB 98.

The ideal depth of firing operations depends on fire behavior, fuel type, and objectives. We chose a 200m buffer after careful consideration of the lead author's personal experience and verified our selection through communications with local managers (Fillmore 2023, *pers. comm.*). Firing operation widths would ideally vary between fuel types due to variable fireline intensities and spot fire risk (Cooper 1969). However, the assumed depth would create a "safety-zone" (an unburnable area 4 times greater than the maximum flame height) under most conditions and may be a best-case scenario during initial attack of a quickly spreading wildfire (Butler, 2014).

Single wind directions and fuel moisture conditions were calculated from 97<sup>th</sup> percentile Energy Release Component conditions (Deeming *et al.*, 1977). Remote Automatic Weather Stations (RAWS) and associated identification numbers were located for each landscape using the IFTDSS Map Viewer. Weather from May 1 to October 31 for the previous 10 years was selected to reflect fire season conditions and avoid extreme wind events, which distort weather variable distributions (NWCG, 2025) (Supplementary Tables 1-2). Fire Family Plus 5.0 was used to create fuel moisture and wind files required for Flammap 6.2 (Jolly and Heinsch, 2024).

Toggles were selected for 60m resolution gridded winds, a 6 hour burn period, and randomly placed ignitions. Gridded winds use a conservation of mass equation with a digital elevation model, vegetation heights, and static wind direction as inputs, allowing wind directions to vary inside of individual grids (Forthoffer and Butler 2007). A six-hour burning period creates a distribution of fire sizes for which fire suppression would be challenging, but potentially successful during high fire danger conditions (Gannon *et al.*, 2023). This selection also limits the occurrence of large fires resembling longer duration events during which responders may be unable to leverage already constructed control features (Bayham *et al.*, 2022). Ignition counts were determined using the minimum number needed to burn 98% of each landscape in preliminary IFTDSS runs, rounded to the next highest number divisible by 5000 to ensure saturation. We selected the Scott/Reinhardt crown fire method, to allow the simulation of crown fire in forested portions of landscapes (Scott and Reinhardt 2001). Spot fires were also enabled, with the default spotting probability of 0.2 selected for all simulations.

All inputs were identical for the four simulations on an individual landscape (control, unstaffed, firebreak, firing operation), but different between landscapes to reflect local climatological influences on fire behavior (Supplementary Tables 1-2). Fire locations from

control simulations were used in subsequent processing of leverage scenarios, limiting stochastic differences in outputs. A 2km buffer was implemented on FBN landscapes to decrease edge effects, allowing fires to burn into and out of study areas. The segment landscape was trimmed further to increase the treated proportion, aiding comparison between fuel break configurations. Final outputs consisted of 30m resolution BP (Burn Probability), Flame Length Probability files to create 30m CFL (Conditional Flame Length), and fire size lists.

## 2.4 Suppression Hazard Metric

We combined BP, CFL and weights derived from suppression effectiveness literature to create a new spatial metric reflecting Uncontrollable Wildfire Risk (UWR). Our metric follows widely accepted definitions of wildfire risk, where BP indicates the likelihood of an area burning, CFL the intensity at which it is likely to experience wildfire, and hazard weights imply an explicit impact on firefighter safety and fire control operations. Analysis was completed in the R Programming Language using the Terra and Tidyverse libraries (Wickham *et al.*, 2019; Hijmans, 2023; R Core Team, 2023).

To begin, BP is calculated by dividing the number of times a given cell burns ( $F$ ) by the total number of fires on the modeling landscape ( $N$ ) (Finney, 2006).

$$BP = \frac{F}{N} \quad (1)$$

The algorithm for CFL, calculated from Flame Length Probability (FLP) files, is the sum of the product of a flame length category's midpoint ( $FL_i$ ) and the probability of that flame length category occurring ( $FLP_i$ ), across all flame length categories. Each burned pixel reflects

conditional flame lengths contingent on the spread direction of overlapping fire polygons (Finney, 2002).

$$CFL = \sum_{i=1}^{20} (FL_i)(FLP_i) \quad (2)$$

Suppression difficulty has a positive relationship with fireline intensity due to the width, quality, and construction rate of fireline needed to halt tall flames (Burgan, 1979; Plucinski, 2019). Hand crews alone are typically ineffective beyond 1000 kW/m, larger resources capable of producing wider containment lines more quickly, such as bulldozers, are ineffective beyond 3000 kW/m, and aircraft applying retardant can reduce fire behavior for ground resources to contain fire spread up to 5000 kW/m (Burgan, 1979; Loane and Gould, 1986; Budd *et al.*, 1997). Fireline intensity was converted to flame length using Byram's (1959) equation and hazard weights were assigned via relationships between flame length categories and resource types required for suppression (Table 1). Generally, the relationship between fireline intensity and suppression hazard follows an S-shaped logistic growth curve, where suppression occurs with relative ease at low flame lengths, and beyond a certain threshold difficulty increases rapidly before plateauing at intensities where suppression becomes ineffective (Burgan, 1979). In the equation below,  $\phi_1$  equals the maximum hazard weight value, while  $\Phi_2$  is the intercept and  $\Phi_3$  is the coefficient of a logit model created from assigned hazard weights and suppression effectiveness thresholds (Figure 3, Equation 3, Table 1).

$$W = \frac{\phi_1}{(1 + \exp(-(\phi_2 + \phi_3 FL)))} \quad (3)$$

UWR at location  $j$  is the natural logarithm of the summed product across flame length categories ( $i$ ) of the Flame Length Probability (FLP), flame length category midpoint (FL),

hazard weights associated with each flame length category ( $W$ ), and the probability that a cell will burn ( $BP_j$ ). A constant is derived from the minimum logged UWR value of a landscape ( $c_l$ ) and added to ensure values are above 0 (Equation 4). Weights representing hazardous flame length categories were derived from Equation 3. The logarithmic transformation was applied to limit exponentially decreasing values, increasing map readability and interpretability of subsequent analysis.

$$UWR_j = \log\left(\sum_{i=1}^{20} (FLP_i \cdot FL_i \cdot W_i) \cdot BP_j\right) + c_l \quad (4)$$

UWR is a dimensionless metric for mapping the risk of uncontrollable wildfire. Across landscapes, values ranged from <0.01 to 13.58 and 95% of the data fell between 0.61 and 12.65. UWR values map closely to CFL while greater dispersion is visible in relation to BP values (Supplementary Figure 1). The metric should be interpreted in the context of the associated risk definition, and high values may represent locations where fire is likely to challenge control efforts due likely fire spread or high CFL values, with the metric weighted towards the latter condition. Therefore, a relatively high UWR value may be associated with a location where higher flame lengths are predicted, but burn probability is low, while the inverse is possible, it is less common (Figure 4).

## 2.5 Analyses

### 2.5.1 Descriptive Statistics

UWR may be interpreted at multiple scales including individual pixels or summarized across regions to assess suppression hazard at the landscape scale. We calculated multiple UWR and fire size statistics for each case study modeling scenario to understand changes in landscape

level fire characteristics. Measurements include mean UWR, percent change from untreated, and the difference of mean UWR between untreated and leverage scenarios multiplied by a normalization metric (ratio of treated area to landscape size), facilitating comparison between case studies. Fire size statistics included change from a uniform distribution of fires in the untreated landscape and total burned area per treatment hectare. We divided fires into 5 equal size classes (quintiles) for untreated landscapes and calculated shifts in the uniform distribution to compare change in the number of fires per size class across leverage scenarios. Fire size lists were summed to total burned area, facilitating calculations of reduction in burned area per treatment hectare.

### **2.5.2 Sampling and Variable Production**

Systematic sampling and variable creation were conducted using the Terra and sf libraries in R (Pebesma and Bivand, 2023). Raster extractions were completed in NAD 1983 and vector relationships were calculated in UTM WGS 1984 to avoid pixel distortion. Our sampling protocol placed sample points in systematic grids with 120m spacing to limit spatial autocorrelation (Ver Hoef *et al.*, 2001). The distance of each sample to the nearest point on a treatment polygon boundary was calculated and each sample point was assigned to the nearest treatment. These boundary locations were used to determine treatment Topographic Position Index (TPI), width, wind alignment, sinuosity, area treated, adjacent treatment proximity, and length for attribution at nearest samples. TPI was calculated by subtracting the average elevation of an individual cell's "neighborhood" with a 9x9 moving window, selected after comparing multiple dimensions. High TPI values correspond to ridges, while low values indicate valleys (Weiss, 2001). Treatment width was calculated at 10m intervals along treatments by intersecting a line positioned orthogonally to the angle between two neighboring perimeter points. This

method produced anomalous values (<2m and >800m), which were excluded from subsequent analysis. We calculated a wind alignment metric from the cosine of the difference of the azimuth between a sample point and nearest fuel break and the landscape's static wind direction. Values of 1 indicate complete alignment with wind direction and are therefore on the leeward side, -1 indicates upwind direction, and 0 indicates points positioned orthogonal to treatments and static wind directions. Sinuosity measures deviation from a straight line path and was measured by dividing fuel breaks into 500m sections. Low values indicate straightness while higher values reflect waviness (Ager *et al.*, 2023). The relative proximity index reflects the clustering (low values) or isolation (higher values) of treatments and was calculated by dividing the distance to nearest treatment at 10 meter intervals along treatment boundaries by total treatment perimeter (Gustafson and Parker, 1992). Approximate linear treatment length was calculated by halving total perimeter lengths and sample points were assigned the length value of the closest treatment section.

### 2.5.3 Linear Mixed Effects Models

We implemented a Linear Mixed Model (LMM) on each landscape to assess relationships between fuel break characteristics, leverage, and fire modeling inputs with UWR using the glmmTMB package (Brooks *et al.*, 2017). LMMs employ maximum likelihood estimation to predict the mean response from a set of explanatory variables, requiring fewer assumptions than linear models using ordinary least squares regression. Mixed models account for hierarchically structured data through random effects, allowing means to vary between groups. The flexibility and computational efficiency of LMMs enhance their utility for complex multivariable modeling with pairwise variable interactions and random effects (Zurr *et al.*, 2009).

Sample distance from treatment was log10 transformed to account for the diminishing influence of treatments on fire behavior over distance. All independent variables were scaled by subtracting the mean from each value and dividing by the standard deviation to facilitate coefficient comparison and interaction term interpretation. Fuel model and slope were included in the model to control for their influence on fire behavior. Fuel models were categorized by broad vegetation type into a factor level variable with grass fuels as baseline (Scott and Burgan, 2005). Leverage scenarios are included as a factor level variable with untreated as the baseline condition. Treatment length and between treatment proximity were excluded from the Single Segment configuration model to decrease unnecessary model parameters with null variance.

UWR for the  $j$ th pixel location is equal to the intercept, the summed product of the 11 main effect coefficients, 7 interaction terms, and random intercept (Supplementary Table 3). Our models uses mean untreated UWR as the intercept ( $\beta_0$ ). The main effect coefficients represent the marginal relationships between predictor variables and average risk on untreated landscapes ( $\beta X_{ij}$ ), while interaction terms capture how these relationships change across the  $i$  leverage scenarios ( $\beta(X_{\text{scenario},i} \cdot X_{(k-10),i})$ ). Interactions were modeled for all variables except fuel model and slope, facilitating clear interpretation of how fuel break leverage may alter these relationships. Model coefficients quantify the influence of each predictor on mean response holding other variables constant. The primary coefficients of interest are from interaction terms, however, these should be interpreted as additive to main effects. For example, the coefficient  $\beta_9$ , (*wind*  $\times$  *scenario* interaction) is added to  $\beta_4$  (main effect of *wind*). Finally, a random intercept for plot locations ( $b_{\text{plot}(i)}$ ) was included to account for repeated measurements under different leverage scenarios.

$$UWR_j = \beta_0 + \sum_{j=1}^{10} \beta X_{ij} + \sum_{k=1}^{17} \beta (X_{\text{scenario},i} \cdot X_{(k-10),i}) + b_{\text{plot}(i)} \quad (5)$$

We checked model validity by comparing residual variance to independent variables and predicted risk with scatter and box plots to check for residual heteroscedasticity and patterns. Variograms of residuals were assessed to detect unacceptable levels of spatial autocorrelation. Model performance was evaluated using ten-fold cross validation with the `cv` package in R, which performs leave-one-out cross validation and calculates Mean Squared Error (MSE) to measure model performance (Fox and Monette, 2024). Data simulations were conducted to visualize assumed model relationships. To assess the variance in the data explained by the model, conditional and marginal  $R^2$  were calculated. Conditional values represent variance explained by fixed and random effects, while marginal values capture only the fixed effects (Nakagawa and Schielzeth, 2013).

In light of White *et al.* (2014), who caution against using ecological model outputs for statistical significance testing due to inflated sample sizes and the sensitivity of outputs to alterations of model inputs, we focus on interpreting direction and magnitude of coefficients in our results rather than exploring whether subtle levels of statistical significance indicate poorly modeled relationships. However, we consider p-values insofar exceeding our significance threshold ( $P < 0.001$ ) indicating a main effect or interaction term that doesn't contribute to meaningful changes in mean risk.

### 3. Results

### 3.1 Landscape Fire Modeling Summaries

We compare untreated landscapes to associated fuel break leverage scenarios, using descriptive UWR and fire size statistics between to illustrate landscape level change across fuel break configurations and leverage scenarios (Table 2). Across landscapes, fire sizes generally shifted left as leverage intensity increased for the firebreak and firing scenarios. Unstaffed fuel breaks increased median fire size and total burned area for all configurations, however there was an overall decrease in landscape-level UWR. A notable exception is the Boundary Ridge-Branching Network, where fire size and UWR metrics decreased across all leverage conditions. Relative to untreated landscapes the uniform distribution of fire sizes centered for unstaffed leverages and shifted left for firebreak and firing leverage in the Limestone Ridge-Single Segment, Boundary Ridge-Branching Network, and Mount Lowe-Enclosed Network landscapes. Fire size distributions and complete quintile tables are available in the supplementary information (Supplementary Figures 2-5 and Tables 4-7).

The 5,400 ha Limestone Ridge-Single Segment landscape contains 1,733 ignitions and features southwest winds. High UWR values are concentrated in the northeast, while lower risk surrounds developed regions in the southwest (Figure 2). When unstaffed, average UWR decreased slightly, while median fire size and total burned area increased. Actual and normalized risk decreased as leverage intensity increased, while the firebreak scenario caused the largest reduction in area burned per treatment hectare. The number of fires in the 1st quintile (0.09-219 ha) decreased by 2 in the unstaffed landscape and increased for the firebreak (+10) and firing (+104) leverage scenarios. The 10th quintile (2,800-4370 ha) decreased by 2, 4, and 3 fires, for unstaffed, firebreak, and firing leverage, respectively.

High UWR dominates the 27,000 ha Boundary Ridge–Branching Network landscape, which contains 3,227 ignitions driven by southwest winds. The northeast corner, which is heavily roaded and mostly covered by grass fuels, exhibits relatively lower risk (Figure 5). Differences between actual UWR and normalized for unstaffed and firebreak leverages were minimal while notable differences between median fire size and area per treatment hectare exist between these scenarios. Median fire size, actual, and normalized UWR decreased as leverage intensity increased, driven by reductions in upper quintile fire size classes. The number of fires in the 10th quintile (899-2,230 ha) decreased by 24, 43, and 190 for the unstaffed, firebreak, and firing scenarios, respectively. In the firebreak and firing scenarios fire counts in the 1st quintile (0.9-278 ha) grew by 11 and 158.

The 35,100 ha Mount Lowe–Enclosed Network landscape contains 3,361 ignitions, northwest winds, and features comparatively low UWR values. Concentrations of high-risk occur in the northeast corner and along Cuesta Ridge, west of Highway 101. Trends between fire metrics and treatment leverage intensity were nonlinear, except for UWR change. A minor decrease in UWR occurred from unstaffed leverage, but median fire size and burned area increased, although the number of 10th (262-1,550 ha) and 1st quintile (0.09-41.9 ha) fires decreased by 1 and 3, respectively. Firebreak and firing leverages shifted 14 and 102 fires from the 10th quintile, while the 1st quintile increased by 25 and 94. Normalized UWR difference from the untreated landscape for the firebreak and firing leverages is comparable, with the latter featuring a slightly higher magnitude of change.

The 22,500 ha North Mountain–Multiple Segment Network contains 3,239 ignitions, southwest winds, and the highest average UWR of all untreated landscapes. A continuous high-risk patch with multiple linear treatments spans the center, east, and southeast regions. This

landscape exhibited the largest absolute and relative influence from firebreak and firing fuel break leverage, with UWR decreasing linearly with intensity. Total burned area and median fire size increased in the unstaffed scenario, although 3 fewer fires were in the 10th quintile (2,260-4,290 ha) and the 1st quintile (0.09-545 ha) grew by 11. Fire size distributions shifted left for firebreak and firing leverages, with the 10th quintile shrinking by 70 and 150 and the 1st quintile increasing by 12 and 124 fires, respectively. The firebreak scenario produced the greatest reduction in area burned per treatment hectare and normalized UWR.

### 3.2 Statistical model results

Model validation and performance assessments were completed using marginal  $R^2$ , which reflects variance explained by fixed effects, and bias-adjusted MSE produced by 10-fold cross-validation ( $CV_{(10)}$ ). The Single Segment model produced the lowest marginal  $R^2$  (0.33) and the Enclosed FBN model cross-validation exhibited the lowest cross-validation assessment  $CV_{(10)} = 0.03$ . The Multiple Segment FBN model marginal  $R^2$  (0.662) and MSE ( $CV_{(10)} = 0.07$ ) were highest compared to other models.

The number of parameters included in models are 36 and 28 for the FBN and Single Segment models, respectively. Parameters include main effects and interaction terms between factored scenario and continuous variables, and a random effect for repeated measurements at sample locations across leverage scenarios. The untreated scenario and grass fuel model were selected as baseline variables in all models. Main effects should be interpreted as the relationship between the independent and dependent variables in question at baseline conditions, holding other values at their means. Interaction terms are additional to the main effect, i.e. a main effect

of 0.05 and an interaction of -0.02 should be interpreted as 0.03. See supplementary information for all model results, performance, and validation metrics (Supplementary Tables 7-8).

### 3.2.1 Landscape Effects

Intercepts represent average UWR at baseline conditions (Segment: 7.57; Enclosed: 2.90; Branching: 6.97; Multiple: 6.78). Among all models, only the Branching FBN predicted reduced landscape risk when unstaffed (-0.01), while firebreak leverage decreased risk compared to controls across FBNs (Enclosed: -0.01; Branching: -0.02; Multiple: -0.04). All models displayed a negative relationship between UWR and firing leverage (Segment: -0.14; Enclosed: -0.06; Branching: -0.13; Multiple: -0.16), with the strongest relationships observed with the Multiple and Single Segment configurations.

Main effects of distance vary dependent upon the placement of fuel breaks relative to areas of risk on a landscape (Segment: 0.14; Enclosed: -0.15; Branching: 0.07; Multiple: -0.58). Lower main effect coefficients indicate homogeneous risk, while higher values suggest changing conditions toward landscape boundaries. Positive values indicate increasing risk with distance from treatment locations and negative values indicate treatments were placed in relatively high-risk areas. Positive interaction coefficients represent lower UWR values adjacent to treatments under a given leverage condition relative to the baseline, which rise to levels observed on untreated landscapes as distance increases (Figure 7). Only the Branching FBN predicted changing risk over distance when unstaffed (0.01). All FBN models include positive interaction terms for the firebreak scenario (Enclosed: 0.03; Branching: 0.03; Multiple: 0.05), an effect that strengthened with the firing operation leverage (Segment: 0.16; Enclosed: 0.13; Branching: 0.24; Multiple: 0.22) (Figure 6).

Main effects for wind alignment show mean UWR was highest upwind of future treatment locations in the Segment (0.29) and Multiple Segment (0.47) models and downwind for the Enclosed (-0.18) and Branching (-0.42) models. Wind alignment did not interact with unstaffed leverage in any model and only interacted with firebreak leverage for the Segment (-0.02) and Multiple Segment (-0.03) models. Across models, wind alignment and firing leverage interacted to decrease risk downwind of treatments (Segment: -0.13; Enclosed: -0.01; Branching: -0.06; Multiple: -0.12).

Relationships between mean UWR and TPI describe the influence of the topographic placement of treatments on landscape-level risk (Main effects: Segment: -0.08; Enclosed: -0.11; Branching: 0.04; Multiple: 0.25). Unstaffed fuel breaks and TPI did not interact relative to untreated values and the Multiple Segment (-0.02) displays the only significant firebreak interaction. Firing leverage interacted with TPI across models, though direction and magnitude varied (Segment: <0.01; Enclosed: 0.02; Branching: -0.02; Multiple: -0.04). FBN interaction terms for firing suggest a weakening influence of TPI when fuel breaks are leveraged with burnout operations as coefficients become closer to zero.

### 3.2.2 Configuration Effects

The main effects of width and length describe how the dimensions of future treatment locations influence landscape UWR. Main effects of width are positive for the Segment (0.12) and negative for the FBN models (Enclosed: -0.10; Branching: -0.08; Multiple: -0.30). Interactions between firing operation and width indicated a weak positive relationship in the Multiple Segment (0.01) FBN model. Risk exhibited weak relationships with treatment length under firing operations across FBN models (Enclosed: 0.08; Branching: -0.03; Multiple: -0.07).

Notably, main effects for the Branching FBN are positive while the Multiple Segment and Enclosed models are positive. Therefore, the relationship should be interpreted as weakening for Branching and Enclosed and strengthening for Multiple Segment configurations.

Sinuosity measures the straightness of linear features, with negative coefficients from interaction terms indicating straighter fuel breaks relate to lower risk under leverage conditions. Important Main effects were positive (Segment: 0.59; Branching: 0.14; Multiple: -0.32). Firebreak scenario and less straight fuel breaks are associated with lower risk in the Enclosed FBN model (0.01). The directions and magnitudes of interactions with the firing scenario varied (Segment: -0.10; Enclosed: 0.02; Branching: -0.04; Multiple: 0.03). Comparing interactions to main effects indicates a weakening relationship across models when fuel breaks are leveraged with firing operations and that sinuous fuel breaks are associated with lower predicted risk in the Multiple Segment and Enclosed model. Conversely, the opposite is true in the Branching and Segment models.

Proximity index values measure the adjacency of treatments, with positive coefficients signaling sections of linear treatments near other fuel breaks are associated with lower UWR at sample locations. Main effects were positive and unchanged by unstaffed leverage conditions. Proximal fuel breaks leveraged with firebreaks slightly lowered landscape level risk in the Branching (0.01) and Enclosed (0.01) configurations and this relationship strengthened with firing operations for these models (Enclosed: 0.05; Branching: 0.03).

#### **4. Discussion**

Our study presents a more comprehensive framework to evaluate the influence of installed fuel breaks on modeled fire risk. This framework employs a novel metric, UWR, which combines elements of firefighter safety and control effort with previously developed components of risk. Compared to controls (i.e., no fuel break installed) unstaffed fuel breaks had more burned area and larger average fire sizes for all case study landscapes except the Branching Network. Conversely, in-treatment reductions in fire behavior decreased the risk of uncontrollable wildfire, even when fuel breaks were unstaffed. Firebreak leverage provided the largest decrease in UWR when adjusted for treatment and landscape size for the Enclosed and Multiple Segment FBNS. While FBNS used for firing operations provided greater unadjusted UWR reductions compared to other scenarios. Statistical modeling suggests FBN segments that were less straight and closer together contributed to lower predictions of decreased risk. Additionally, portions of the landscape that were closer to treatments and on the leeward side of treatments were associated with lower risk under firebreak and firing leverage conditions.

#### **4.1 Uncontrollable Wildfire Risk**

UWR captures some critical aspects of the socio-ecological risk management logic underpinning fuel break construction by combining flame lengths, control difficulty weights, and burn probability (Thompson *et al.*, 2022). UWR joins a suite of spatial tools designed for fire and fuels management planning such as WHP) and IH, and should be viewed as a flexible midpoint between the two in terms of calculation complexity (Scott *et al.*, 2012; y Silva *et al.*, 2014; Dillon *et al.*, 2015). While IH is simply the product of BP and CFL, WHP provides a dimensionless metric that should be interpreted as the likelihood of fire behavior in the context of controllability, similar to UWR. Complex WHP calculations challenge reproducibility for fire and fuels management planners and researchers (Scott *et al.*, 2012; Dillon *et al.*, 2015).

Conversely, UWR is easily produced at 30m and relies on fire modeling software widely available to managers and researchers. Therefore, enabling wildland fuels managers to evaluate the efficacy of treatments in aiding wildfire control at the treatment and landscape scale through counterfactual analysis (Green, 1977; Agee *et al.*, 2000; Drury *et al.*, 2016).

UWR may be used to evaluate the efficacy of fuel treatments and other fire risk prevention strategies, determining the effectiveness of theoretical arrangements, placements, and types of treatments under fixed conditions. Additionally, the dearth of empirical suppression effectiveness literature provides an opportunity for improvements in our calculations through future research. Currently used thresholds of suppression effectiveness have frequently occurred in eucalypt fuel types (Loane and Gould, 1986; Budd *et al.*, 1997), or have been fuel type agnostic (Byram 1979). Future research should investigate whether fireline intensity thresholds hold true for or vary across fuel types, requiring different weighting schemes in different locations (Plucinski, 2019). Other investigations could validate the metric with recently available containment line data in the USA (; Arkowitz *et al.*, 2025). Importantly, any improvements should balance trade-offs of gained accuracy with additional complexity, ensuring that this metric remains useful for practitioners (Thompson and Calkin, 2011).

#### **4.2 Fuel Break Network Configurations**

Establishing common fuel break configurations provides information on tailored approaches to target location-specific risk, while allowing us to investigate the effectiveness of treatments implemented in a barrier laden environment. Managers must consider the challenges to complete construction fuel break networks face while planning treatments, such as limited resources, land management policy, and public opinion (Reinhardt *et al.*, 2008; Collins *et al.*,

2010; Reiner *et al.*, 2014; Urza *et al.*, 2023). Our classification approach produced four configurations, which influenced risk differently across leverage scenarios: Branching Networks, Enclosed Networks, Multiple Segment Networks, and Single Segments. While the explicit objectives and limitations of individual fuel break projects are beyond the scope of our study, inferences may be made when considering adjacent and intersecting landscape features, treatment extent, and continuity.

Single Segment (Figure 2A) and Multiple Segment (Figure 2D) fuel breaks typically surround or abut roads and ridges while individual treatments are frequently adjacent to Highly Valued Resources and Assets (HVRAs). The small extent and isolation of individual treatments suggest the existence of incomplete extensive treatment networks, targeted protection of HVRAs from specific fire spread directions, connection to adjacent areas unavailable for treatment, or where treatments are deemed unnecessary (Collins *et al.*, 2010; Massada *et al.*, 2011; Scott *et al.*, 2013; Oliveira *et al.*, 2016; Tubbesing *et al.*, 2019). Relative to the other configurations we examined, these arrangements produced greater normalized risk reductions when leveraged with firebreaks or firing operations, and produced larger burned areas when unstaffed. Multiple Segment FBNs provide strategic options across landscapes, and treatment discontinuity can be used advantageously, disrupting growth along the heel and flanks of individual perimeters where fuel breaks are known to be most effective (Finney, 2001; Young *et al.*, 2024). Single Segments provide fewer opportunities, but orthogonal placement relative to wind direction and proximal to fire spread barriers such as downwind roads acting as secondary firelines interacted to increase the likelihood of fire intersection and reduce fire size (Finney, 2007). While assessments of isolated treatments are rare, our results reinforce successful leverage by first responders can limit negative wildfire outcomes when placed respective of probable spread directions, near HVRAs,

with access and appropriate treatment intensity (Syphard *et al.*, 2011; Massada *et al.*, 2011; Collins *et al.*, 2013; Oliveira *et al.*, 2016).

Branching Networks (Figure 2B) are situated in topographically complex areas, where lateral fuel breaks extend from treatments on primary ridges down into valleys and along sub-ridges. Empirical studies show probability of successful use is highest for primary treatments, whereas safety concerns and placement may limit operations on lateral breaks, which often involve longer travel distances to safety zones (Omi, 1977; Syphard *et al.*, 2011; Young *et al.*, 2024). The Branching FBN landscape contained the highest proportion of treated area (1.04% unstaffed) and was the only configuration to decrease burned area when unstaffed. Exclusive ridge top placement enhances the treatment's ability to disrupt fire spread by combining the influence of landform with a fuel type exhibiting lower flame lengths, increasing likelihood of extinguishment (Holsinger *et al.*, 2016). Additionally, lateral treatments offer managers strategic opportunities to integrate fuel breaks into broader risk reduction planning by providing access for landscape treatments activities within key portions of watersheds (North *et al.*, 2015; 2024).

Enclosed Fuel Break Networks (Figure 2C) surround areas with high ignition potential, such as highway corridors, or areas prioritized for fire exclusion, such as communities (Massada *et al.*, 2011; Oliveira *et al.*, 2016; Aparício *et al.*, 2022). Relative to other configurations, Enclosed Networks frequently follow mid-slope roads until roads intersect with ridges, exemplified in the case study treatment. Extensive Networks planned in Portugal limited cross-boundary transmission of fire, decreasing fire size, likelihood, and building exposure in simulation analyses (Oliveira *et al.*, 2016; Aparício *et al.*, 2022). Poor performance in our case study analysis likely results from the relatively lower landscape risk, small width, and the

amount of mid-slope treatment (Van Wagendonk *et al.*, 1996; Holsinger *et al.*, 2016; Zong *et al.*, 2021).

### 4.3 Fuel Break Leverages

Increased burned area and average fire size on unstaffed fuel break landscapes is potentially attributable to vegetation conversion (represented by fuel model) inside treatments, which included the replacement of roads with herbaceous fuels. Inspecting the proportion of pretreatment polygon interiors containing unburnable fuel models (Segment: 0.5%, Branching: 12%, Enclosed: 18%, Multiple: 10%) suggests road removal is not the sole driver of this phenomenon (Supplementary Table 10). Depending on pre-existing vegetation and treatment type, fuel manipulations may introduce continuous light fuels and remove tall vegetation, elevating surface winds, which increase fire spread rates and overall fire size but not fire intensity (Cochrane *et al.*, 2012; Cochrane *et al.*, 2013). Therein lies a tradeoff where fire spreads more rapidly, while the risk of crown fire and long-range spotting is reduced (Albini and Baughman 1979; Cochrane *et al.*, 2012; Cochrane *et al.*, 2013). This compromise is captured by cumulative landscape-level evaluations with UWR, where lower risk from decreased flame lengths in and adjacent to treatments compensated for higher burn probabilities (Table 2).

Accurately evaluating cumulative landscape-level fuel break effects requires ecological context, such as historical fire regime and current vegetation type. In ecosystems adapted to frequent fire, area burned does not indicate meaningful ecological or human impacts from wildfire (Stephens *et al.*, 2013; North *et al.*, 2015). However, in crown-fire adapted systems, such as Southern California chaparral, the management paradigm has been to limit fire size due to the consequences of frequent burning on native vegetation and HVRAs (Keeley and Brennan,

2012; Halsey and Syphard, 2024). Empirical studies show fuel breaks in this region are frequently unstaffed during fire intersections, and that burned fuel breaks can spread invasive species further into wildlands (Merriam *et al.*, 2006; Syphard *et al.*, 2011). If an additional consequence is larger fires, then including firebreaks, which aid local objectives by increasing firefighter safety and decreasing average fire size, are a logical management recommendation (Thompson *et al.*, 2021). Our evaluation of burned area per treatment hectare indicates fuel breaks leveraged with firebreaks may improve cost-benefit ratios and limit the negative externalities from larger treatments, subject to the cost and environmental consequences of road construction relative to treatments (Table 2) (Boston, 2016; Shinneman *et al.*, 2019). Accompanying firebreaks decrease fire size and may delay impact times to areas targeted for fire exclusion even when unstaffed (Young *et al.*, 2024). In these cases, well timed aerial ignitions with piloted or unmanned aircraft may be used to increase the likelihood of either containment or slowing spread when ground operations are deemed unsafe (Lawrence *et al.*, 2023).

Firing operations leveraging fuel breaks consistently contributed to the greatest absolute reductions of landscape-level risk. Unsurprisingly, simulating fuel breaks as unburnable surfaces leads to improved outcomes in terms of fire spread and transmission (Oliveira *et al.*, 2016). It is important to acknowledge fire modeling faces limitations from static inputs that make firing operations unrealistic (Finney, 2006). In reality, myriad factors including heterogeneity of fuels, operational timing, environmental conditions, and direction and speed of wildfire spread influence firing operation depth and fuel consumption (Holsinger *et al.*, 2016). Additionally, fire interactions between intentional ignitions and wildfire, and spotting from firing operations are not captured in simulations (Finney, 2006). Our improved approach to modeling firing operations adds some realism by removing adjacent fuels, but does not account for whole fire

containment with firing operations, burnover probabilities, or the environmental factors and interactions listed above (Aparício *et al.*, 2022). Future iterations may pair our approach with wildfire perimeter trimming functions, assess effectiveness using spread direction calculated from fire perimeter datasets, and include intersecting roads as containment line to simulate firing operations at scale (Petrovic and Carlson, 2012; Thompson *et al.*, 2021; Gannon *et al.*, 2023). Aside from a robust solidification of the concept that fuel breaks should be utilized in conjunction with firing operations, implications include the construction of fuel breaks adjacent to features with fewer sources of spot fire causing embers. In practice, this would look include building fuel breaks along linear features with already reduced fuels or areas where fuels are already completely removed, such as roads, the latter of which is already common practice (Green 1977). These areas require less pre-treatment on the “green” or “black” sides in the event of a wildfire, enhance firefighter safety, and increase the likelihood of limiting fire spread, however, targeting areas with reduced fuels for adjacent treatment construction may be viewed as essentially building one fuel break alongside another. Ultimately, managers may deem other areas without pre-existing buffers as higher priority targets for linear fuel reduction, while locating these treatments where first responders can quickly deploy to initiate indirect attack tactics.

#### **4.4 Fuel Break Arrangement and Geometry**

The findings in our fuel break configuration case studies provide intriguing hypotheses for future research. Generally, closer proximity, lower sinuosity, and longer fuel breaks were associated with lower risk when treatments were leveraged with firebreaks or firing operations. Treatment proximity mitigates fire spread, behavior, and subsequent risk at multiple scales of analysis (Ott *et al.* 2023). Individual fires may encounter multiple treatments at different angles,

limiting or forcing flanking or backing behavior contingent upon spread direction and fuel types inside treated areas. In probabilistic fire modeling environments, areas nearby treatments are sheltered from fires spreading from multiple directions, limiting total burned area and reducing risk dependent upon treatment configuration (Finney, 2001; Finney, 2007). A previous investigation of fuel break sinuosity and length found that straighter and longer treatments intercepted more fires, but interception lengths were generally longer for non-sinuuous treatments (Ager *et al.*, 2023). Fires intersecting with less sinuous treatments may be less likely to flank towards fuel break portions that are either more susceptible to spotting due to smaller widths, or that change angles or terminate, allowing fires to spread beyond treatments (Finney, 2007).

The relationship between UWR, leverage intensity, distance from treatment, and wind-treatment alignment were generally positive and effect sizes varied between case study configurations. Increasing leverage intensity was associated with decreasing risk values further from treatments, especially on leeward fuel break sides (Figure 7; Supplementary Table 7). Fuel breaks that are unstaffed or leveraged with a firebreak exert minimal, but visually detectable influence on risk over distance compared to controls (Figure 5; Figure 6). Firing operation leverage on the Branching FBN decreased risk up to 3km from treatment boundaries, while the Single Segment fuel break and Enclosed Networked exhibited more minimal impacts on UWR (Figure 6). The influence of wind and treatment alignment also reduced risk, albeit to a lesser degree than distance. While we did not include an interaction between distance and wind alignment due to the number of parameters already included in our models, visibly larger reductions on leeward treatment sides are apparent (Figure 7; Supplementary Table 7).

Previous research using burn probability modeling shows that treatments reduced burn probability until about 10km downwind of treatments and 5km on the upwind side in Boreal

forests (Stockdale *et al.*, 2019). Managers commonly place treatments orthogonal to wind directions occurring during times of fire danger (Collins *et al.* 2013), especially those intended for firefighter leverage, so that they are well positioned to intersect with head fire spread (Finney, 2007). Alternatively, if treatments are placed to control backing fire spread locations upwind of high risk areas may be favored (Gannon *et al.*, 2023; Young *et al.*, 2024). Positioning strategic treatments like fuel breaks near HVRAs or along fire excluded area boundaries further from protection objectives can mitigate negative impacts and provide fire management options when probable directions of incoming fire spread are considered (Aparício *et al.*, 2022; Ortega *et al.*, 2024; Nguyen *et al.*, 2024).

#### **4.5 Limitations and Future Research**

Burn probability modeling is widely used by managers and researchers assessing planned and existing fuel treatments. However, there are many limitations of this approach that should be disclosed to provide appropriate caution in interpreting findings from such studies (including the present one). Rothermel-based surface fire spread and linked crown fire models exhibit unrealistic overestimations of burned area while underestimating wind driven runs (Finney *et al.*, 2011). Future research may assess individual fires-fuel break intersections using Rothermel based models, however, the coarse resolution of inputs and consequent lack of detail describing fine-scale interactions on treatment boundaries creates opportunities for computational fluid dynamics modeling and fine scale fuel models derived from LiDAR scanning (Marcozzi *et al.*, 2023; Atchley *et al.*, 2024).

While ignitions were placed in identical locations across each simulation of the same landscape, stochastic differences from the program's spotting algorithm, which assigns a random

likelihood for spot fire ignitions from fire brands, cause minor differences between simulations (Finney, 2006). Additionally, random ignition placement is a limitation of this study and future research using our framework may consider ignition probability datasets to place fire origins, increasing realism by simulating the influence of human and natural wildfire sources (Oliveira *et al.*, 2016; Moran and Thompson 2024).

Challenges persist for attribution of the influence of fuel break configurations on UWR using case study examples with differing fuel profiles. The hypotheses articulated in this manuscript may guide future fire modeling research on fuel break configurations where identical inputs for topography, weather, and fuels are used, or sample sizes are increased to make comparisons robust (Holsinger *et al.*, 2016). Additionally, few empirical studies have examined the influence of linear treatment configuration on suppression leverage (Omi, 1977). While more recent evaluations have focused on vital human and ecological factors, fire outcomes should be modeled in the context of their many existing antecedent factors, including treatment configuration (Finney *et al.*, 2001; Syphard *et al.*, 2011; Gannon *et al.*, 2023; Ott *et al.*, 2023; Young *et al.*, 2024).

The use of linear mixed modeling provides interpretable results and statistical significance thresholds to determine relevant relationships, while limiting data quantity and the number of parameters (Zurr *et al.*, 2009). Spatial subsampling and random effects for plot locations controlled for some spatial autocorrelation (Ver Hoef *et al.*, 2001). Future iterations may include spatial lag terms and machine learning algorithms to maximize data, but interpretation of results may be challenging relative to linear models (Ver Hoef *et al.*, 2018). While additional parameters including interaction terms may be desirable, linear models risk over-fitting or non-convergence errors as parameters increase (Zurr *et al.*, 2009). Additional

interaction terms, such as between distance and wind-treatment alignment, may provide additional information useful for managers constructing fuel breaks. Despite existing flaws, assessing the intersections of wildfire hazard and fuel break characteristics and leverages provides relevant management findings on landscape level fuel break effects on risk and treatment parameters for fuel breaks.

## **Conclusion**

Lengthening dry seasons and increasing human ignitions during adverse weather events are regularly increasing wildfire related losses in Southern California (Keeley and Syphard 2025). As hazardous conditions intensify, fire managers require improved risk mitigation strategies for planning and emergency response. Our research demonstrates that even during adverse conditions, fuel breaks can reduce hazardous risk to first responders while creating opportunities for fire control within and adjacent to linear treatments. However, these benefits depend on adequate construction planning. Fuel managers should ensure linear treatments are placed in areas easily accessible to firefighters and include pre-established containment line or roads to minimize ignition spread from invasive annual grasses. Managers should consider how any mitigation action affects the level of risk to first responders and the metric and methods presented in this study contribute to this critical goal.

Future fuel break evaluations should incorporate treatment arrangement and shape when measuring outcomes. Our framework provides a mechanism to measure and assess these previously underexamined features of linear treatments. The hypotheses developed in this work offer additional opportunities to strengthen management practices through continued investigation.

As wildfire continues to threaten life and property, novel research approaches are essential for improving historical management practices. This work advances that effort by providing practical guidance for planning and methodological tools for future research.

## **Glossary**

BP – Burn Probability

CAL FIRE – California Department of Forestry and Fire Protection

CFL – Conditional Flame Length

FACTS – Forest Activity Tracking System

FBN – Fuel Break Network

FLP – Flame Length Probability

HVRA – Highly Valued Resources and Assets

IFTDSS – Interagency Fuel Treatment Decision Support System

IH – Integrated Hazard

LMM – Linear Mixed Model

NVC – Net Value Change

PODs – Potential Operational Delineations

SDI – Suppression Difficulty Index

TPI – Topographic Position Index

USDA – United States Department of Agriculture

UWR – Uncontrollable Wildfire Risk

WHP – Wildfire Hazard Potential

### **CRedit authorship contribution statement**

**Andrew Johnson:** Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization, Data curation, Formal analysis, Methodology, Visualization, . **Brandon Collins:** Writing – Reviewing and editing, Methodology, Conceptualization. **Philip Omi:** Writing – Reviewing and editing, Funding acquisition, Conceptualization. **John Battles:** Writing – Reviewing and editing, Methodology. **Matthew Thompson:** Writing – Reviewing and editing, Conceptualization. **Scott Stephens:** Writing – Reviewing and editing, Funding acquisition.

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### **Competing Interests**

All authors declare that they have no personal, professional, or financial interests that would have influenced the work reported in this paper.

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During the preparation of this work the author(s) used ChatGPT in order to revise R scripts and edit the abstract. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

### **Data Availability**

The data used in this study are hosted on Zenodo (<https://doi.org/10.5281/zenodo.18166814>). All code to create UWR, CFL, and BP rasters, and to conduct the fuel break evaluation framework is hosted on Github ([https://github.com/johnsonas6/Johnson\\_FuelBreakConfigurations\\_EI](https://github.com/johnsonas6/Johnson_FuelBreakConfigurations_EI)).

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Fireline Intensity (kW/m)	Flame Length (m)	Hazard Weight	Firefighting Resource Explanation	Citation
1000	1.86	5	Handcrews are effective up to this threshold.	Burgan 1979 Budd et al. 1997
2000	2.55	15	Aerial retardant holds for 1 hour at intensities below this threshold.	Budd et al. 1997 Loane and Gould 1986
3000	3.08	20	Authors estimate that aerially applied retardant is effective if ground forces arrive within 1 hour.	Budd et al. 1997 Loane and Gould 1986
5000	3.9	30	Occasional effectiveness with aerially applied retardant and ground force combinations. Bulldozers effective.*	Budd et al. 1997 Loane and Gould 1986 Burgan 1979*
6700	4.49	40	Aerially applied retardant ineffective in barley stubble	Plucinski 2010

\* Bulldozer effectiveness is slightly above 5000 kW/m according to Burgan 1979.

Table 1: Thresholds of firefighting effectiveness using different resources and resource

combinations with inferred difficulty weightings and associated citations. The literature and data in this table were used to compute weights for Uncontrollable Wildfire Risk.

Treatment Size (ha)	Proportion of Landscape Treated	Median Fire Size (ha)	Mean UWR	Area Burn Change Per Treatment Area (ha)	UWR Percent Change	Differenced Hazard Normalized
Single Segment - Limestone Ridge – Southern California Coastal Scrub						

Untreated	0	0%	456.21 ± 1239.60	7.60 ± 1.76	-	0	0
Unstaffed	17.92	0.33%	457.29 ± 1238.73	7.60 ± 1.77	+123.71	-0.04%	-0.99
Firebreak	17.92	0.33%	445.86 ± 1242.53	7.59 ± 1.76	-1043.22	-0.23%	-5.46
Firing	94.11	1.74%	423.63 ± 1256.35	7.50 ± 1.81	-761.33	-1.43%	-6.24
Branching Network - Boundary Ridge – Southern California Dry-Mesic Chaparral							
Untreated	0	0%	578.25 ± 346.95	7.72 ± 1.87	-	0	0
Unstaffed	282.35	1.04%	572.22 ± 342.80	7.68 ± 1.88	-72.08	-0.45%	-3.37
Firebreak	282.35	1.04%	566.19 ± 339.48	7.68 ±1.88	-164.80	-0.48%	-3.55
Firing	689.71	2.56%	486.00 ± 336.58	7.56 ± 1.92	-338.51	-2.06%	-6.21
Enclosed Network - Mount Lowe – Northern and Central California Dry-Mesic Chaparral							
Untreated	0	0%	82.08 ± 278.67	4.17 ± 2.62	-	0	0
Unstaffed	203.75	0.58%	81.99 ± 280.63	4.16 ± 2.62	+15.31	-0.18%	-1.32
Firebreak	203.75	0.58%	81.18 ± 267.18	4.15 ± 2.60	-93.25	-0.47%	-3.36
Firing	872.47	2.49%	78.93 ± 207.36	4.08 ± 2.53	-135.93	-2.09%	-3.51
Multiple Segment Network - North Mountain – Southern California Dry-Mesic Chaparral							
Untreated	0	0%	1050.57 ± 951.47	8.64 ± 2.38	-	0	0
Unstaffed	135.63	0.60%	1052.19 ± 963.43	8.63 ± 2.39	+98.60	-0.12%	-1.76
Firebreak	135.63	0.60%	1018.98 ± 889.73	8.59 ± 2.36	-1863.03	-0.59%	-8.41

Firing	632.63	2.81%	822.06 ± 788.54	8.43 ± 2.33	-1417.39	-2.41%	-7.41
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Table 2: Descriptive statistics for treated proportions of landscapes, change of uncontrollable wildfire risk, fire size, and burned area organized by landscape and fuel break leverage scenarios. Area burned reductions, UWR percent change, and Normalized UWR difference were calculated in reference to untreated landscapes. The most commonly occurring vegetation type inside of and within a 50m buffer of FBN polygons (LANDFIRE, 2020) is described in the top row of each section.

Figure captions.

Figure 1: Map of Southern California with EPA level III ecoregions (Griffith *et al.*, 2016). Fuel break case study locations are labeled and UWR rasters extents are used to highlight the location and size of fire modeling landscapes.

Figure 2: Case study fuel break configurations overlaid onto rasterized Uncontrollable Wildfire Risk, with communities and roads masked to NA values. Firing operation polygons are included due to the small size of some treatments. A) The Mount Lowe Enclosed Network, located northeast of San Luis Obispo, CA. B) The Boundary Ridge Branching Network, located southeast of Wrightwood, CA. C) The North Mountain Multiple Segment Network, located east of Hemet, CA. D) The Limestone Ridge Single Segment fuel break, located in Limestone Canyon Regional Park.

Figure 3. Logistic growth model of control hazard over increasing flame length, which reflects the initial ease and progressive difficulty of fire suppression (Equation 3). Conditional Flame

Length Categories were input into this model and outputs were used as hazard weights to compute Uncontrollable Wildfire Risk (Equation 4). Orange dots represent thresholds of suppression effectiveness of differing resource types and combinations at varying flame lengths, which were derived from previous empirical literature. The first and final thresholds were added by researchers to ensure weights remained above 0 and below 50.

Figure 4. Heat map of average Uncontrollable Wildfire Risk (UWR) (Equation 4) at intersecting categories of Burn Probability (BP) and Conditional Flame Length (CFL) using a 120-meter subsample of UWR, BP, and CFL values at identical locations on untreated case study landscapes. Relative to BP, UWR maps closely onto CFL, therefore lower levels of risk are possible when CFL is low, and BP is high.

Figure 5. Uncontrollable Wildfire Risk on the Boundary Ridge Branching Fuel Break Network's leverage scenarios subtracted from risk values on the untreated landscape. Southwest winds and identical ignition locations were used on all modeling runs. Values above 0 are associated with decreased risk compared to control conditions, while negative values indicate increased risk. A) Unstaffed fuel break. B) Fuel break leveraged with a firebreak. C) Fuel break leveraged with a firing operation.

Figure 6. Linear models of predicted Uncontrollable Wildfire Risk (UWR) over actual distance with 95% confidence intervals in shaded gray. Each panel is for a fuel break configuration and each line is a leverage condition. Predicted values were calculated across the range of fuel model inputs. Confidence intervals for fuel break and indirect leverage overlap with untreated for all configurations, while firing leverage shows a significant local decrease in risk near treatments, which converges with untreated risk levels as the distance from fuel breaks increase. The largest

local decrease in risk is apparent for firing operation leverage on the Branching and Multiple Segment Networks, while the smallest difference is visible in the Single Segment and Enclosed Network graphs.

Figure 7. Average predicted Uncontrollable Wildfire Risk at intersecting values of distance from sample point alignment with wind and treatment direction (1 = downwind of treatments/-1 = upwind of treatments), on the Boundary Ridge Branching Fuel Break Network. The influence of fuel break leverage is apparent on the leeward side of treatments as leverage intensity increases. Predicted values were calculated across the range of fuel model inputs, reflecting realistic predictions for actual landscape conditions.

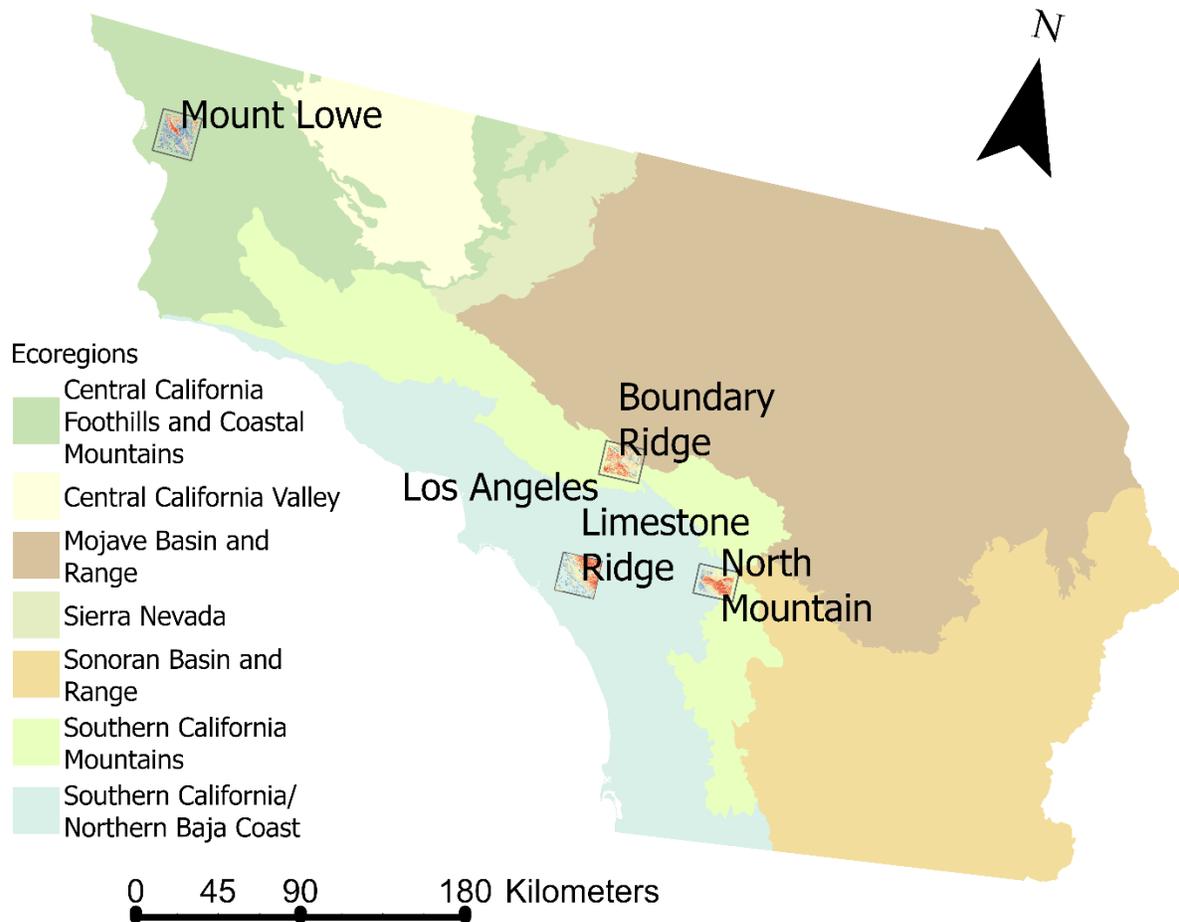


Figure 1:

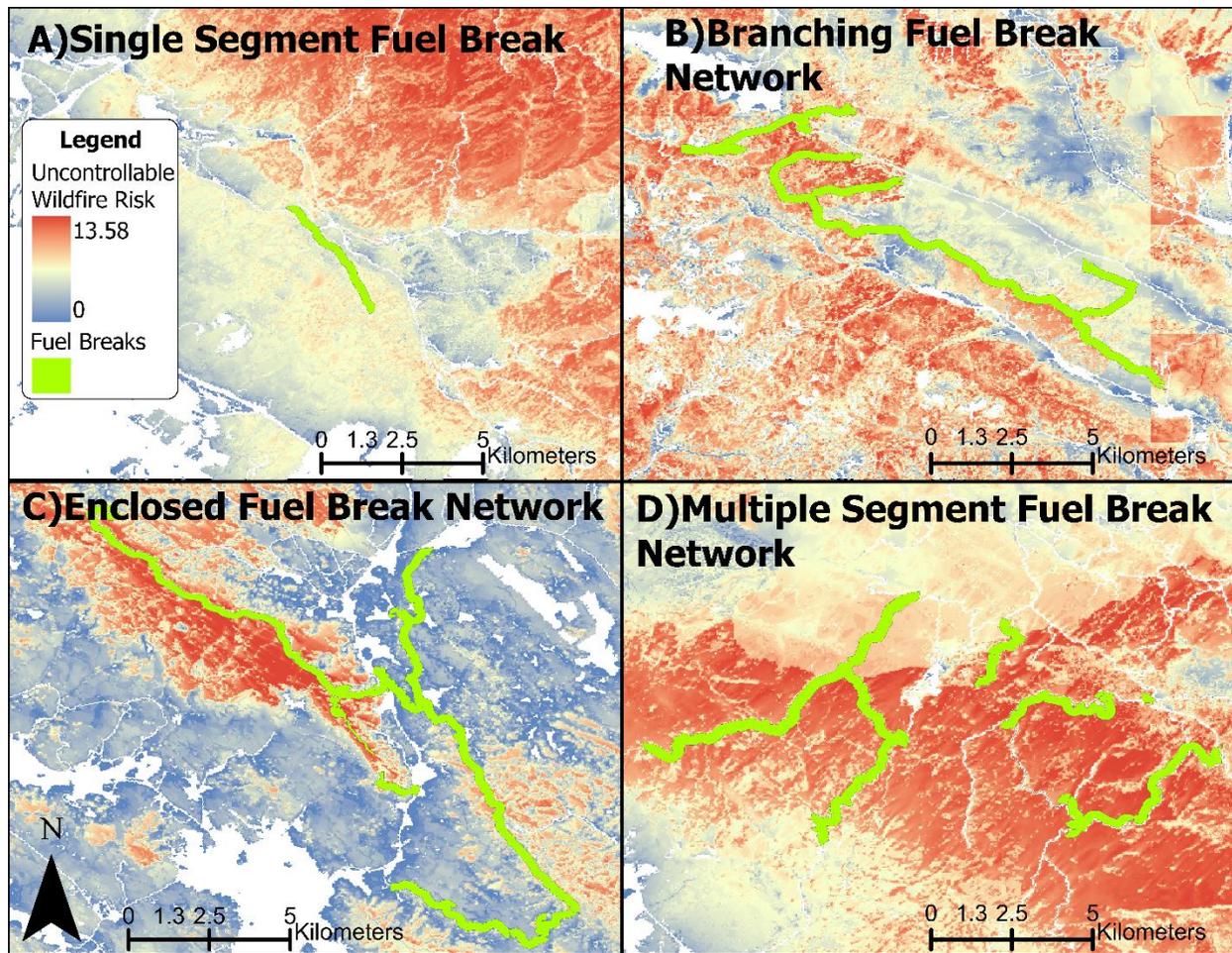


Figure 2.

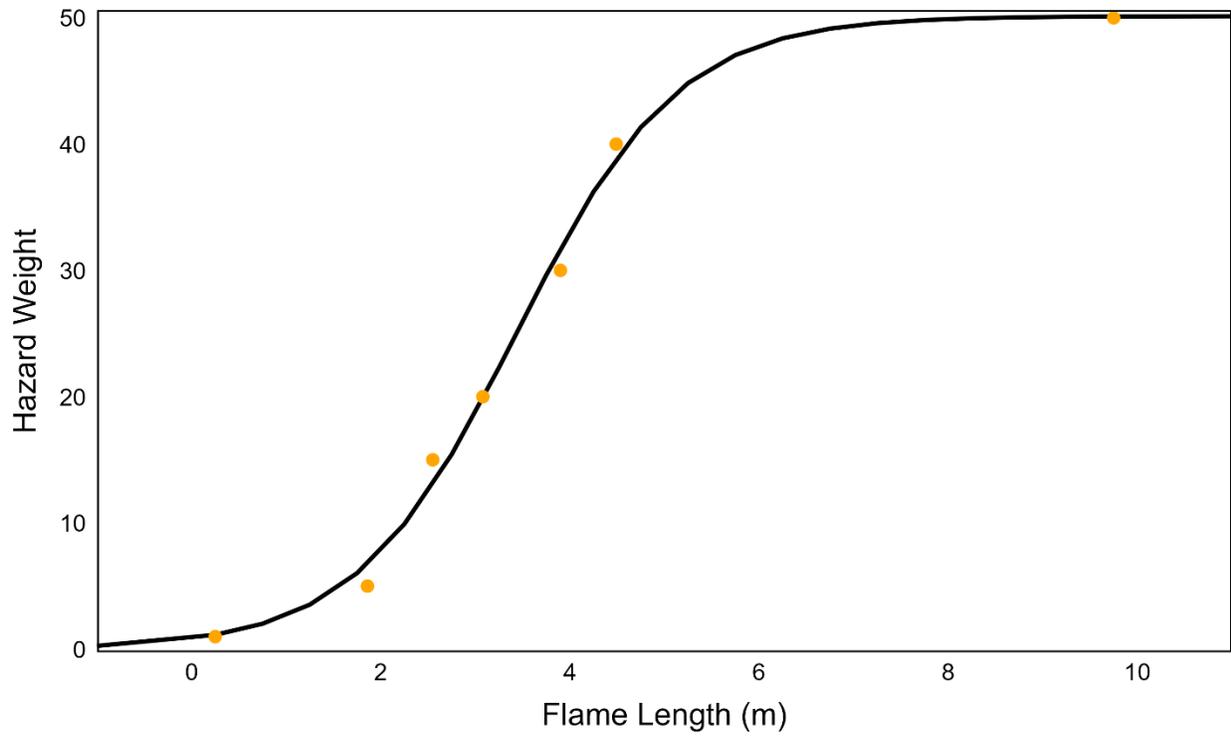


Figure 3.

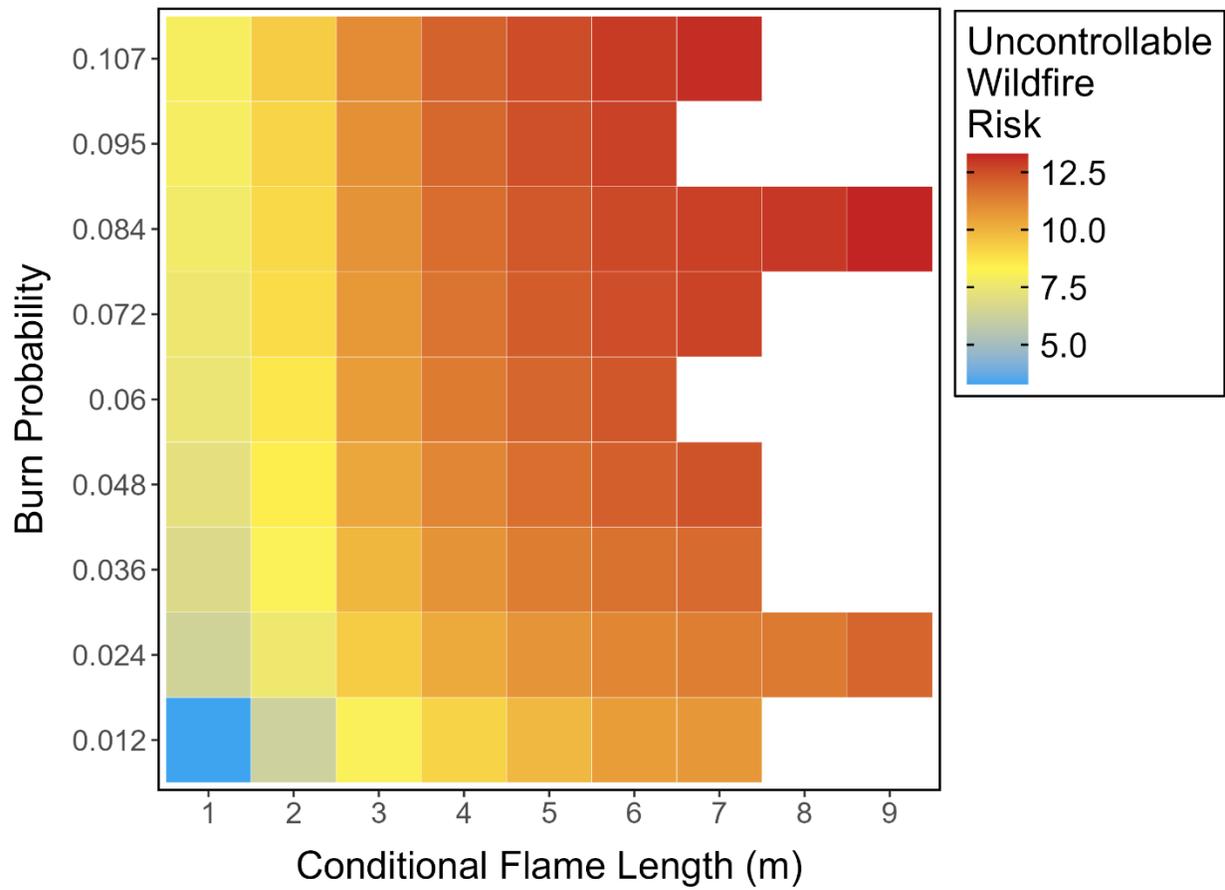


Figure 4.

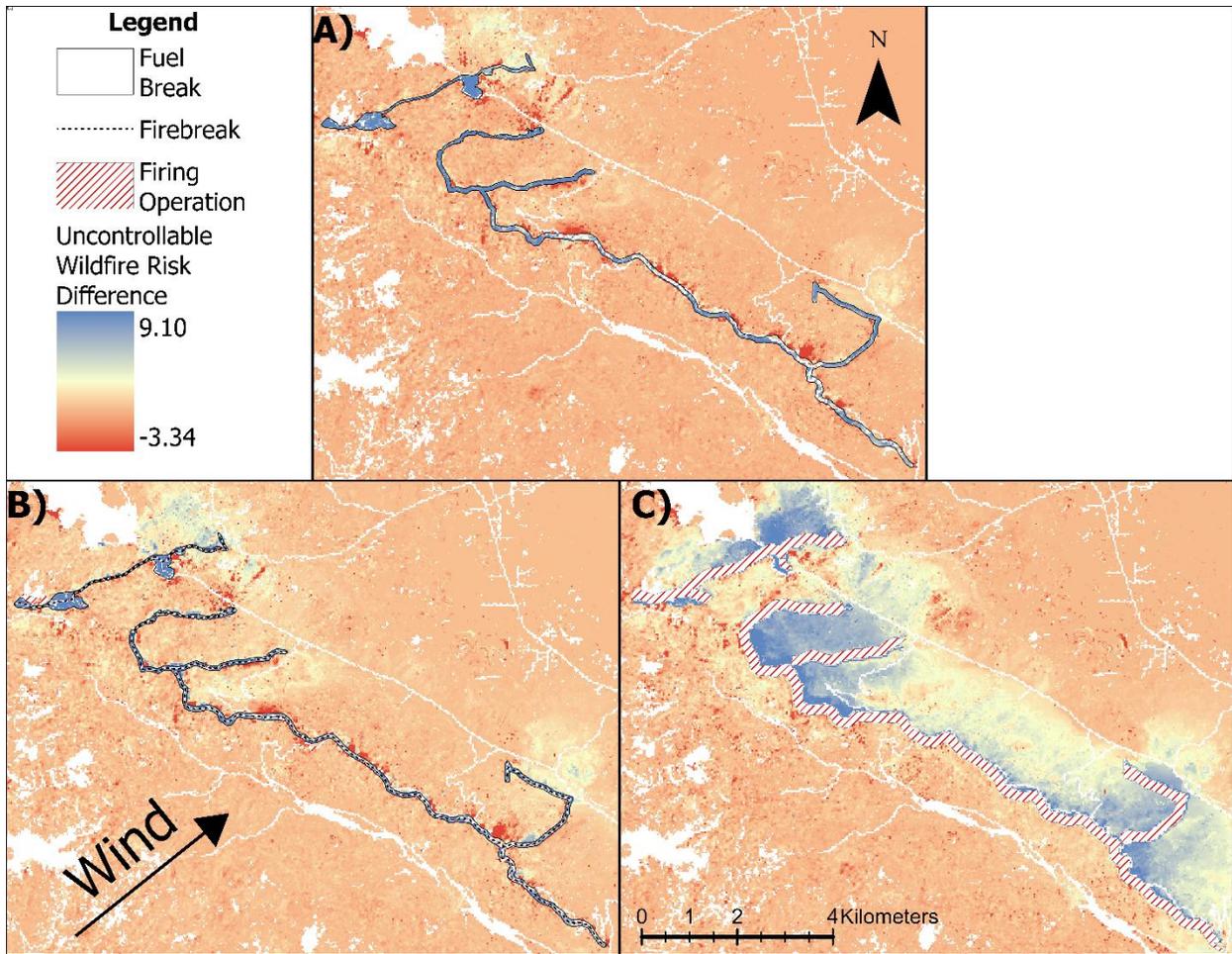


Figure 5.

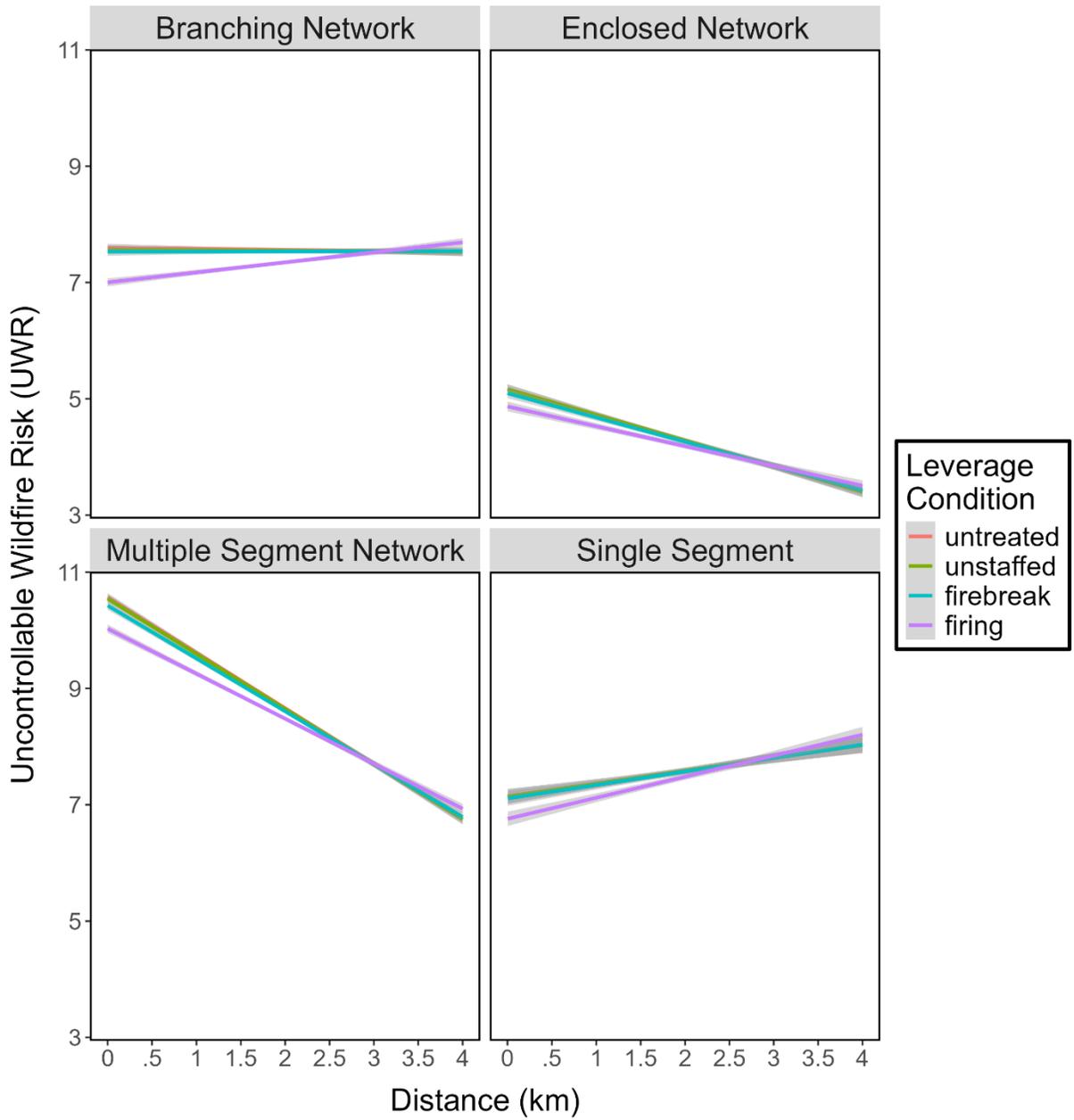


Figure 6.

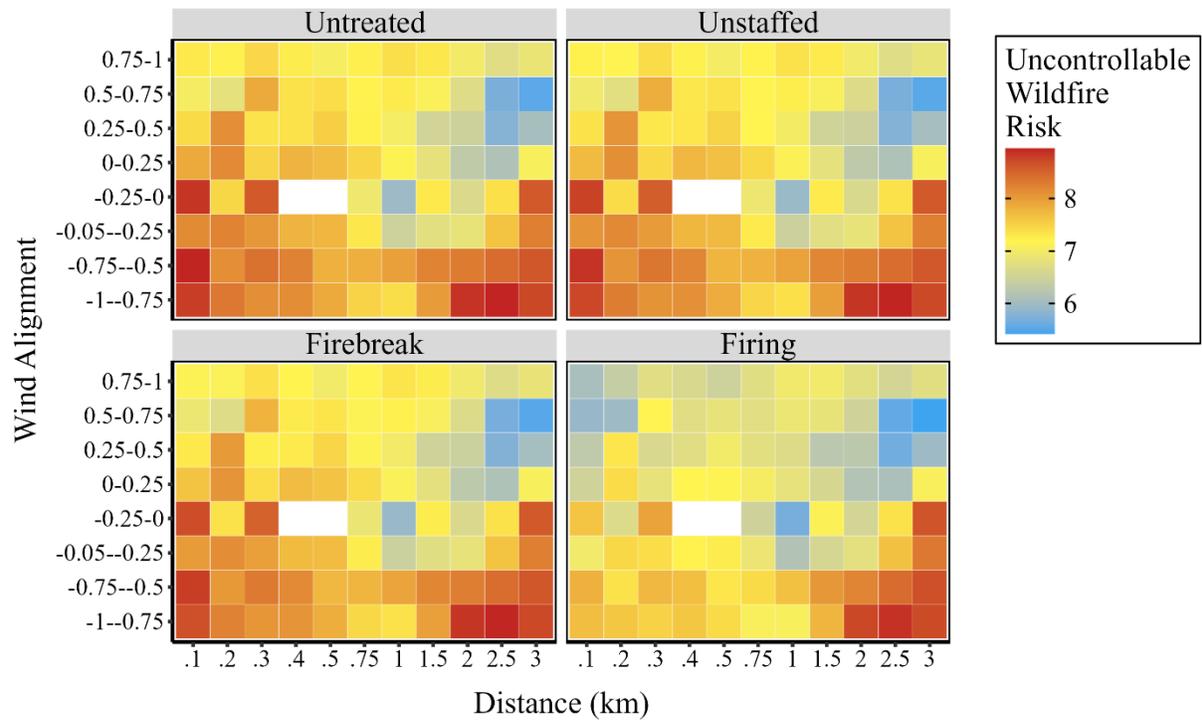


Figure 7.

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Scott Stephens reports financial support was provided by Joint Fire Science Program. Andrew Johnson reports financial support was provided by Climate and Wildfire Institute. Brandon Collins reports a relationship with USDA Forest Service Pacific Southwest Research Station that includes: employment. John Battles reports a relationship with California Wildfire and Forest Resilience Task Force that includes: board membership. Matthew Thompson reports a relationship with Vibrant Planet that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

- Fuel break configurations vary by location across California
- The risk of uncontrollable wildfire was simulated across case study fuel breaks under simulated conditions of suppression leverage
- A framework to assess how fuel break geometry and layout modulate uncontrollable wildfire risk is presented
- In some instances, unstaffed fuel breaks increase the amount of burned area from simulated wildfires

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