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# Optimizing fuel break management for core habitat protection against wildfires in the northern Great Basin

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ABSTRACT

In many fire-prone landscapes, protecting ecological values is an important objective of wildfire management. Here, we develop a mixed integer programming model for managing a network of linear fuel breaks to minimize wildfire impacts on the sagebrush (*Artemisia* spp.) core habitats in the northern Great Basin. The model uses simulated wildfires for 20,000 fire seasons, calibrated to historical fire occurrence data from 2006 to 2020. It coordinates treated fuel breaks to create opportunities to contain each simulated fire. Multiple treatment options with fuel break widths of 30 to 122 m are examined to facilitate effective suppression and prevent breaching by fires with flame lengths between 0.6 and 2.4 m. Both fires' burned areas and fuel breaks' treatment areas cause direct losses to the sagebrush core habitats. Our model was tested by constraining the direct habitat loss from treatments to within 0 to 8910 ha, repressing two extreme scenarios with no fuel break treatment or treating all fuel breaks at 122-m width. Model results highlight the importance of treating linear fuel breaks in the northern Great Basin, which can reduce the expected core habitat loss to wildfires by up to 38 % compared to the no-treatment scenario. More extensive treatment would cause diminishing returns, with no further reduction to core habitat loss to wildfires once treatment-related habitat loss exceeds 5346 ha. Our further analyses of the spatial fuel break layout solutions and their tradeoffs offer region-specific insights to support decision making. However, the model formulation is flexible for customizations to support broader applications in other fire-prone landscapes with different wildfire management objectives and requirements.

## 1. Introduction

Common fuel treatment methods, such as mechanical treatments, prescribed fires, herbicides, and chemical applications (Agee and Skinner, 2005; Bernau et al., 2018; Brennan and Keeley, 2015; Diamond et al., 2012), can alter fire behavior and support firefighting efforts. Fuel treatments can cover large and contiguous areas (i.e., area-wide treatments) to slow fire spread (Gonzalez et al., 2008), reduce fire size (Bevers et al., 2004; Hirsch et al., 2004; Loehle, 2004), and decrease fire intensity and severity (Mell et al., 2010; Reinhardt et al., 2008). Fuel treatments can also be implemented as linear fuel breaks to facilitate fire suppression and containment efforts rather than directly altering fire behavior (Ingalsbee, 2005). Linear fuel breaks are typically interconnected narrow strips of land where fuels are treated (vegetation is removed or reduced) to facilitate wildfire management (Agee et al., 2000; Green, 1977; NWCG, 2018). In fire-prone landscapes worldwide, there has been growing interest in implementing linear fuel breaks for wildfire management and protection of landscape values (Ager et al., 2019; Aparício et al., 2022; Belavenutti et al., 2022; Zong et al., 2021). For instance, approximately 18,000 km of fuel breaks are being constructed or maintained in the Great Basin region of the western US to protect its native ecosystems from escalating wildfire threats (Pilliod et al., 2021). Effective fuel treatment management and planning can be challenging and often requires support from simulation modeling, empirical analyses, or case studies (Hood et al., 2022; Jain et al., 2021; McKinney et al., 2022; Omi, 2015; Ott et al., 2023).

Modeling can provide valuable insights to inform fuel break management and planning decisions. Two widely used modeling

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approaches, simulation and optimization, allow for evaluating trade-offs among various management scenarios. Both approaches may use simulated future wildfires to examine the effectiveness of treatment alternatives in changing future fire outcomes (Haas et al., 2013; Salis et al., 2014). Past research shows that while simulation-based approaches dominate the growing body of fuel treatment modeling studies, there have been relatively few efforts to develop mathematical programming based optimization models (Jain et al., 2021; Ott et al., 2023). Compared to simulation, optimization models can explore a broader range of potential solutions to find the most effective one, but computational complexity is often a challenge for the optimization approach (Chung, 2015). Additionally, most existing optimization models targeted area-wide fuel treatments rather than linear fuel breaks, with their focus on examining fire behavior changes, such as reductions in fire spread rates and intensities, in landscapes delineated into raster cells (Carrasco et al., 2023; Minas et al., 2013, 2014; Nguyen and Wei, 2022; Rachmawati et al., 2018; Wei, 2012), nodes (Pais et al., 2021; Yemshanov et al., 2021), or polygons (Granda et al., 2023; León et al., 2019; Murray and Church, 2023; Rachmawati et al., 2016). In contrast, linear fuel breaks are more concerned with facilitating wildfire suppression along line segments to support fire containment or control, but few modeling efforts have been directed toward optimizing fuel break configuration and evaluating their effectiveness.

Previous modeling studies have used a variety of methods to characterize fire-landscape interactions and several metrics to reflect fuel break effectiveness in fire risk reduction and containment. Oliveira et al. (2016) compared the effectiveness between fire breaks (fully removing all vegetation within a 120-m-wide strip) and shaded fuel breaks (partially removing vegetation within a 120-m-wide strip to maintain 22 % canopy cover) in reducing fire size and burn probability. Similarly, Zong et al. (2021) examined different fuel break designs with varying densities, widths, and spatial configurations to assess their impacts on burn probability reduction. Ager et al. (2023) analyzed tradeoffs in fire interception between two alternative strategies where fuel breaks either form linear or “radical” (i.e., clustered) shapes without explicitly considering the spatial interaction between wildfires and linear fuel breaks for fire containment. Aparício et al. (2022) took this spatial interaction into account by delineating an “ignition polygon” for each simulated fire, which is the smallest possible fire container enclosed by fuel breaks. Each simulated fire will either be contained within its corresponding ignition polygon, or escape. The effectiveness of each fuel break is evaluated separately by its possible effect of containing all simulated fires within their corresponding ignition polygons. Nguyen et al. (2024) implemented this same concept by developing a mixed integer programming (MIP) model to optimize the investment on a fuel break network to simultaneously contain many simulated fires within their corresponding ignition polygons. Both approaches from Aparício et al. (2022) and Nguyen et al. (2024) account for the effect of using fuel breaks to contain fires within ignition polygons, but did not account for other possible enclosed polygons formed by fuel breaks to contain fires beyond their ignition polygons. This inherent limitation prevents the exploration of more flexible fire containment strategies using fuel breaks, other than containment by the ignition polygons, and may therefore underestimate their overall effectiveness in decreasing landscape fire risks.

While fuel breaks can facilitate fire risk reduction and fire containment efforts, there are also potential negative ecological impacts caused by the creation and maintenance of these fuel breaks. For example, landscape core habitat and biodiversity can be negatively influenced by both wildfire damage (Kelly et al., 2020) and fuel break treatments (Hummel and Calkin, 2005; Stevens et al., 2016). However, existing literature shows a lack of research regarding the ecological impacts from both fuel breaks and wildfires (Shinneman et al., 2019). Quantifying those impacts remains a challenge (Driscoll et al., 2010) and has only been addressed by a few optimization models. Rachmawati et al. (2018) developed an optimization model to simultaneously fragment fuel loads and maintain a desired level of landscape habitat connectivity that is defined by contiguity of areas of higher fuel loads. León et al. (2019) employed an optimization model to break contiguous hazard fuels and preserve habitat quality that is measured by fuel age. Shifting the focus from habitat fragmentation, Carrasco et al. (2023) designed an optimization model to maximize ecological protection, quantified by direct habitat losses due to both fire break construction and fire damage. While these previous studies focus on area-wide fuel treatments, similar considerations are likely necessary for the development, maintenance, and use of linear fuel breaks, which remain rarely explored by modeling studies.

In this study, we introduce a mixed integer programming (MIP) based optimization model that strategically manage a network of linear fuel breaks to support wildfire suppression and containment in a northern Great Basin landscape. Here, management is referred to as maintaining or improving fuel breaks in the network, with multiple options to treat fuels within specific widths of a fuel break segment so it can potentially halt fire spread at certain fire intensities (or flame lengths); explicitly considering maintenance is important because vegetation regrowth after initial treatment can reduce fuel break effectiveness over time (Aubard et al., 2020). Our model considers the ecological impacts from both fuel break management and wildfire damage to the landscape's core habitat areas, and aims to find the best treatment configuration and coordination of fuel breaks for the optimal habitat protection outcome. The landscape's habitat of focus is the sagebrush (*Artemisia* spp.) ecosystems, which have been increasingly threatened by wildfire-induced loss (Doherty et al., 2022). Protecting these ecosystems is vital for supporting the greater sage grouse (*Centrocercus urophasianus*) populations, a species that has been the centerpiece of conservation efforts across the sagebrush biome for decades (Sparklin et al., 2024).

Our model focuses on the strategic management of a linear fuel break network for efficient fire containment, which differs from many previous optimization models that targeted area-wide fuel treatments and aimed at reducing burn probability. Two key features distinguish our model from existing fuel break modeling efforts. First, our method significantly advances recent models by Aparício et al. (2022) and Nguyen et al. (2024), which assess fire containment based solely on the smallest polygon (or ignition polygon) enclosed by linear fuel breaks intersecting each fire's perimeter. In contrast, our model evaluates the full solution space by identifying and assessing all possible containment polygons formed by the intersection of fuel breaks with each simulated fire. This broader exploration reduces the risk of underestimating potential opportunities to contain fires by fuel breaks, and enhances our ability to assess their overall effectiveness in mitigating fire risk. Second, our model is among the few that jointly consider the impacts of both future wildfire damage and fuel break treatments on a landscape's critical habitats. While a previous model from Carrasco et al. (2023) integrated these impacts on a landscape characterized by area-wide treatment units, our model adapts a similar ecological accounting framework to linear fuel breaks and offers new insights into balancing ecological protection with wildfire suppression and containment efforts, rather than with broad landscape modification of fire behavior.

Our MIP model is tested against a large set of simulated wildfires, with the objective of minimizing the total core habitat loss across the northern Great Basin landscape. Through scenario-based tradeoff analyses, we demonstrate how the model can inform strategic fuel break management and the broader implications for more effective and ecologically informed wildfire management and planning.

## 2. Materials and methods

### 2.1. Study site, data collection and processing

The continental US has been delineated into 128 pyromes (Fig. 1A), each having relatively homogeneous fire characteristics, to facilitate

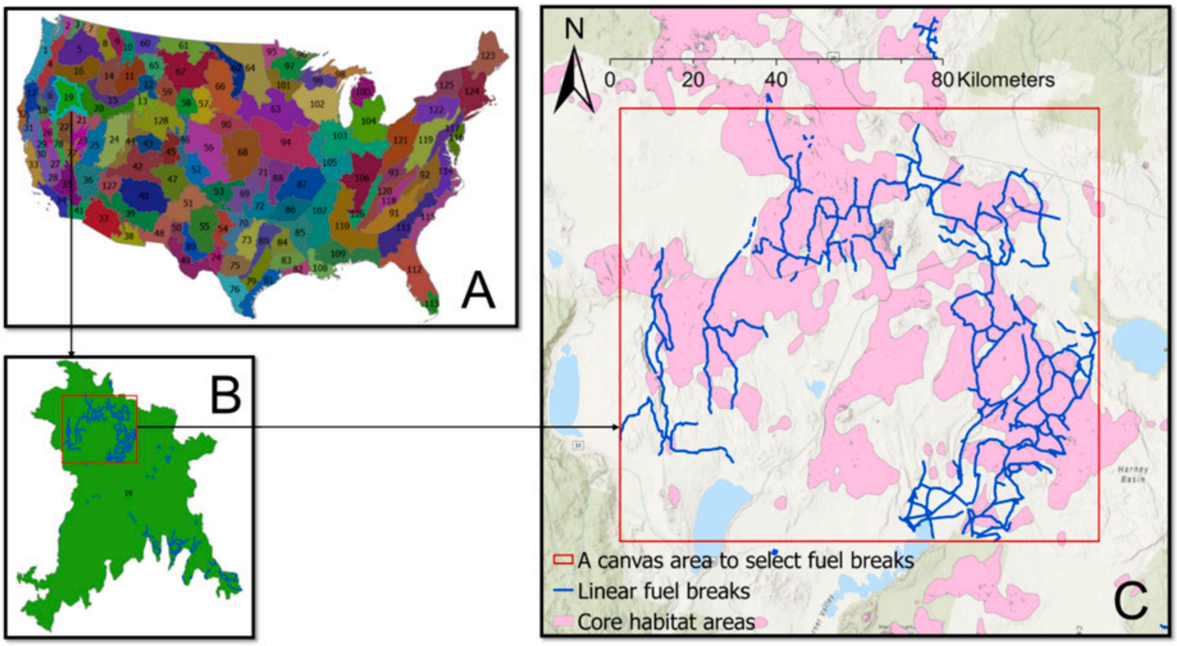


**Fig. 1.** Study landscape with spatial locations of linear fuel breaks and core habitat areas. Pyromes spatial data are obtained from Short et al. (2020). **A**: Pyromes within the contiguous US. **B**: Pyrome 19 - the "Highland Lava Planes". **C**: Fuel breaks and core habitat areas within the study landscape.

location specific fire management (Short et al., 2020). Our study landscape lies in the northern area of pyrome 19 (i.e., the Highland Lava Planes, Fig. 1B), within the Great Basin region of the western US. Most of the landscape area is dominated by the sagebrush shrublands and is influenced by a semiarid to arid climate with warm summers, wet springs, and cold winters. Historically, fire return intervals in sagebrush ecosystems varied between 163 and 225 years for low sagebrush, 50–120 years for Wyoming big sagebrush, and 17–50 years for mountain big sagebrush communities (Baker, 2006). However, higher precipitation in recent decades has increased the expansion of nonnative annual grasses, especially the cheatgrass (*Bromus tectorum*), resulting in changing fire regimes in the Great Basin (Pilliod et al., 2017; Strand et al., 2025). Past studies have shown that greater cheatgrass cover has increase fire size and frequency. For example, around 11 % of the Great Basin's area where cheatgrass cover exceeds 15 % has been burned during the period from 2000 to 2014 (Bradley et al., 2018). Altered fire regimes due to the continued expansion of nonnative annual grasses posed the biggest contemporary threat to the sagebrush ecosystems, which provide critical habitats for more than 350 species of conservation concern (Wisdom et al., 2005).

We selected the northern Great Basin landscape for our study because it has two important characteristics as illustrated by Fig. 1C: 1) a significant portion of the study landscape was designated for protecting the core habitats (Doherty et al., 2022), characterized by intact and functioning sagebrush ecosystems which are increasingly threatened by escalating wildfire frequency and damage (Crist et al., 2023; Maestas et al., 2022; Weise et al., 2023) and 2) a network of linear fuel breaks exists (Weise et al., 2023) and can be maintained or improved to facilitate the protection of those core habitats against wildfires. There are 345 linear fuel break segments within our study site that span the total length of 1304 km (fuel breaks inside the red rectangular in **Fig. 1B** or **1C**). We obtained these fuel break data from a prior study by Gannon et al., which delineated extensive networks of existing fuel breaks across California (Gannon et al., 2023) and a large portion of the Great Basin that encompasses our study landscape. A spatial layer delineating the core habitat areas within this landscape was also available (Doherty et al., 2022) to facilitate our test cases.

We used simulated wildfires from the national dataset generated by the Wildfire Risk Simulation Software (FSIM) (Scott et al., 2024). Wildfires were generated and calibrated by FSIM using several inputs, including fuelscape (spatial data layers generated by LANDFIRE 2.2.0 that describe fuels, vegetation, and topography inputs for fire behavior modeling) which represents landscape conditions at the end of 2020, historical fire occurrence and burn probability within the landscape from 1992 to 2020, and daily temperature and precipitation during each fire season (or year) from 2004 to 2018 (Scott et al., 2024). For pyrome 19, the FSIM simulation process included replications of 20,000 fire seasons, calibrated to reflect historical fire occurrence records from 2006 to 2020. Each season has multiple fires, and each fire was generated based on a Monte-Carlo stochastic process with randomized values of ignition location and spread duration (in days), and randomized daily values of wind speed, wind direction, moisture content, and energy release content during its spread. This extensive simulation process resulted in a total number of 292,560 simulated fires, from which we identified 11,747 fires that intersect with at least one fuel break within the study landscape (Fig. 2). We focused exclusively on examining the impacts from these 11,747 fires. The remaining fires that do not engage with any fuel breaks in the landscape were excluded from analyses.

For each of the 11,747 selected fires, two FSIM data outputs were collected for spatial processing, including fire footprint (polygon feature) and fire flame length (raster with resolution of 270 m). Here, we select two fires as examples to illustrate the two spatial processing steps for each fire:

- In the first step, we overlayed each simulated fire footprint (polygon feature) with all fuel breaks (multiple-line feature) and the core habitat areas (multiple-polygon feature), as illustrated in Fig. 3. These overlay processes allow for the identification of the set of fuel breaks that can split the fire footprint into multiple ***sub-footprints***. Information about the size of each sub-footprint, core area within each sub-footprint, and the adjacency relationships between all sub-footprints were recorded after this step (**Supplementary Table A1**).
- In the second step, for each pair of adjacent sub-footprints of a fire identified in step 1, we identified all fuel break segments that delineate the boundary of the two adjacent sub-footprints. Those fuel break segments were then overlaid with the corresponding fire flame length raster. Note that each simulated fire would have its own flame length raster from FSIM. Along each fuel break segment there would

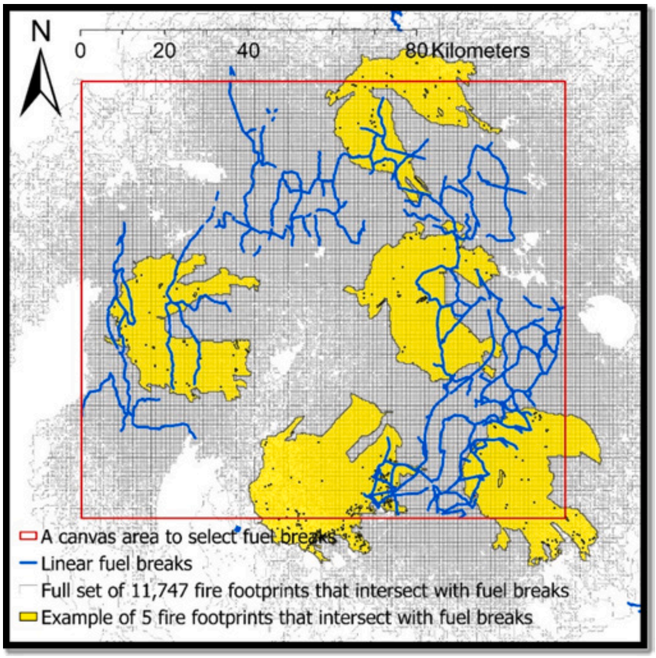


**Fig. 2.** FSIM simulated wildfires that were included in this study. Since fire footprints can overlap, it is difficult to differentiate each individual footprint while all 11,747 footprints are displayed simultaneously (in gray). Thus, an example with 5 large fire footprints (in yellow) is shown here for illustration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

be a set of raster cells storing the fire flame length values; from which we used the maximum flame length value recorded (**Supplementary Table A2**) to indicate the most severe fire behavior along each fuel break segment between the adjacent sub-footprints of a fire.

The above process is repeated for each FSIM fire. Data extracted from the above two steps were then used to populate the MIP model, which we will describe with details in the next section.

### *2.2. Fire containment logic*

Our model is designed for managing (i.e. treating) linear fuel breaks to create opportunities for fire containment and reduce wildfire loss across a landscape, measured by the total core habitat areas burned. Each fuel break, if treated up to certain standards (such as extending treatment width as described later in the test cases), can facilitate safer and more efficient fire suppression that assumably will stop approaching fires at specific intensities (or flame lengths) from breaching through. Under a constrained management plan, only a subset (not all) of fuel breaks in the landscape may be selected for treatment. Our MIP model formulation uses simulated future wildfires to evaluate and identify this optimal subset of fuel breaks to treat, such that their combined effect would help achieve the greatest reduction in core habitat losses by all these fires.

Simulated fires are used to evaluate fire containment through the management of fuel breaks in the studied landscape. When no fuel breaks are treated, all fires are assumed to spread into their originally simulated footprints. Treated fuel breaks (with associated suppressions) can limit fire spread and result in a smaller final burn area within a portion of each fire. That portion of a fire is considered “contained”, given that two condition are met: 1) it is enclosed by treated fuel breaks, and 2) the maximum fire flame length approaching these fuel breaks do not exceed the flame length protection capacity of these fuel breaks after they are treated. Because we consider multiple options to treat each fuel break (i.e. multiple width expansion options that can enhance the flame length protection capacity to different levels), determining whether a portion of a fire can be contained by treated fuel breaks requires assessing the coordination of fuel breaks, their specific treatment decisions, and their associated protection capacity levels. Even if treated fuel breaks completely enclose a portion of a fire footprint, the fire can still escape if at least one of these fuel breaks fails to hold (i.e. if the fire's flame length exceeds the fuel break's protection threshold). For each individually simulated fire, its unburned portion can be used to calculate the value protected, such as fire size reduction or wildland-urban interface (WUI) damage reduction as in Nguyen et al. (2024), or protected core habitat areas from burning in this study. The aggregated impact (such as accumulated core habitat area losses) from many simulated fires can be calculated to evaluate the overall effectiveness of a managed fuel break network in mitigating potential future fire risks. By testing alternative fuel break network management plans, we can analyze their trade-offs to inform strategic planning decisions.

### *2.3. Model formulation*

Results from data processing help identify information about each fire to use in our model as presented in Table 1 and illustrated in Fig. 5. Intersecting all fuel breaks (indexed by $b$) with the original footprint of each fire (indexed by $e$) can generate a set of sub-footprint polygons (indexed by $i$ or $j$) within the fire, including the ignition polygons $I_e$. For example, the fire $e = 55{,}002$ presented in **Figs. 3 and 4** has five sub-footprint polygons ($i$ or $j$ in the range from 1 to 5, more details in **Supplementary Table A1**) and polygon #1 is the fire ignition polygon, which is considered as always “burned” by the model. The boundary between each pair of adjacent polygons $i$ and $j$ can be created by a set of fuel breaks denoted by $S_{e,i,j}$, such as the two fuel breaks 319 and 335 which form the boundary between polygon 1 and 5 of fire 55,002 (more details in **Supplementary Table A2**). Since our model tracks fire spread between adjacent polygons of each fire, this adjacency information has to be identified for every polygon within that fire (these neighboring polygons are denoted by the set $P_{e,i}$, with results for the two example fires shown in the last column of **Supplementary Table A1**). Additional model parameters identified from data processing include: the maximum fire flame length $f_{e,b,i,j}$ of fire $e$ along each fuel break segment $b$ (not the entire fuel break) that belongs to the boundary of adjacent polygons $i$ and $j$ (see the last column of **Supplementary Table A2**), which is used to check the possibility of fire escape even when it is intercepted by fuel breaks; and core habitat areas $w_{e,i}$ within each sub-footprint polygon that would be lost if they are burned (**Supplementary Table A1**), which facilitate calculating the overall fire loss as described later in our model objective function.

Our model considers multiple options $k$ for treating each fuel break $b$. Only a single decision option $D_{b,k}$ can be selected for each fuel break, which would enhance its protection capacity to

$Q_b$ (every fire with maximum flame length less than $Q_b$ when approaching the treated fuel break is assumed to not breach though it). However, implementing a $D_{b,k}$ treatment option also causes a direct loss $c_{b,k}$ to the core habitats (**Supplementary Table A3**). Variable $B_{e,i,j}$ is used to model fire spread between adjacent polygons $i$ to $j$ as long as $i$ has been already burned. But even when a fire spreads from the burned polygon $i$ to $j$ ($B_{e,i,j} = 1$), it may not be able to burn $j$ when treated fuel breaks successfully stopped the spread. The final burn outcome for each polygon was captured by variable $X_{e,i}$, which will be used together with $w_{e,i}$ to estimate the cumulative loss of core habitat areas within the burned polygons across all fires.

Using the simulated fire with an ID of 60,112 from the FSIM runs in **Figs. 3 and 4** as an example, if we maintain only fuel breaks #317 and #335 so that they can stop fire spread at flame lengths not exceeding 4 ft, the sub-footprint polygons 1, 2, and 4 will be burned by this fire, while only polygon 3 remains protected. A more extensive fuel break

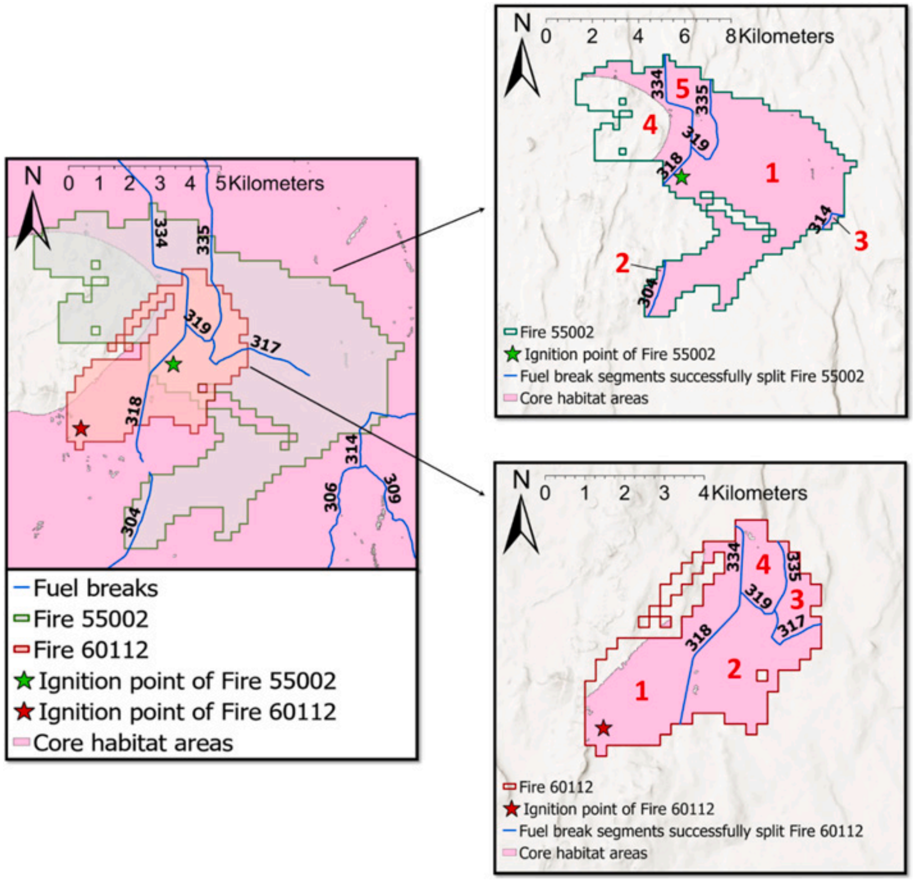


**Fig. 3.** Data processing's Step 1 for two example fires. Sub-footprints were delineated for each fire by overlaying the fire footprint with fuel breaks and core habitat areas. In this figure, black numbers represent fuel break IDs and red numbers represent fire's sub-footprint IDs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

management plan can improve landscape protection against future fires. For example, by investing in the two longer fuel breaks #318 and #334 to increase their protection capability against up to 4-ft flame length, the final fire size can be reduced substantially (only sub-footprint polygon 1 of this fire is burned while the other 3 polygons are protected). Fuel breaks selected for management often can benefit the containment of multiple simulated future fires. For example, selecting fuel breaks #318 and #334 will help contain both fires with IDs of 60,112 and 55,002, resulting in smaller burn sizes than the fully simulated footprints for both fires (as illustrated by Figs. 3 and 4). These examples emphasize that different fuel break management plans may provide different fire containment opportunities and result in different fire spread patterns. While management decision for each fuel break involves selecting only one among multiple available treatment options, coordinating decisions for all fuel breaks to find the optimal maintenance strategy would involve examining a very large pool of feasible solutions. This task can be assisted by a linear programming optimization model formulation as presented below.

Our MIP model formulation includes following equations:

$$Min \sum_e \sum_i w_{e,i} X_{e,i} \tag{1}$$

*Subject to:*

$$\sum_k D_{b,k} \leq 1 \forall b \tag{2}$$

$$Q_b = \sum_k q_{b,k} D_{b,k} \forall b \tag{3}$$

$$f_{e,b,i,j} Y_{e,i,j} \leq Q_b \forall e, b \in S_{e,i,j} \neq \varnothing, i, j \in P_{e,i} \text{ and } j > i \tag{4}$$

$$X_{e,i} = 1 \forall e, i \in I_e \tag{5}$$

$$B_{e,i,j} \leq X_{e,i} \forall e, i, j \in P_{e,i} \text{ and } j \notin I_e \tag{6}$$

$$\begin{cases} X_{e,j} \leq \sum_{i \in P_{e,j}} B_{e,i,j} \forall e, j \notin I_e \\ \sum_{i \in P_{e,j}} B_{e,i,j} = 0 \forall e, j \in I_e \end{cases} \tag{7}$$

$$\begin{cases} Y_{e,i,j} \geq X_{e,j} - X_{e,i} \forall e, i, j \in P_{e,i} \text{ and } j > i \\ Y_{e,i,j} \geq X_{e,i} - X_{e,j} \forall e, i, j \in P_{e,i} \text{ and } j > i \end{cases} \tag{8}$$

$$\begin{cases} B_{e,i,j} \leq 1 - Y_{e,i,j} \forall e, i, j \in P_{e,i} \text{ and } j > i \\ B_{e,i,j} \leq 1 - Y_{e,j,i} \forall e, i, j \in P_{e,i} \text{ and } j < i \end{cases} \tag{9}$$

$$C_b = \sum_k c_{b,k} D_{b,k} \forall b \tag{10}$$

$$\sum_b C_b \leq m \tag{11}$$

*Note: variables $Q_b$, $C_b$, and their associated eqs. (3) and (10) can be omitted for a compact formulation, but we choose to keep them to facilitate explanation of the model's logic.*

The objective function (1) minimizes the sum of weighted net loss from all burned sub-footprint polygons of all simulated wildfires. For our test cases, FSIM is used to simulate numerous fire seasons. The objective function can be changed to eq. (12) if we are interested in the average loss per season:

**Table 1**
Model notations.

| | |
|---|---|
| Indices | |
| $b$ | Index of a fuel break. |
| $e$ | Index of a simulated fire. We could select many fires from multiple fire seasons to build the model. |
| $i$ or $j$ | Index of each the sub-footprint polygon within a simulated fire footprint. When both $i$ and $j$ are used as indices in a variable, they represent a pair of two adjacent polygons within a fire footprint. |
| $k$ | Index of a management option for each fuel break. In the test cases, we examined 4 options of $k = 1, 2, 3$, or 4 that respectively implement fuel break treatments at a width of 100, 200, 300, or 400 ft surrounding each linear fuel break. |
| Variables | |
| $X_{e,i}$ | 0/1 variable; 1 if fire $e$ burned its sub-footprint polygon $i$; 0 if not. |
| $Q_b$ | Continuous variable representing a maximum flame length protection threshold of though fuel break $b$. When the maximum flame length of a fire along fuel break $b$ is beyond $Q_b$, that fire is assumed to breach though fuel break $b$ to continue spreading; otherwise, the fire is stopped from crossing break $b$. |
| $D_{b,k}$ | 0/1 variable; 1 if maintenance option $k$ is selected for fuel break $b$; 0 if not. |
| $Y_{e,i,j}$ | 0/1 variable; 1 if fire $e$ stopped by all fuel break segments constituting the boundary of two adjacent polygons $i$ and $j$; 0 if not. This variable is only created for the case $j > i$. |
| $B_{e,i,j}$ | 0/1 variable; 1 if fire $e$ spreads from polygon $i$ to $j$; 0 if not. |
| $C_b$ | is the total core habitat area loss associated with implementing the maintenance decision selected for fuel break $b$ |
| Parameters | |
| $c_{b,k}$ | Direct core habitat area loss due to implementing maintenance option $k$ for fuel break $b$. $c_{b,k}$ is identified by intersecting a specific buffered area along a fuel break with the core habitat areas, where the buffer width is determined by the management option $k$. |
| $q_{b,k}$ | The maximum flame length that fuel break $b$ with implemented maintenance option $k$ can be effective in stopping fires (fires with flame length of $q_{b,k}$ or less when approaching break $b$ cannot spread across that break). |
| $f_{e,b,i,j}$ | The maximum flame length of fire $e$ along a segment of break $b$ (not the entire break) that belongs to the shared boundary of two adjacent polygons $i$ and $j$. |
| $w_{e,i}$ | Weigh for the loss value of polygon $i$ of fire $e$ when if it is burned by fire $e$. In the test cases, we calculated the total core habitat area within each polygon $i$ of fire $e$ and use it as $w_{e,i_e}$ |
| $m$ | A management constraint which represents a threshold that the total core habitat areas being lost directly by fuel break maintenance is not allowed to exceed. |
| Sets | |
| $I_e$ | The ignition polygons of fire $e$. Although our model can consider a fire that simultaneously ignites from multiple polygons, in the test cases every FSIM simulated fire ignites from a single polygon, which is referred to as "ignition polygon". |
| $S_{e,i,j}$ | The set of fuel breaks that creates the boundary between two adjacent polygon $i$ and $j$ of fire $e$ |
| $P_{e,i}$ | The set of sub-footprint polygons that are adjacent to the sub-footprint polygon $i$ of fire $e$ |

$$Min\ \frac{1}{Number\ of\ fire\ seasons\ simulated}\sum_{s}\sum_{e_s}\sum_{i} w_{e_s,i}\, X_{e_s,i} \tag{12}$$

*With $s$ denoting each fire season, and $e_s$ denoting each fire within the fire season $s$.*

In this model, we assumed there can be multiple options (indexed by $k$) to manage a fuel break. For each fuel break, the decision is either "do nothing" or implement one of the management options $k$, as enforced by eq. (2). Once a management option is selected for a fuel break, it must be implemented for the entire fuel break's length. Depending on the implemented management option, a fuel break can be capable of stopping a fire up to a flame length threshold value $Q_b$ when encountered. The value of $Q_b$ for each fuel break $b$ is identified by eq. (3). Eq. (4) specifies that a fire can be stopped from spreading across the boundary between two adjacent fire polygons if and only if all fuel break segments along that boundary (each segment is often a portion of a fuel break) can stop the fire, i.e., $f_{e,b,i,j} \le Q_b$ for all $b$ will allow $Y_{e,i,j} = 0$ *or* 1; otherwise $Y_{e,i,j} = 0$.

Eqs. (5) to (9) model fire spread across adjacent polygons of each fire. A fire when discovered may have already burned one or multiple sub-footprint polygons $I_e$, which are defined as "ignition polygons" in eq. (5). Each fire can spread from a burned polygon to its adjacent polygons as represented by eq. (6). Specifically for each polygon $i$, all of its adjacent polygons $j$ are examined for potential fire spread: if $i$ has not been burned by fire $e$ yet ($X_{e,i} = 0$), $B_{e,i,j}$ would be forced to zero indicating that fire cannot spread from $i$ to every $j$ adjacent to it; in the other case if $i$ has been already burned by fire $e$ ($X_{e,i} = 1$), $B_{e,i,j}$ would be free to receive a value of either zero or one, indicating that fire can spread from $i$ to $j$. Therefore the value of $B_{e,i,j}$ is determined by the model based on fuel break treatment decisions. For example, when $B_{e,i,j}$ is free, the model can decide to treat fuel breaks constituting the boundary of $i$ and $j$, which can force $B_{e,i,j}$ to zero if the enhanced protection capacity of these treated fuel breaks can prevent fire spread from $i$ to $j$. Eq. (7) allows fire $e$ spreading to polygon $j$ only if at least one fire spread path from its neighboring polygon exist (at least one $B_{e,i,j}$ receive the value of one), otherwise fire cannot spread to $i$ ($X_{e,j} = 0$ when every $B_{e,i,j} = 0$). Because the ignition polygons are always burned first, they are excluded from being the destination of fire spread from other adjacent polygons (the second part of eq. 7). Eq. (8) defines that, for any two adjacent polygons $i$ and $j$, if one was burned and the other was not burned, there must be treated fuel breaks (controlled by eq. 4) that can effectively stop fire $e$ from spreading between these two polygons. Note that $Y_{e,i,j}$ does not specify the spread direction of fire $e$ between polygons $i$ and $j$; it only indicates the existence of an effectively controlled boundary between them. With $Y_{e,i,j} = 1$, fire $e$ cannot spread across the boundary of the two adjacent polygons in either direction (eq. 9). However, if $Y_{e,i,j}$ is set to zero by eq. (4) when $f_{e,b,i,j} \ge Q_b$, fire will burn both $i$ and $j$ if any of them is burned, which is controlled by eq. (8).

Eqs. (10) and (11) represent a constrained fuel break management plan where management activities may be limited by a predefined budget or within an acceptable level of direct negative impact to core habitats. In this study, instead of using a budget limit constraint, we used a constraint to limit the direct loss of existing core habitats when they intersect with management (or treatment) areas surrounding linear fuel breaks. Specifically, the sum of core habitat areas lost due to the fuel break treatments will be calculated by eq. (10) and constrained to not exceed a pre-defined upper-bound $m$ in eq. (11).

## 3. Test cases

### 3.1. Model parameter setups

Three primary types of linear fuel breaks have been commonly used in the Great Basin including brown strips, mowed fuel breaks, and green strips which can be configured with varying widths to disrupt vegetation continuity. Effective fuel break widths are largely based on empirical experiences and past fire behavior (Shinneman et al., 2019), and typically do not exceed 500 ft (152 m) in practice (Bureau of Land Management, 2020). One of the largest fuel break projects in the region, the Soda fire fuel break project which involves maintaining 711 km of linear fuel breaks, has identified 400 ft (122 m) as the optimal fuel break width for effectively managing fires at flame lengths of up to 8 ft (2.4 m) (Bureau of Land Management, 2017). For our test cases, we examined 4 different options to manage linear fuel breaks at the width of either 100, 200, 300, or 400 ft (approximately 30, 61, 91, or 122 m), respectively corresponding to management option $k = 1, 2, 3$, or 4 in our MIP model formulation. For each fuel break, the treated area following a given option $k$ was calculated by multiplying the fuel break's width and length.

Although there is limited empirical evidence linking fuel break width to flame length thresholds, past experimental and assessment studies suggest that expanding the width of a fuel break can increase its success

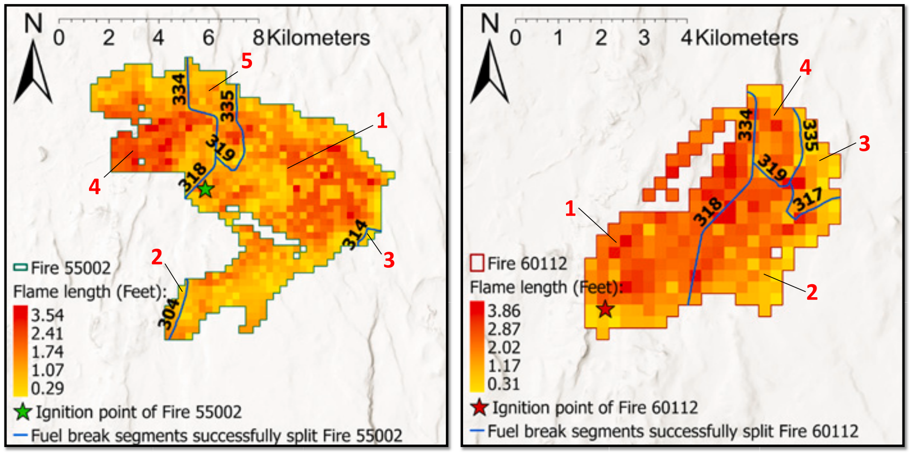


**Fig. 4.** Data processing's Step 2 for two example fires. Fuel break segments along the boundary of each pair of two adjacent sub-footprints were intersected with fire flame length raster to extract the maximum flame length along each fuel break segment. In this figure, black numbers represent fuel break IDs and red number represent fire's sub-footprint IDs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

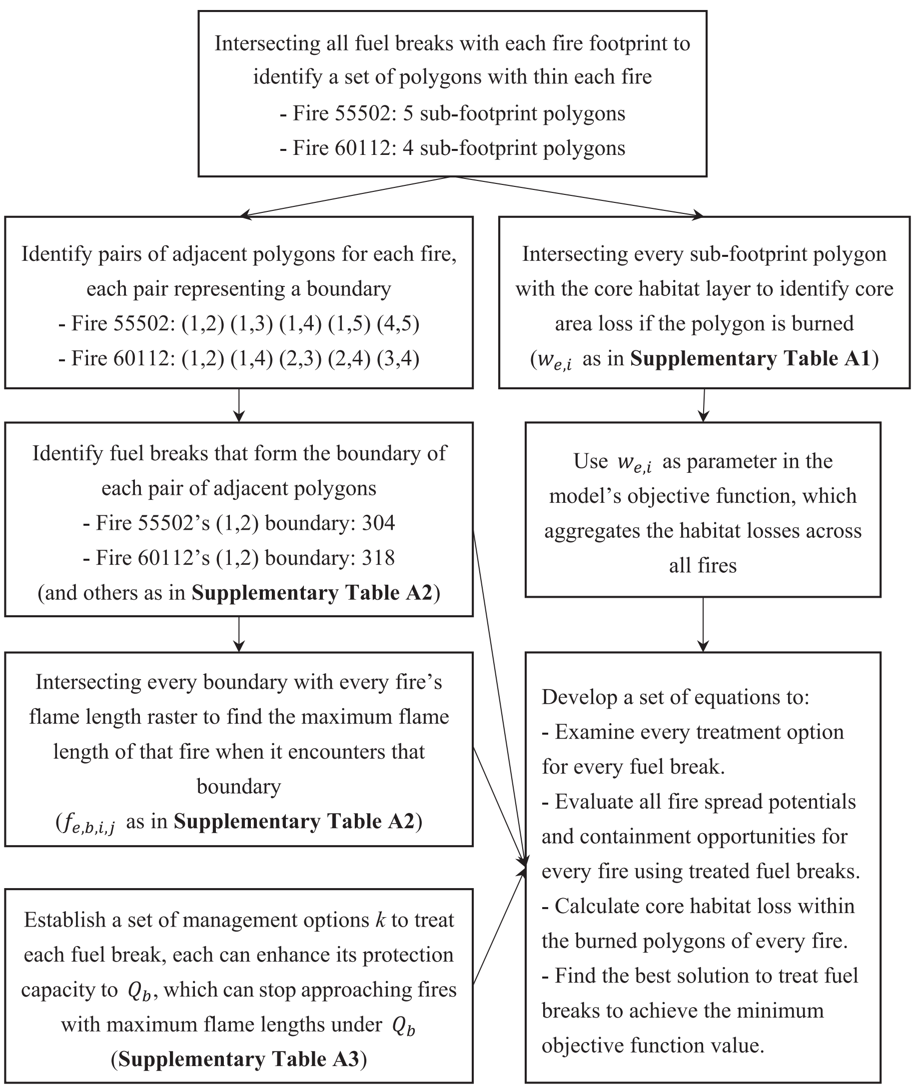


**Fig. 5.** Schematic illustration of the methodological approach using two example fires as shown in Figs. 3 and 4.

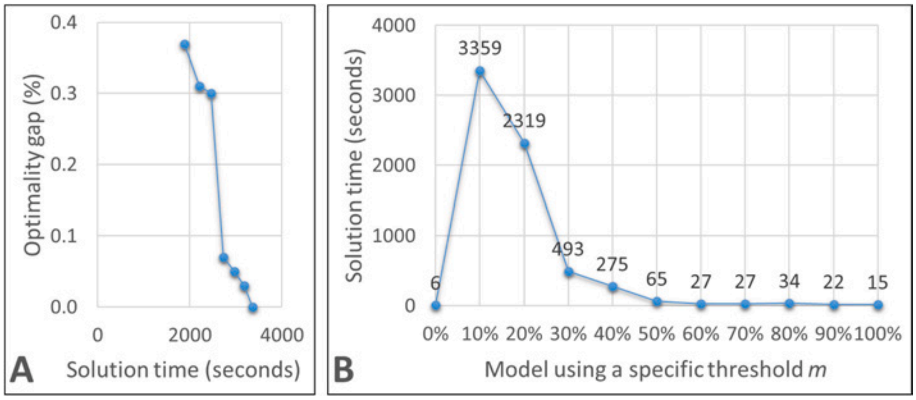


**Fig. 6.** Illustration of solution process. A: Solution time and optimality gap to solve a model with management constraint threshold m set to 10 %) to the optimal solution. B: Times for solving 11 models with different management constraint threshold $m$ (0 % to 100 %) to optimality.

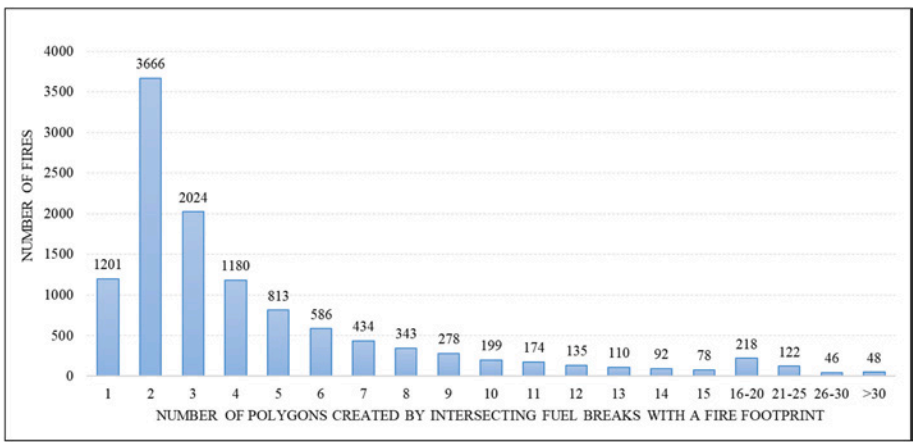


**Fig. 7.** The distribution of simulated fires that can be split into different numbers of polygons by overlaying fuel breaks with simulated fire footprints.

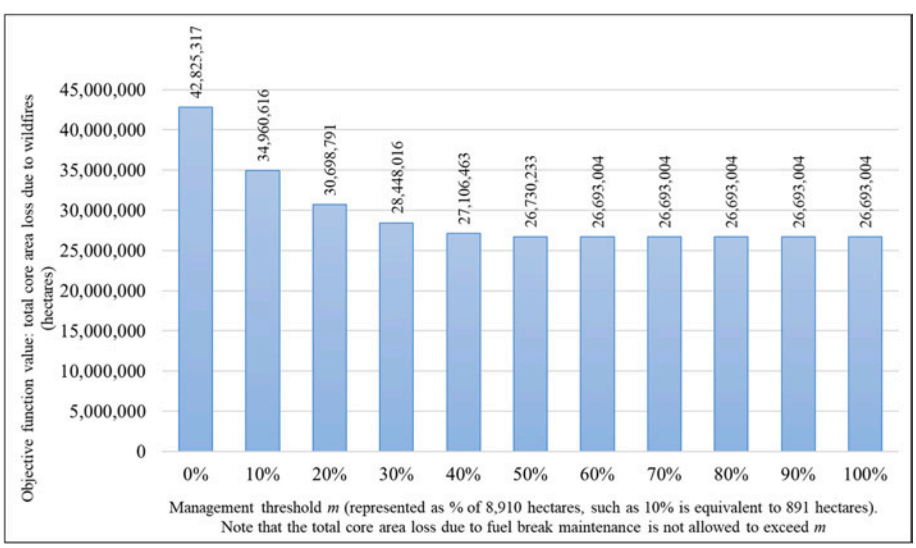


**Fig. 8.** Optimal objective function values from different models.

rate in controlling higher intensity fires (Frangieh et al., 2021; Wilson, 1988; Young et al., 2024). For our test cases, we assumed that selecting a management option $k = 1, 2, 3, 4$ for a specific fuel break $b$ would respectively improve its capability to stop fire at a maximum flame length threshold of $q_{b,k} = 2, 4, 6, 8$ feet (approximately 0.6, 1.2, 1.8, 2.4 m) (**Supplementary Table A3**). This assumption is based on insights from the Soda project, which identified fuel break width of 400 ft as optimal for controlling fire at 8-ft flame length. It is reasonable to assume that narrower fuel break width could support controlling fires with lower flame length values. Specific flame length thresholds were

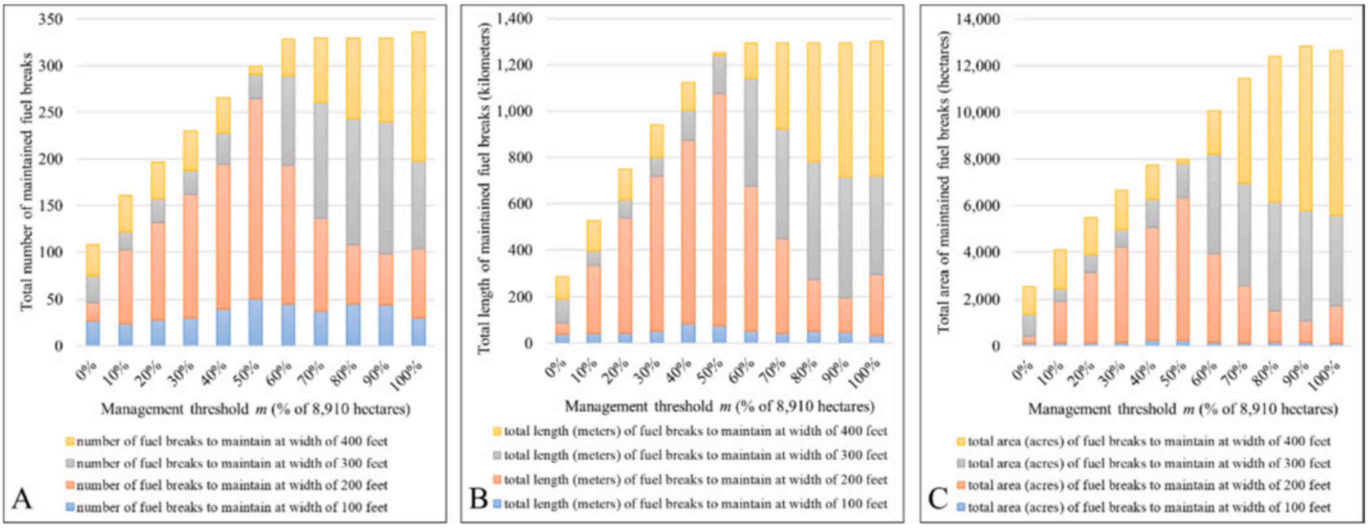


**Fig. 9.** Details of the optimal solutions from different models.

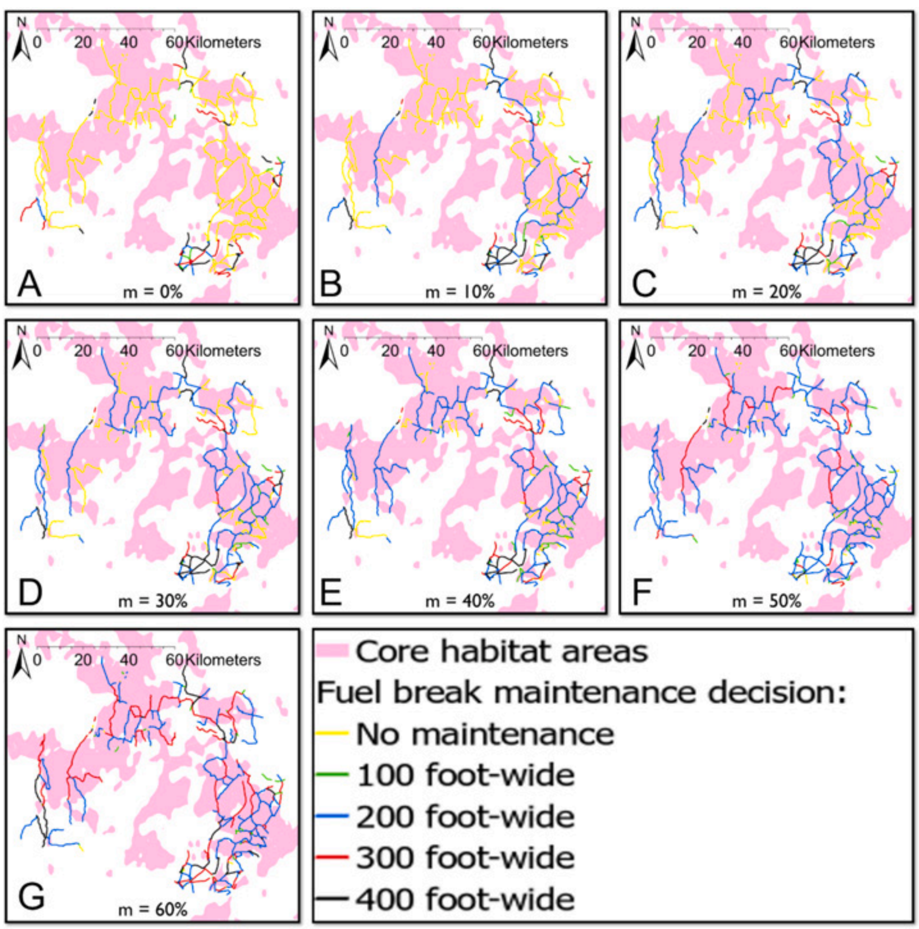


**Fig. 10.** Optimal fuel break maintenance layouts of models with management threshold *m* ranging from 0 to 60 %. Sub-figs. **A** to **G** represent these layouts with increasing values of *m* displayed at the center bottom of each map.

selected based on prior studies, which reflect realistic expectations for successful suppression efforts: fires with flame lengths under 4 FT can be attacked at heads or flanks by persons using hand tools, while fires with flame lengths from 4 to 8 FT often require heavy equipment such as plows, dozers, pumpers, and retardant aircraft, and fires with flame lengths exceeding 8 FT may present serious challenges for effective suppression due to torching, crowning, and spotting (Andrews, 1982; Hirsch and Martell, 1996).

Two model parameters, $w_{e,i_e}$ and $f_{e,b,i,j}$ (see definitions in Table 1), were calculated through the data processing steps as previously described in section 2 of this paper. For example, $w_{e,i_e}$ would be the “Polygon's core area” column in **Supplementary Table A1**, and $f_{b(i_e,j_e)}$

would be last column in **Supplementary Table A2**. Another key parameter for running our model is the management constraint threshold *m*, which limit the total core area loss directly due to the maintenance of fuel breaks to a certain value. Considering the range of fuel break maintenance widths from 100 to 400 ft, the most extensive management plan would be maintaining all fuel breaks in the landscape to the width of 400 ft. Under this plan, we overlayed all fuel break maintenance areas with the core habitat areas to identify 8910 ha of intersection, which served as the maximum possible value of *m*.

We constructed 11 distinct models to represent different fuel break management plans with increasing impact of direct habitat loss due to treatment. These models tested 11 different values of *m*, ranging from 0 to 8910 ha (0 % to 100 % of the maximum *m* value), with an increment of 891 ha (10 %) between successive models. The tradeoffs among these models were analyzed to gain insights into strategic fuel break management and planning decisions.

We used the 2-fire example as illustrated by **Figs. 1 and 2** to demonstrate data processing outcomes and model solutions under different management constraint threshold *m* (presented in **Supplementary Tables A1, A2, A3, A4**). The complete set of 11 models were tested using all 11,747 fire samples to generate results and perform trade-off analyses.

### 3.2. Computer and solver setups

All models were run using a 64-Bit computer equipped with a dual-core 2.5 GHZ processor and 32 GB of RAM. Each model contains the same number of variables (118,146) and constraints (206,474). CPLEX 12.8 was used as the solver, with the optimality gap set to zero to ensure that every model would be solved to the true optimal solution. Solving large and complex MIP models to optimality was time-consuming. This is depicted by the solution time and optimality gap for solving the model with the management constraint threshold *m* set to 10 % (Fig. 6A). The remaining models were easier to solve and took significantly less time to achieve optimality (Fig. 6B).

## 4. Results and discussion

### 4.1. Interaction between potential wildfires and fuel breaks within the study landscape

Existing fuel breaks within our study landscape form a spatial network that facilitates fire containment. Generally, fires with larger simulated sizes have a higher likelihood of being fragmented into multiple sub-footprint polygons. Among the 11,747 simulated fires that engage with existing fuel breaks, 10,529 fires (90 %) can be split by fuel breaks into two or more sub-footprint polygons (Fig. 7), allowing for

**Table 2**
Solution details across different models.

| Report ID | Report Category | Optimal Solution Details | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *m*: threshold for core habitat loss due to fuel break maintenance (%) | 0 % | 10 % | 20 % | 30 % | 40 % | 50 % | 60 % | 70 % | 80 % | 90 % | 100 % |
| 2 | *m*: threshold for core habitat loss due to fuel break maintenance (hectares) | 0 | 891 | 1782 | 2673 | 3564 | 4455 | 5346 | 6237 | 7128 | 8019 | 8910 |
| 3 | solution objective value: total core area loss due to wildfires (million hectares) | 42.83 | 34.96 | 30.70 | 28.45 | 27.11 | 26.73 | 26.69 | 26.69 | 26.69 | 26.69 | 26.69 |
| 4 | number of fuel breaks without maintenance | 237 | 184 | 148 | 115 | 79 | 46 | 16 | 15 | 15 | 15 | 9 |
| 5 | number of fuel breaks with maintenance | 108 | 161 | 197 | 230 | 266 | 299 | 329 | 330 | 330 | 330 | 336 |
| 6 | number of fuel breaks with maintenance option k = 1 | 27 | 24 | 28 | 30 | 40 | 51 | 45 | 37 | 45 | 44 | 30 |
| 7 | number of fuel breaks with maintenance option k = 2 | 19 | 78 | 104 | 132 | 154 | 214 | 148 | 99 | 63 | 54 | 73 |
| 8 | number of fuel breaks with maintenance option k = 3 | 29 | 20 | 25 | 26 | 34 | 26 | 96 | 124 | 135 | 142 | 95 |
| 9 | number of fuel breaks with maintenance option k = 4 | 33 | 39 | 40 | 42 | 38 | 8 | 40 | 70 | 87 | 90 | 138 |
| 10 | total length (kilometers) of fuel breaks without maintenance | 1017 | 777 | 555 | 365 | 179 | 52 | 11 | 10 | 10 | 10 | 3 |
| 11 | total length (kilometers) of fuel breaks with maintenance | 287 | 526 | 749 | 939 | 1125 | 1252 | 1293 | 1294 | 1294 | 1294 | 1301 |
| 12 | total length (kilometers) of fuel breaks with maintenance option k = 1 | 38 | 41 | 45 | 53 | 85 | 76 | 54 | 45 | 52 | 49 | 33 |
| 13 | total length (kilometers) of fuel breaks with maintenance option k = 2 | 49 | 292 | 492 | 664 | 788 | 1001 | 620 | 403 | 221 | 149 | 264 |
| 14 | total length (kilometers) of fuel breaks with maintenance option k = 3 | 104 | 61 | 80 | 83 | 130 | 164 | 466 | 477 | 509 | 519 | 423 |
| 15 | total length (kilometers) of fuel breaks with maintenance option k = 4 | 97 | 132 | 132 | 138 | 122 | 11 | 154 | 369 | 512 | 577 | 580 |
| 16 | total area (hectares) of fuel breaks with maintenance | 2540 | 4076 | 5476 | 6657 | 7739 | 7968 | 10,074 | 11,455 | 12,403 | 12,840 | 12,652 |
| 17 | total area (hectares) of fuel breaks with maintenance option k = 1 | 116 | 126 | 136 | 163 | 259 | 231 | 163 | 138 | 159 | 150 | 102 |
| 18 | total area (hectares) of fuel breaks with maintenance option k = 2 | 299 | 1778 | 3001 | 4049 | 4802 | 6102 | 3782 | 2457 | 1349 | 906 | 1612 |
| 19 | total area (hectares) of fuel breaks with maintenance option k = 3 | 947 | 561 | 734 | 762 | 1191 | 1499 | 4257 | 4360 | 4655 | 4747 | 3868 |
| 20 | total area (hectares) of fuel breaks with maintenance option k = 4 | 1179 | 1611 | 1605 | 1684 | 1486 | 136 | 1872 | 4500 | 6241 | 7037 | 7069 |
| 21 | total area (hectares) of core habitat loss due to maintenance | 0 | 891 | 1782 | 2673 | 3564 | 4455 | 5344 | 6226 | 7098 | 7426 | 7380 |
| 22 | total area (hectares) of core habitat loss due to maintenance option k = 1 | 0 | 33 | 61 | 96 | 155 | 118 | 64 | 59 | 67 | 67 | 17 |
| 23 | total area (hectares) of core habitat loss due to maintenance option k = 2 | 0 | 856 | 1716 | 2517 | 3140 | 3337 | 2509 | 1769 | 710 | 381 | 859 |
| 24 | total area (hectares) of core habitat loss due to maintenance option k = 3 | 0 | 3 | 5 | 60 | 269 | 1000 | 2545 | 2157 | 2652 | 2650 | 1800 |
| 25 | total area (hectares) of core habitat loss due to maintenance option k = 4 | 0 | 0 | 0 | 0 | 0 | 0 | 226 | 2241 | 3669 | 4328 | 4703 |

containment opportunities to reduce fire spread and associated damage. The remaining 1201 fires (10 %) could not be fully split by any existing fuel breaks.

### 4.2. *Influence of fuel break maintenance on total core habitat area loss by fires*

Based on the objective function used in our MIP model, an individual unit of core area habitat could be burned multiple times by different simulated fires, and those core areas that repeatedly burned were summed in the objective function. In the worst-case scenario without considering the benefit from any fuel break treatment (i.e., all fires are allowed to freely spread), a total of 43.2 million hectares of core habitat areas were burned repeatedly by the 11,747 simulated fires; within those fires, 20 % of the largest fires (2349) are responsible for 74.6 % of the total core habitat area loss (32.2 million hectares). The "no management" scenario serves as a reference to compare with the other 11 test cases. Each test-cases adopted a specific value of $m$ as a management constraint threshold, which ensures that the direct core area loss due to fuel break treatment does not exceed a certain limit. Model solutions are detailed in Table 2 and also illustrated by **Figs. 8** and **9**.

Across the landscape, some fuel breaks are not in close proximity to any core habitat areas, and can therefore be maintained at specific widths without causing any direct loss to core habitats. This is illustrated by the solution from a model with $m$ set to zero (Fig. 10A and the 0 % columns in **Figs. 8** and **9**), where 106 fuel breaks are selected for treatment, covering a total treated area of 2540 ha that do not intersect any core areas. This model resulted in 42.8 million hectares of total core area loss to wildfires, a slight improvement over the worst-case "no maintenance" scenario with 43.2 million hectares of core area loss. The improvement is insignificant because those treated areas are generally not near existing core area habitats.

The optimal solutions across all 11 models demonstrate that increasing the threshold $m$ for fuel break management reduces the total core area loss to wildfires. However, this benefit quickly diminishes, with no further improvement in the solutions once $m$ reaches or exceeds 5345 ha (60 % of the maximum allowable core habitat loss to fuel break maintenance), as shown in Fig. 8. The same optimal objective function value (26.7 million hectares or core area loss to wildfires) was obtained from models with $m$ at or beyond the 60 % level, approximately 38 % reduction compared to the reference model without fuel break maintenance (43.2 million hectares of loss). However, all models with $m$ beyond 60 % are likely to be less desirable to managers, as they impose greater direct habitat loss from fuel break treatment without yielding additional benefits of core area protection against wildfires.

For further treatment layout analysis, we excluded all models having management threshold $m$ greater than 60 %. As $m$ increases from 0 % to 60 %, the models generally recommend treating a greater number of fuel breaks (Fig. 9A) with a longer total break length (Fig. 9B) and a larger total treatment area across the landscape (Fig. 9C). Fuel breaks are rarely managed at widths of either 100 or 400 ft in the model results, as shown in **Figs. 9** and **10**. Instead, most fuel breaks selected by the models are managed at 200-ft width (Fig. 10), which is sufficient to stop fires at flame lengths under 4 ft from breaching through. This reflects the model's sensitivity to the simulated fire behaviors used in our case study, as many of them have low flame lengths during their spread. Increasing the threshold $m$ from 50 to 60 % results in a noticeable rise in the number of fuel breaks maintained at 300 ft (**Figs. 9** and **10**). However, the improvement in model outcomes, measured by total core areas repeatedly burned by fires, was relatively minor between these two models (Fig. 8).

### 4.3. *Comparing tradeoffs among alternative models*

Understanding the tradeoffs among model solutions with varying $m$ values requires comparing the impacts of core habitat losses due to both fuel break treatment and simulated wildfire damage. The impact of wildfires on the core habitat was measured by summing the cumulative core habitat areas burned by all simulated fires over 20,000 fire seasons (or years). In contrast, the impact of fuel break treatment was measured as the direct habitat loss from a one-time implementation of a selected management plan. Because we are accounting for those two types of impact with different temporal scales, it may not be appropriate to simply sum the impacts from wildfires and from fuel break treatment without the temporal consideration. One potential way for this evaluation is to weight the total core area loss from all fires by a fraction of the total 20,000 seasons (e.g., using 10 out of 20,000 fire seasons as a temporal scale), then add it to the losses from treatment of fuel breaks, and compare the weighted sums between different models.

Table 3 shows tradeoffs among model solutions based on various temporal scales. Each row presents the total weighted habitat loss for a set of models that share the same number of fire seasons but vary in the management threshold $m$ value. The highlighted value in each row identifies the best-performing model (i.e., the one with the lowest total loss). For example, when considering only a single fire season (a temporal scale of 1 out of 20,000), the best model recommends no fuel break treatment in the entire landscape ($m = 0$ %), resulting 2141 ha of total core habitat loss due to both fuel break and wildfire, which is substantially less than the 8714 ha of loss under a strategy that treats all fuel breaks ($m = 100$ %). A notable but not surprising finding is that a more extensive fuel break treatment plan (i.e., larger $m$ value up to 60 %) will perform better when considering the effect of using fuel breaks to mitigate fire risks to core habitats over a longer term (more fire seasons). Conversely, a less extensive fuel break treatment plan may yield a better habitat protection outcome when assessing wildfires within a shorter time frame.

In addition to analyzing tradeoffs based on the direct core habitat losses due to treatment and wildfires, practical decision-making often requires evaluating other important factors such as habitat fragmentation in a landscape. Spatial fuel break treatment layouts recommended by our model (Fig. 10) can be used to assess the potential impact of treatments on habitat fragmentation. For example, it is not difficult to recognize that treatment layouts associated with larger $m$ values would involve treating more fuel breaks and result in more fragmented core habitat areas (Fig. 10). These spatial treatment layouts can be further analyzed by external tools, such as *FragStats* (https://www.fragstats.org ), to generate more detailed habitat metric to facilitate tradeoff analysis.

### 4.4. *Implications*

Habitat protection is a key consideration in fire-prone landscapes with valuable ecological assets at risk. In such landscapes, fuel breaks have been well recognized as a key preemptive fuel treatment approach to facilitate suppression and protect ecologically significant areas (Maestas et al., 2016). Our study selected site within the Great Basin region exemplifies this, where extensive efforts are underway to build and maintain 17,000 km of fuel breaks to protect native sagebrush ecosystems from wildfires (Shinneman et al., 2019). However, comprehensive assessments of fuel break effectiveness are still lacking (Weise et al., 2023), posing challenges for making strategic fuel break management decisions. Our proposed model addresses this need by offering an integrated approach that considers the impacts of both management actions and wildfire spread to support decision-making.

Findings from our test cases offer insights to assist wildfire managers in developing alternative fuel break management plans and evaluating their trade-offs to make better decisions. The stark difference (38 % reduction) in core habitat loss to wildfires between the no fuel break treatment and extensive treatment scenarios highlights the importance of investing on fuel break treatments in the northern Great Basin region. However, diminishing returns observed beyond a certain management threshold ($m$ at 60 %) suggest that there could exist an efficient management level, beyond which additional fuel break treatments will cause

**Table 3**
Tradeoffs among models based on the combined impacts from both wildfires and fuel breaks on core habitats. The combined impacts were calculated by summing the core habitat area loss to fuel breaks with the weighted core habitat area loss to wildfires (core habitat loss from wildfires across all 20,000 fire seasons × number of fire seasons as a temporal scale ÷ 20,000). On each row of this table, the highlighted number corresponds to the best model (smallest sum value) associated with a specific temporal scale (i.e., the same number of fire seasons or years).

| Number of | Management threshold *m* (as percent of 8910 ha) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **fire seasons** | 0 % | 10 % | 20 % | 30 % | 40 % | 50 % | 60 % | 70 % | 80 % | 90 % | 100 % |
| 1 | 2141 | 2639 | 3317 | 4095 | 4919 | 5792 | 6679 | 7561 | 8433 | 8761 | 8714 |
| 3 | 6424 | 6135 | 6387 | 6940 | 7630 | 8465 | 9348 | 10,230 | 11,102 | 11,430 | 11,384 |
| 5 | 10,706 | 9631 | 9457 | 9785 | 10,341 | 11,138 | 12,018 | 12,899 | 13,771 | 14,100 | 14,053 |
| 10 | 21,413 | 18,371 | 17,131 | 16,897 | 17,117 | 17,820 | 18,691 | 19,572 | 20,445 | 20,773 | 20,726 |
| 30 | 64,238 | 53,332 | 47,830 | 45,345 | 44,224 | 44,550 | 45,384 | 46,265 | 47,138 | 47,466 | 47,419 |
| 50 | 107,063 | 88,292 | 78,529 | 73,793 | 71,330 | 71,281 | 72,077 | 72,958 | 73,831 | 74,159 | 74,112 |
| 100 | 214,127 | 175,694 | 155,276 | 144,913 | 139,096 | 138,106 | 138,809 | 139,691 | 140,563 | 140,891 | 140,845 |
| 300 | 642,380 | 525,300 | 462,264 | 429,393 | 410,161 | 405,409 | 405,739 | 406,621 | 407,493 | 407,821 | 407,775 |
| 500 | 1,070,633 | 874,906 | 769,252 | 713,873 | 681,226 | 672,711 | 672,670 | 673,551 | 674,423 | 674,752 | 674,705 |

greater negative impacts on the landscape's core habitat with little or no benefits in wildfire risk reduction. This emphasizes the importance of careful planning to avoid excessive investment in fuel break management without commensurate gains.

Our tradeoff analysis suggests that the effectiveness of a fuel break treatment plan can vary greatly when considering different time frames, and thus planning decisions should be made with extra attention on the temporal aspect. Treating fewer fuel breaks appears more desirable when accounting for fire threats within a smaller number of future fire seasons, while a more extensive treatment plan (up to a threshold level *m* of 60 %) may be more preferred when considering a longer planning horizon with more fire seasons. This discovery is not surprising because managing a fixed set of fuel breaks will cause a constant direct loss to core habitats, but the core habitat loss to wildfires will increase when considering more future fire seasons. During a longer planning horizon, fuel breaks have to be periodically maintained to function as effective linear fire barriers. Maintaining fuel breaks through time as well as planning fire suppression resources to respond effectively were not addressed by our study but should be also considered when making wildfire management decisions, as the costs of on-going treatments and potential suppressions in a long term may put additional pressure on budgets (Crist et al., 2023).

In the scenario we modeled without treating any fuel breaks, 20 % of the largest simulated fires would be responsible for 74.6 % of the total core area losses if allowed to spread freely. This indicates that across our models, the greatest benefit of managing fuel breaks in the northern Great Basin comes from containing large fires to reduce their spread. The model's solutions typically chose to treat fuel breaks at a 200-ft width instead of 100, 300, or 400 in this region. Since we assumed fuel break treatment widths were positively correlated with fire flame lengths that could be controlled (i.e., 2, 4, 6, and 8 ft of flame lengths were controllable by treating fuel breaks at 100, 200, 300, and 400 ft respectively), it would imply that the strategic response recommended by our model is to prioritize a medium level of fuel break treatment, which would be sufficient to contain many fires in this region before they grow large and become too intense to control. This strategy reflects our risk-neutral model design, which considers all fire scenarios equally to minimize the expected fire loss. However, such a strategy may fail to contain some rare but extreme fire events that are associated with substantial habitat losses. This raises an important implication for the interpretation of model outputs, especially when fire mangers want to take a risk aversion approach to avoid high-consequence failures. In such cases, treating wider fuel breaks may better respond to the risk aversion prioritization, but the consequence is more losses of the core habitats due to increased treatments. While our model does not currently account for risk aversion, its objective function can be modified to address this need (i.e., minimizing the worst-case fire loss rather than the average or the total fire loss).

### *4.5. Limitations and potential improvements*

Our model was built to examine impacts on core habitats within a landscape, represented by direct losses of core habitat areas due to both fuel break treatment and wildfire damage. In practice, a more comprehensive assessment of impacts on habitats would involve considering both the direct and indirect effects of fuel break treatment and wildfires. For example, managing interconnected fuel breaks may lead to habitat fragmentation (Shinneman et al., 2019; Weise et al., 2023), but its negative consequence will show in the long term rather than immediately. While our model did not examine habitat fragmentation due to fuel breaks, it provided spatial fuel break treatment layouts that could serve as inputs for post treatment analysis. Modeling core habitats with more spatial and ecological details can be challenging (Chambers et al., 2023; Rachmawati et al., 2018; Wei and Hoganson, 2006), but would be a promising avenue for future research.

While our model currently focuses on minimizing wildfire impacts on core habitat areas as a primary objective, it can be readily adapted to address other management objectives. For instance, in landscapes prioritizing the protection of the wildland-urban interface (WUI), spatial data specific to the WUI, similar to the core area data, could be processed and used in our model to tailor management strategies accordingly. In landscapes where multiple objectives are of concern, such as protecting both WUI and ecological assets (Ager et al., 2010), our model could be modified to implement a goal programming based multi-objective function. One challenge of multi-objective goal programming models is determining reasonable weights (or parameters) for different objectives, as they can have large impacts on model outcomes (Nguyen et al., 2022).

Insights from our model are limited by the assumptions underlying our modeling approach. Here, we considered treating existing fuel breaks within a landscape simply by extending their widths. However, treating fuel breaks should also consider other factors such as topology, fuel break type, and time since last treatment at each existing fuel break's location. A more detailed assessment of fuel breaks' current conditions would allow for model solutions to even better respond to conditions on the ground, which is critical for real-world fuel break management and planning.

We assumed that fuel breaks management with specific widths can support effective suppression of fires at certain flame lengths when they approach those breaks. Assuming more effective fire control on fuel breaks when they are assisted by suppression efforts is consistent with empirical studies, which have suggested that relying upon fuel breaks alone may not always successfully halt fire progression without fire suppression support (McKinney et al., 2022; Syphard et al., 2011a, 2011b). However, the assumption of successful suppression may not hold if fires spread too quickly from their ignition points and cross the treated fuel breaks before any suppression personnel can arrive. Although FSIM provides a raster output of fire arrival time (in days) which can be used to estimate spread rates and potential response time windows, our model does not currently incorporate this information. Incorporating spread rate and fire crew response time could improve the realism in suppression modeling, but it is often challenging due to increased model complexity and data requirements, which may reduce model's scalability for large-landscape applications (Belval et al., 2016, 2019; Minas et al., 2013; Nguyen and Wei, 2022). We also recognize that suppression effectiveness does not solely depend on fuel breaks. In practice, fuel breaks serve as access points for firefighters, but their usability for firefighting operations may vary. Additional construction of fire lines near fuel breaks may be necessary to enhance suppression capacity. Additionally, small area-wide treatments adjacent to fuel breaks may offer safer and more ideal locations for direct attack. While our current model focuses on the strategic management of linear fuel breaks, future versions could also incorporate area-wide treatments and other tactical fire suppression details to better reflect operational realities.

Our study relies on wildfires simulated by FSIM, which integrates key landscape characteristics, such as fuels, topography, and stochastic weather to generate a large set of future fire events across 20,000 independently simulated fire seasons, calibrated to observed fire records from the past two decades. However, FSIM did not incorporate potential future changes in fuels and land use/land cover (LULC), such as urban expansion, vegetation shifts, or the spread of invasive species, which could alter landscape conditions and influence both fire behavior and the effectiveness of fuel break management strategies. Additionally, while FSIM can capture variability in daily weather and other fire conditions through a Monte Carlo process, temporal dependencies among fires across seasons and their effects on fuel break performance remain unexamined. These limitations highlight opportunities for future research to assess how the temporal dynamics of fire simulations and the spatial variability introduced by LULC changes may influence the robustness of fuel break strategies over time.

Our model could also be improved by accounting for additional uncertainties that arise from both management and natural disturbances, as they may influence model solutions. For example, fire containment predicted by the model may become ineffective under unexpected wind conditions that cause long-distance spotting fires (Alexander, 2000; Storey et al., 2020). Similarly, management uncertainties such as limited budgets, inconsistent implementation or delayed maintenance may reduce the effectiveness of a well-designed fuel break management plan. Integrating such stochastic elements in wildfire modeling is challenging due to data limitation and additional model complexity that may affect its computational efficiency and scalability (Crist, 2023; Ott et al., 2023; Thompson et al., 2022). Nevertheless, incorporating these uncertainties would improve the model's representation of real-world conditions to provide more resilient management plans.

## 5. Conclusions

Evaluating the effectiveness of linear fuel breaks for wildfire containment has been done by several optimization models that typically assessed only a limited set of containment opportunities and fire spread pathways. Our presented model can explore a broader range of fire spread and containment potentials influenced by fuel break treatment decisions, offering a risk neutral evaluation of their effectiveness to inform wildfire management strategies. Accounting for potential spread outcomes and alternative containment strategies for each fire adds complexity to our model. However, through intensive fire simulation, spatial data processing and an efficient MIP formulation design, the model was able to quickly solve large-scale problems to optimality. Application in the northern Great Basin demonstrates the model's ability to integrate multiple components, such as ecological impacts from both fuel break maintenance and wildfire damage, to address specific landscape management objectives. The model design is flexible enough to allow for adaptation to other fire-prone landscapes with diverse management objectives and constraints. Future applications will benefit from incorporating more detailed data and operational requirements to enhance the model's practical relevance and effectiveness in real-world planning.

## CRediT authorship contribution statement

**Dung Nguyen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yu Wei:** Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition, Conceptualization. **Erin J. Belval:** Writing – review & editing, Validation, Project administration, Funding acquisition, Data curation, Conceptualization. **Jesse D. Young:** Writing – review & editing, Validation, Conceptualization. **Christopher D. O'Connor:** Writing – review & editing, Validation, Conceptualization. **David E. Calkin:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

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.


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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2025.103357.

## Data availability

The Java source code of our MIP model formulation along with its inputs derived from FSIM simulations are publicly released at doi: 10.5281/zenodo.14271050

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