Optimal Prescribed Burn Configuration to Reduce Wildfire Propagation and Impact

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Abstract

Prescribed burns are a key wildfire management strategy, helping to reduce fuel loads and mitigate fire spread. The effectiveness of prescribed burns depends on their spatial configuration, which can vary widely in shape and size. This study aims to determine the optimal spatial arrangement of prescribed burns for minimizing wildfire impact. We investigate two main patterns for prescribed burns: discontinuous (fragmented) and continuous (connected), to evaluate how each affects wildfire spread. Through computational simulations on a 100×100 grid, we examine how different prescribed burn ratios influence how much vegetation is burned, using a probabilistic ignition system. Experimental results show that connected burn patterns consistently result in lower fire impact than fragmented configurations. Specifically, medium-to-high prescribed burn proportions (30-50%) provide optimal containment with predictable outcomes, whereas lower proportions (20%) lead to greater variability and inconsistent fire suppression. These findings indicate that wildfire management strategies should prioritize connected prescribed burn configurations at 30-50% proportions for effective fire mitigation in fire-prone regions like California.

1 Introduction

Every year, California faces some of the most destructive wildfires, causing severe damage to wildlife, homes, and urban areas. These wildfires pose significant threats to wildlife, leading to the death of animals and destruction of their habitats. Additionally, wildfires emit harmful gases and particulates, including toxic chemicals released from burning man-made materials such as plastics found in homes and vehicles, significantly reducing air quality and causing respiratory health issues.

To mitigate these extreme fires, Cal Fire strategically reduces the fuel of fires through prescribed burns. According to the California Air Resources Board (CARB), approximately 125,000 acres of wild lands in California are treated annually with prescribed burns. The use of prescribed burns is expected to increase, as they effectively reduce existing fuel loads and make the remaining vegetation less flammable. As a result, the likelihood of a wildfire igniting in an area that has undergone a prescribed burn is significantly lower.

Understanding how prescribed burns influence fire propagation requires accurate predictions based on the effects of different burn configurations. These predictions help anticipate wildfire behavior, guide response efforts, and improve strategies for fire management.

In this paper, we explore how the configuration of prescribed burns within a confined area influences wildfire spread and impact. To investigate this, we employ a simulation-based approach to model fire propagation under different terrain conditions. In Section 2, we demonstrate the process of how different terrains on which we plan to experiment with fire propagation are created. Section 3 presents the algorithm that spreads the fire across our terrain. In Section 4, we detail our experimental setup, report the results, and analyze the data to identify the most effective terrain configuration. Finally, Section 5 summarizes our findings, discusses the limitations of our study, and offers recommendations for the effective use of prescribed burns to prevent extreme wildfires.

2 Terrain Generation

To model different terrain conditions, we generate random landscapes with a specified fraction of prescribed burns and live vegetation. The prescribed burns are arranged in two distinct configurations: scattered patches and contiguous regions. To model the propagation of fire, we use a cellular automaton where fire propagates probabilistically in discrete timesteps from one area to neighboring areas. The probability of propagation is assumed to be much lower in burn areas than in areas with live vegetation. This allows us to assess how different prescribed burn configurations influence fire behavior and determine the most effective terrain layout for minimizing wildfire risk through prescribed burning.

2.1 The Terrain Matrix

These simulations use a grid-based framework to realistically simulate different proportions of live vegetation and prescribed burns. The terrain is represented by a 100×100 matrix, where each cell encodes information about vegetation distribution and prescribed burns. In our terrain matrix, each cell is represented by a Boolean value where True indicates a prescribed burn area and False indicates a live vegetation area.

To generate the initial terrain, we use random value generation, matrix filtering, and a probabilistic approach. First, each cell (i, j) independently draws a random variable $r_{i,j}$ from a uniform distribution between $[0, 1]$, i.e., $r_{i,j} \sim U(0, 1)$. Before assigning these values to a Boolean data type, we apply a Gaussian filter to smooth out the randomness and avoid producing white noise. Without this filtering step, simply using the uniform random values leads to an unrealistic representation of what prescribed burns would look like.

To create larger, yet still random burn areas, a Gaussian filter is applied to the terrain matrix. The `gaussian_filter` function in SciPy performs Gaussian smoothing to create patches of prescribed burns on a typical user-defined length scale sigma.

The Gaussian filter smooths the initial random matrix by convolving it with a Gaussian kernel. The weights of the Gaussian kernel matrix are derived from the function:

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \tag{1.2}$$

where the coordinates (x, y) are relative to the center of the kernel.

In this expression, the scalar σ, representing the standard deviation, influences the size of the kernel. This directly affects how much smoothing occurs over the random matrix. A larger σ creates a larger kernel, leading to more smoothing and contiguous terrain configurations. In contrast, a smaller σ preserves the granularity of the initial random matrix. Therefore, manipulating σ directly controls the size of the clustering and configuration of the prescribed burn areas.

After smoothing the initially random matrix, we apply a normalization step that enables us to adjust the proportion of prescribed burns. This process scales the smoothed values so that they fall proportionally within the $[0, 1]$ range.

Now, our smoothed random matrix is ready for Boolean classification using a probabilistic system. Each cell $V_{i,j}$ in the terrain matrix is assigned a Boolean value of either True or False, and is defined as:

$$V_{i,j} = \begin{cases} \text{True}, & \text{if } r_{i,j} < \text{prop}, \\ \text{False}, & \text{otherwise}, \end{cases} \tag{1}$$

where prop is a predefined threshold value for the proportion of prescribed burn area. We can control the proportion of prescribed burns in the terrain by manipulating the prop parameter. After all the cells have been transformed into Boolean data, a green color is assigned to represent vegetation and a black color is assigned to represent prescribed burns. Figure 1 demonstrates the complete terrain matrix for varying values of σ, based on a balanced proportion of vegetation and prescribed burns.

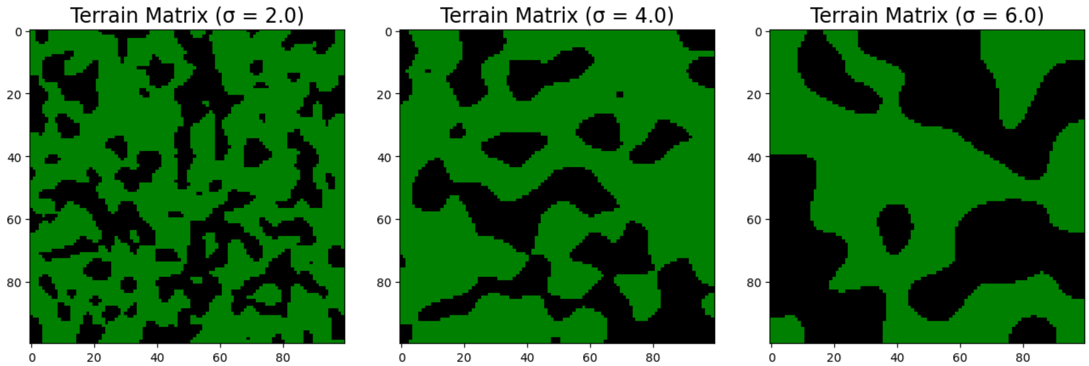
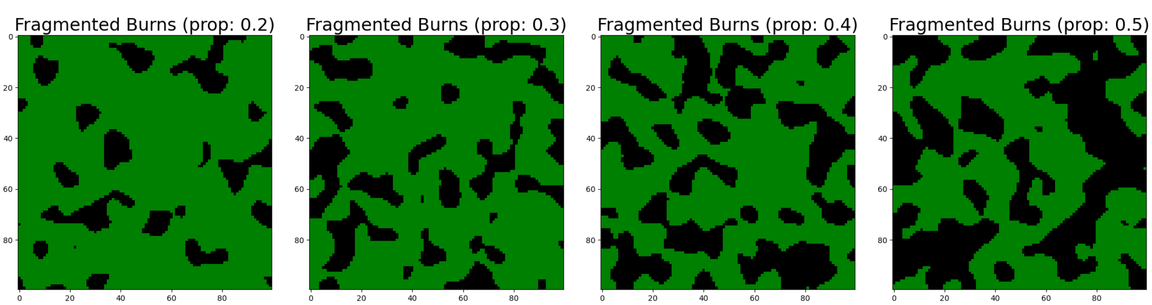


Figure 1: Comparison of three terrain matrices with varying σ values of 2.0, 4.0, and 6.0 for a constant prescribed burn proportion of 50%. As σ increases, the formation of the prescribed burns increases in size and decreases in frequency. In all matrices, green cells represent areas of vegetation (False), while black cells represent prescribed burns (True).

Holding the proportion of prescribed burns fixed at 50%, Figure 1 shows three terrain matrices that illustrate the effect of varying σ on the size and frequency of the clustering and configuration of the prescribed burn areas. We observe that at $\sigma = 2.0$, the prescribed burns are small and numerous across the terrain matrix. At $\sigma = 4.0$, the burns increase in size, resulting in fewer clusters. When $\sigma = 6.0$, the burns become even larger and appear as only a few dominant clusters.

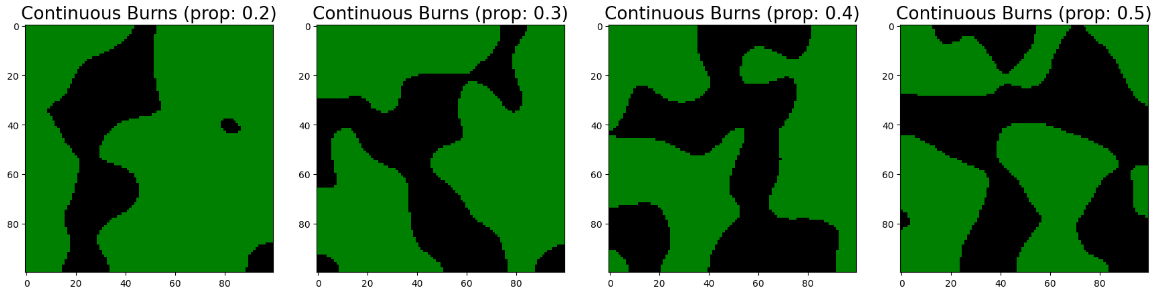
2.2 Prescribed Burn Configuration

In our experiment, we manipulate the proportion of vegetation and prescribed burns, as well as the configurations of the prescribed burn shapes. We aim to examine how two different configurations of prescribed burns impact the effectiveness of fire containment. We choose to experiment with fragmented and connected prescribed burns. Fragmented burns form small, scattered clusters, whereas connected burns create large, river-like, continuous patterns. For both fragmented and connected burns, we select four different proportions—0.2, 0.3, 0.4, 0.5—to determine how much prescribed burning is needed to effectively contain the fire. In Figures 2 and 3, we present eight different terrain matrices used for fire propagation experiments.



(a) (b) (c) (d)

Figure 2: This figure presents four different terrains with fragmented prescribed burns designed for fire propagation experiments. The Gaussian filter's standard deviation is fixed at $\sigma = 3$, while the proportion of prescribed burns varies at 0.2, 0.3, 0.4, and 0.5. As the proportion increases, the burn patterns spread more widely, covering a larger portion of the vegetation terrain in a discontinuous and irregular manner.



(a) (b) (c) (d)

Figure 3: This figure presents four different terrains with connected prescribed burns designed for fire propagation experiments. The Gaussian filter's standard deviation is fixed at $\sigma = 8$, while the proportion of prescribed burns varies at 0.2, 0.3, 0.4, and 0.5. As the proportion increases, the burn patterns progressively cover a larger portion of the vegetation terrain, representing a fire break that extends from one border to the next.

2.3 Validation of Terrain Proportions

To ensure the simulation is accurate, we validate that the actual proportion of prescribed burns in the terrain matrix matches the desired proportion. Each terrain matrix is validated by counting the number of 'True' values and dividing by the total number of cells (10,000) for both fragmented and connected terrain configurations. In the following figure, we show the validation of terrain matrices with a prescribed burn proportion of 0.5.

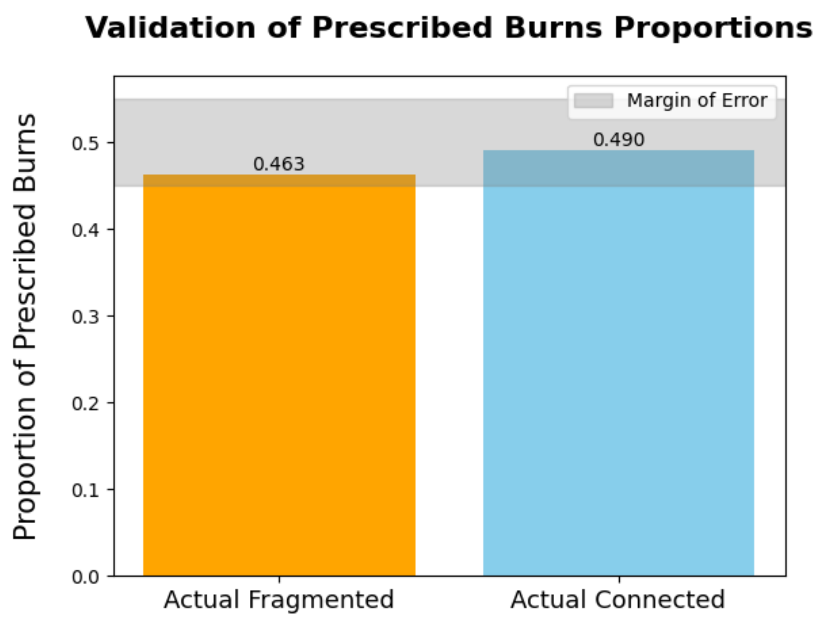


Figure 4: This figure compares the expected proportion of prescribed burns with the actual proportions observed in fragmented and connected terrains. The yellow and blue bars show the actual proportions for fragmented (0.463) and connected (0.490) terrains, respectively. The shaded gray region represents a margin of error of 0.05. Since both actual proportions fall within this margin, the prescribed burn proportions for fragmented and connected terrains are considered valid for further experiments on fire propagation.

3 Fire Propagation

To simulate how fire spreads across different terrains, we developed a fire propagation algorithm. In this method, we assume a 25% chance for fire to spread from a burning cell to an adjacent vegetation cell, while the chance of fire spreading to a burned area is only 0.5%. Prescribed burns, which are treated areas with limited fuel, have an even smaller chance of catching fire, as they lack the necessary resources to sustain burning. The 25% probability for vegetation to catch fire is somewhat arbitrary, but we chose this value to avoid an unrealistically rapid spread that would cause the fire to expand in an unnatural square-like pattern. This square-like pattern typically occurs in uniformly vegetated grids where fire spreads to neighboring cells. This approach helps maintain a more realistic simulation of fire behavior.

3.1 The Fire Matrix

To simulate fire propagation on the computed terrain matrices, we create a fire matrix that uses a propagation algorithm to model the fire spread. We initialize a 100×100 matrix, the same size as the terrain matrix. The matrix stores the fire state of the terrain in binary values. The fire matrix contains cells defined as:

$$\mathrm{F}_{i,j} = \begin{cases} 1, & \text{if the cell } (i,j) \text{ is on fire,} \\ 0, & \text{if the cell } (i,j) \text{ is not on fire.} \end{cases} \tag{1.3}$$

We assume the fire initializes randomly within the vegetation area of the terrain matrix. The vegetation acts as fuel for fire spread. In contrast, prescribed burns are designed to slow or stop fire spread. Starting the fire in a prescribed burn area would be ineffective because in practice it is unlikely that a fire would ignite in an area that has already been burned.

3.2 Fire Propagation

The fire propagation process works as follows. At each timestep of the simulation, the algorithm locates an ignited cell and examines its neighboring cells, checking whether they contain vegetation or are part of a prescribed burn, as defined by the terrain matrix. For each neighboring cell that is not already on fire, a random value r is generated from a uniform distribution. This value is then evaluated using a logical condition: if the cell contains vegetation and the random value is less than 0.25, the fire spreads to that cell. The same logic applies to prescribed burn cells but with a much lower probability of catching fire—only 0.005. If the random value is greater than or equal to the respective threshold (0.25 for vegetation or 0.005 for prescribed burns), the fire does not ignite the cell, and the algorithm proceeds to evaluate the next neighboring cell. This process ensures a controlled and realistic simulation of fire spread across different terrain types.

Then we measure fire impact as the quantity of ignited cells after 100 iterations of the fire propagation. A higher iteration count ensures a longer simulation. This captures the fire's progression more accurately.

3.3 Validation of Fire Spread Probability

To verify that our fire propagation algorithm behaves as expected, we use a 6×6 matrix where each cell is classified as either a prescribed burn (`True`) or vegetation (`False`). We initialize four fires in the center of this matrix on vegetation and simulate a single timestep of fire spread over 1000 realizations. After accumulating the fire spread matrices from 1000 realizations, we average them to obtain the propagation probability for each cell. We observe the average fire propagation relative to the terrain classification in Figure 5.

```
      Boolean Terrain Matrix
[False False  True  True False False]
[False False False False  True  True]
[ True  True False False False False]
[False False False False  True  True]
[ True  True False  True  True  True]
[False False  True False  True  True]

   Average Fire Propagation Matrix
[0.000 0.000 0.000 0.000 0.000 0.000]
[0.000 0.260 0.425 0.424 0.002 0.000]
[0.000 0.012 1.000 1.000 0.453 0.000]
[0.000 0.448 1.000 1.000 0.012 0.000]
[0.000 0.004 0.463 0.010 0.005 0.000]
[0.000 0.000 0.000 0.000 0.000 0.000]
```

Figure 5: Average fire propagation probabilities with four initial center fires are shown alongside the corresponding Boolean terrain classification. The decimal values indicate the average propagation probability computed over 1000 realizations. The Boolean Terrain Matrix verifies that the fire spread probabilities match the expected terrain type.

The corner cells adjacent to the center fires are evaluated with expected values of approximately 0.25 for vegetation areas and 0.005 for prescribed burn areas. Additionally, we notice that cells directly adjacent to the center fire have an average propagation probability close to 0.4375 and 0.0099. These values align with the expected behaviors for vegetated cells and prescribed burn cells exposed to two center fire neighbors, as verified by the equation:

$$1 - (1 - p)^2,$$

where p is the probability of fire spreading to a `True` or `False` cell. We should anticipate slight deviations from these probabilities due to the law of large numbers; however, the margin of error should be small.

Because the values in the validation matrix align with our expected probabilities for a single timestep, we can confirm that our fire propagation algorithm is functioning as intended. This validation supports the reliability of our experiments and ensures that we can derive meaningful and conclusive results from our simulations.

4 Results

To complete our simulation, we apply the fire propagation algorithm to eight terrain matrices with prescribed burn proportions of 0.2, 0.3, 0.4, and 0.5, using sigma values of 3 and 8, respectively. To visualize the results, we create animations where we randomly initiate fires in vegetation cells and simulate fire spread with probabilistic conditions covered in Section 3. At each animation frame, we overlay the fire matrix on the terrain matrix to visualize the behavior of the fire spread. Figure 6 presents these snapshots of the final state after 100 timesteps of fire propagation for each of our eight terrain matrices, capturing the end result of the fire propagation process.

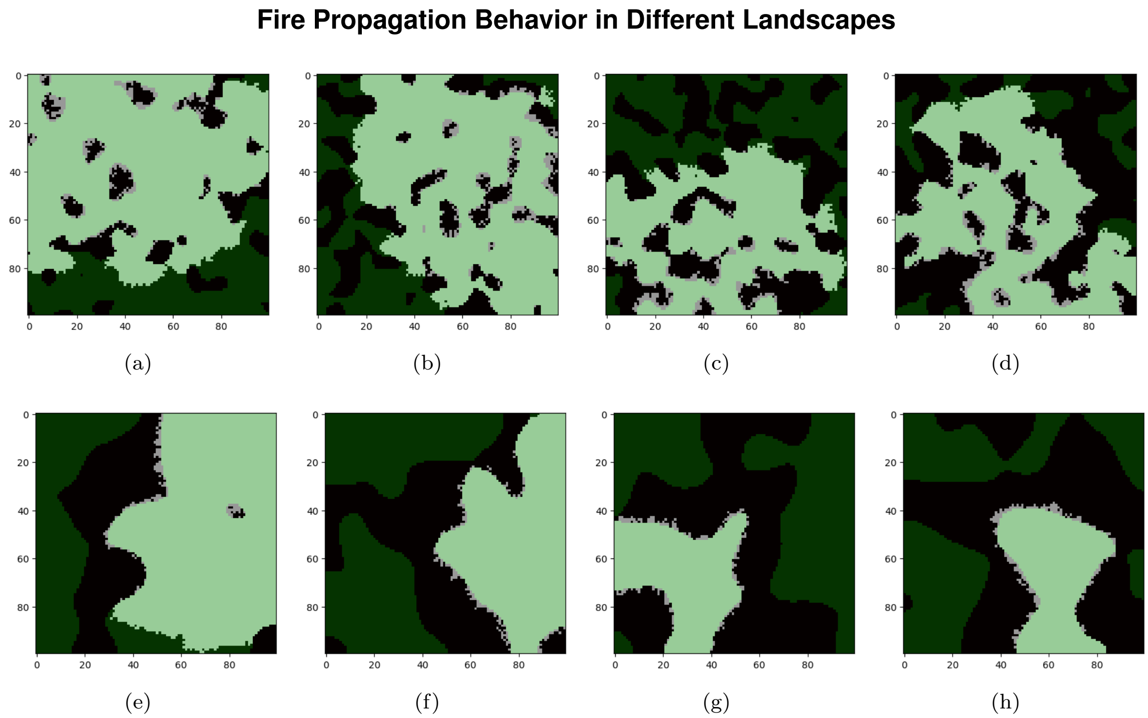


Figure 6: Final snapshots of fire propagation on eight different terrains from Figures 2 and 3 with varying proportions and configurations of prescribed burns. Snapshots (a) through (d) represent the final state of fire propagation on fragmented prescribed burns. Snapshots (e) through (h) represent the final state of fire propagation on connected prescribed burns. The light green areas represent vegetation ignited by fire, while dark green and black represent unburned vegetation and prescribed burns.

From the final timestep snapshots, we provide a visual comparison of fire propagation paths across our test terrains. Each simulation begins with a single ignition point randomly placed in vegetated areas and evolves over 100 timesteps. The results demonstrate a clear difference in fire behavior between configuration types. In terrains with fragmented prescribed burns, fires spread between the isolated burn patches, covering the majority of the vegetation area. We notice that this seems to be more common in configurations with lower proportions of prescribed burns. In contrast, terrains with connected prescribed burns isolate the vegetation areas, trapping fires within the area where they were created. The continuous characteristic of the prescribed burns creates a firebreak and prevents it from spreading to other isolated vegetation areas. While some edges of the prescribed burns catch fire due to a small but non-zero fire spread probability, the connected configurations consistently demonstrate more efficient containment of the fire. These visual results provide a qualitative conclusion that connected prescribed burns effectively minimize wildfire spread and impact better than fragmented patterns.

After conducting 200 experiments of fire propagation for each terrain type, we calculated the average and standard deviation of the total number of cells burned at the final timestep for each terrain matrix. This analysis helps determine which prescribed burn pattern—fragmented or connected—is more effective at suppressing fire. The results for each tested proportion are presented in Figure 7:

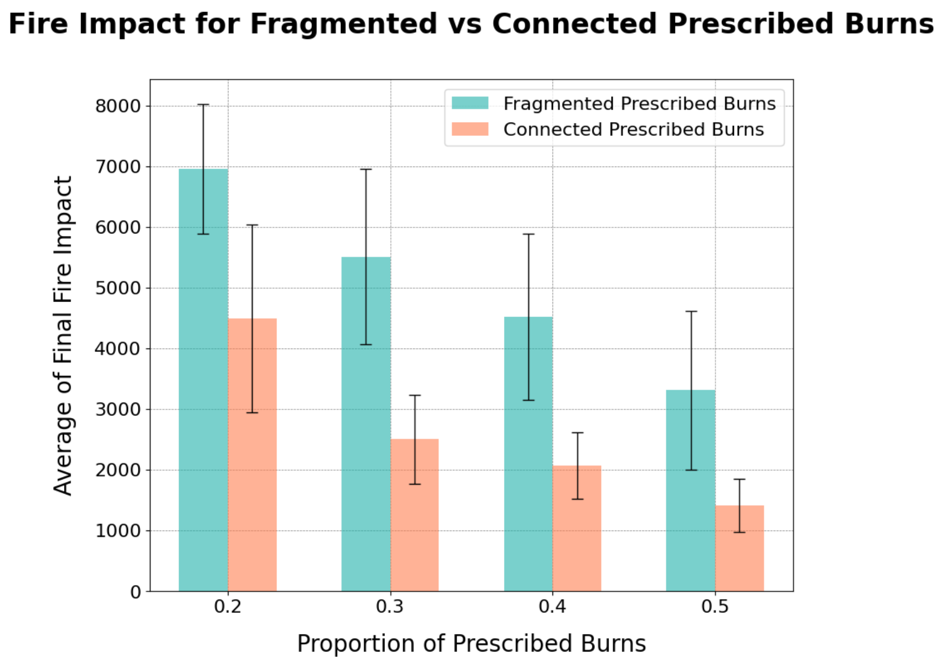


Figure 7: In this figure, we compare the mean final fire impact across 200 experiments for eight terrain matrices with varying proportions of prescribed burns. The x-axis shows the tested prescribed burn proportions of 20%, 30%, 40%, and 50%, while the y-axis represents the mean final fire impact, measured in the number of burned cells. The light blue bars illustrate the mean fire impact for fragmented prescribed burns, whereas the light pink bars show the impact for connected prescribed burns. The error bars on top indicate the standard deviation of the fire impact.

The figure shows the average and standard deviation of the final fire impact for each terrain pair with fragmented and connected prescribed burns with varying proportions. Across all prescribed burn proportions (0.2, 0.3, 0.4, and 0.5), connected prescribed burns consistently result in a lower final average fire impact compared to fragmented prescribed burns. The variability in standard deviations for proportions 0.3, 0.4, and 0.5 further supports this trend, indicating that connected burn patterns provide more consistent fire containment.

For a burn proportion of 0.2, the results are less conclusive due to higher variability. This variability arises from the terrain configuration, where fires can spread in two distinct scenarios: one with a smaller, quickly contained burn area and another with a larger, prolonged burn. This dual behavior increases uncertainty, making it difficult to definitively conclude the superiority of connected prescribed burns at this proportion, despite their lower mean fire impact.

Overall, the data highlights a clear pattern: larger connected fire breaks lead to a significant reduction in fire spread, while fragmented burns result in greater fire spread. This reinforces the importance of connectivity in prescribed burn strategies for wildfire mitigation.

5 Discussion and Conclusion

In this paper we examined how prescribed burns affect fire spread by comparing fragmented versus connected burn configurations using computational simulations. This study explores how varying proportions of prescribed burns on vegetation influence the final fire impact. The data in our results show that connected prescribed burns consistently lead to lower mean fire impact across all tested proportions, except very low proportions. We can use these findings to promote the use of connected prescribed burn configurations for effective wildfire risk management.

There are several caveats to bear in mind, however. While our simulation captures the qualitative aspects of terrain with prescribed burns, it does not account for their impact on fuel load. In our model, fire propagates through prescribed burn areas without losing fuel, burning for the entirety of the simulation. This oversimplification fails to reflect real-world fire behavior, where the fire only burns for as long as there is fuel. If we incorporated fuel load effects, we could assume that prescribed burns would further reduce fire impact by decreasing the time over which the area can burn, saving vegetation from catching on fire.

Wind is another crucial element missing in our model. The common occurrence of strong winds in California accelerates fire spread, allowing embers to travel across the terrain and skip prescribed burns. As a result, prescribed burns can lose their effectiveness. Because of wind's strong affect on fire spread, we can expect that overall fire impact will remain uncertain and difficult to measure accurately.

Given our findings that connected prescribed burns are more effective in mitigating fire propagation, wildfire management should be advised to treat wildlands with burns in connected patterns. Taking this approach brings us one step closer to preserving California's lush landscapes, diverse wildlife, and densely populated residential areas.