Optimizing Prescribed Burn Risk Management: A Computational and Economic Modeling Approach Using QUIC FIRE Simulations

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Abstract. This paper introduces a computational framework for optimizing vegetation removal, modelled via so-called blackline or fireline widths, to enhance efficiency and cost-effectiveness of a prescribed burn for planned reduction of vegetation density. The QUIC FIRE simulation tool is employed to conduct simulations across fireline widths ranging from 8 to 24 m in 2-m increments within a strategically chosen burn unit that covers the usecase of a wildland urban interface located around the region of Auburn, CA. Through visual analysis and quantitative cost function assessment, incorporating polynomial fit and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm within a basin-hopping framework, an optimal fireline width is computed that minimizes costs, efforts and the risk of fire escapes. Findings indicate that strategic adjustments in fireline widths significantly influence the success of prescribed burns, underscoring the value of advanced simulation and optimization techniques. This work provides a foundational framework for subsequent studies, advocating for the development of dynamic, adaptive models that are scalable across varied ecological and geographical settings. Contributions extend to a computational and economic perspective on sustainable risk mitigation, underlining the pivotal influence of technology and advanced modeling in the evolution of prescribed burn strategies.

Keywords: Prescribed burns · wildfire management · computational optimization · QUIC FIRE simulation · blackline width

1 Introduction

In recent years, the United States has faced an alarming increase in wildfire incidents, marked by their growing intensity and frequency [5]. This increasing trend requires the urgent need for innovative fire management strategies to mitigate wildfire risks effectively. Among these strategies, prescribed burning has emerged as one of the prominent techniques [8]. By intentionally applying controlled fires, this planned treatment of vegetated land aims to manage vegetation

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and reduce the accumulation of fuel, thereby protecting assets and lives from the devastating impact of uncontrolled wildfires [16].

The work in this paper utilizes QUIC FIRE, a simulation tool that is designed for modeling the spread and behavior of prescribed fire scenarios [13]. QUIC FIRE possesses the capability to accurately predict the behavior of fires across a spectrum of weather and terrain conditions. Understanding QUIC FIRE simulations requires knowledge of concepts such as the Burn Unit [11] and the Acceptable Fire Boundary. During Prescribed Burns, even in the most favorable weather conditions, there exists a possibility of fire breaching its Acceptable Fire Boundary [22]. This makes fuel management, particularly fuel removal, a key strategy to avoid fire escape [3]. A fundamental practice in fuel management during prescribed burns is the creation of a back line or fire line – a cleared strip of land intended to act as a barrier to stop the fire from spreading [7,24].

Various fuel removal strategies include ground-based mechanical whole tree, manual whole-tree, manual log, cut-to-length, and cable-operated systems. Following the comparative 2007-dollar analysis in [4], ground-based mechanical whole tree removal is the most cost-effective, averaging \$0.1532 per m^2, while manual whole tree removal costs around \$0.2526 per m^2. Cable systems, designed for challenging steep terrains, represent the higher end of the cost spectrum, with expenses starting at \$0.6955 per m^2 for whole tree removal. Even with these capabilities, the risk of fire escape and consequent damage persists [23]. Also, excessive fuel removal, i.e. creating wide firelines to prevent the escape of fire can limit the use of prescribed burns [9,10,12]. This leads to a critical question: What is the most cost-effective fireline width that balances the costs of fuel removal and the potential damages from fires breaching prescribed boundaries?

This research explores the use of prescribed burns also called Interface burns [3,6] when practiced near residential areas to reduce wildfire risks, emphasizing the crucial role of fire lines, termed "black lines" in QUIC FIRE simulations. This paper provides a comprehensive cost analysis of fuel removal by analyzing various fuel removal methods and their associated costs and the characterization of costs associated with fire escape driven by fire simulation using QUIC-FIRE. It then formulates an optimization problem to define the optimal width of fuel removal, thereby guiding the creation of economically viable firelines.

By laying the groundwork for optimal trade-off concepts, this research establishes a foundational framework for advancing multi-dimensional control strategies in fireline creation and fuel management. This research enhances wildfire management discourse, providing insights and strategies to protect communities and ecosystems from wildfires.

2 QUIC-FIRE and Urban Interface Use Case

QUIC-Fire [11] is a simulation tool designed for the planning of prescribed burns. It offers a solution to understand and predict the complex interactions of fire with the atmosphere without the need for high-performance computing resources. This model integrates the 3-D rapid wind solver QUIC-URB [15,18] with a physics-based cellular automata fire spread model called FIRE-CA [1,2]. QUIC-Fire employs a probabilistic approach to simulate fire spread, where energy packets are dispersed based on local environmental conditions, yielding variable fire behavior across simulation iterations. This tool aids in prescribed fire management by enabling planners to design burn plans with complex ignition patterns and assess fire-atmosphere interactions.

To demonstrate the cost-benefit analysis of creating a fireline and taken into account the costs related to fire escape, this paper applies QUIC-Fire to a region around Auburn, CA. A visualization of this use case is summarized Fig. 1 and was chosen following an examination of Wildland Urban Interface (WUI) [17] zones where urban developments meet or intermingle with wildland vegetation. This analysis stands as the inaugural application of the proposed framework, constituting a novel initiative within the field. Therefore, it delves into uncharted areas, devoid of the comparative frameworks often available through established benchmarks or historical studies.

Fig. 1. Image describing real world zoning of use case scenario near Auburn, CA

The selected area is characterized by a sloped terrain interspersed with residential zones within the buffer area. These topographical and residential features underscore the necessity for rigorous fire containment strategies, making it a good case for investigation. To fully comprehend the analysis and the model itself, it is crucial to highlight and summarize the Quic-Fire simulation parameters used to describe the use case in Fig. 1:

– Wind Speed: Established at 32.18 kph to accurately simulate conditions that can affect the spread of fire.
– Wind Direction: Considered to be moving from left to right in Figure 1 or West to East i.e. 270°, with 15° perturbations.

– Topography and Vegetation: Incorporation of the terrain's features and existing vegetation information for prediction of fire dynamics.
– Ignition Pattern: The simulation adopts a head fire ignition pattern, chosen for its representation of how fire fronts typically advance with the wind. This approach is specifically relevant to the wind conditions and topographical layout of the study area as illustrated in Fig. 1.

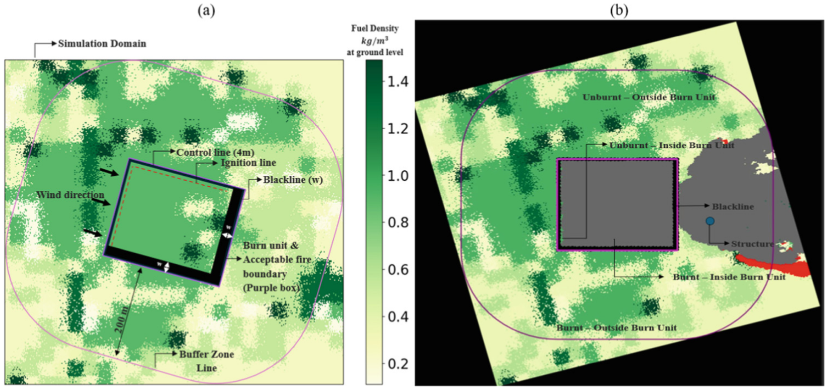

Fig. 2. (a) Image describing QUIC FIRE simulation domain, burn unit, acceptable fire boundary, buffer line, black line, and control line (b) Visual representation of the simulation domain depicting the blackline, the burnt and unburnt areas within and outside the burn unit, and the location of structures.

To further complete the terminology associated to QUIC-Fire simulations, terms such as Simulation Domain, Burn Unit, Buffer Zone, Acceptable Fire Boundary, Black Line, and Width are defined followed by a visual representation provided in Fig. 2(a). In particular, the following definitions are used:

– Simulation Domain: This term refers to the spatial extent under consideration for the simulation, capturing the prescribed burn area and its surroundings. It encompasses the entire landscape within which the fire dynamics are modeled.
– Burn Unit: This area denotes the specific parcel of land designated for the implementation of the prescribed burn within the simulation domain.
– Buffer Zone: A strategically established margin encircling the burn unit, designed to mitigate the risk of fire escape beyond the intended boundaries.
– Acceptable Fire Boundary: This indicates the maximum permissible boundary for fire spread, established to ensure the containment of the burn within predefined limits.
– Control Line and Black Line Width: This line serves as a narrow boundary along the wind inflow direction, established through the removal of fuel. In this specific scenario, its width is set to be 4 m. Additionally, the 'Black Line' is implemented as a preventive measure, placed strategically in alignment

with the wind direction and characterized by an absence (active removal) of fuel/vegetation. The 'Width' of the Black Line is subject to variation, serving as the key variable for prediction within this use case.

3 Cost Function Analysis

Spatial concepts of burned and none-burned areas within the simulation domain, and construction of the blackline, are graphically represented in Fig. 2(b). This visualization distinctly identifies regions inside and outside the burn unit, demarcates the blackline, and pinpoints structures, thereby offering clarity on the areas considered when calculating the associated costs of fuel removal. This section introduces a framework for systematically estimating blackline construction costs and penalties incurred when fires breach acceptable boundaries.

3.1 Fuel Removal Cost

The cost of fuel removal is comprehensively evaluated across the designated burn unit. This burn unit is depicted as a grid G with dimensions $x \times y$, which effectively represent the total area of the burn unit. For the purpose of this model, the following parameters are established:

- Base cost of fuel removal, $f(a, b)$, based on the slope at cell (a, b):

$$f(a,b) = \begin{cases} 0.3, & \text{if slope at } (a,b) < 40\% \\ 1.02, & \text{if slope at } (a,b) \geq 40\% \end{cases} \tag{1}$$

Ground-based mechanical and manual whole tree removal costs averaged \$0.1532 and \$0.2526 per m^2, respectively. For slopes above 40%, cable systems incurred costs starting at \$0.6955 per m^2 [4]. After adjusting for inflation from 2007–2023 [21], fuel removal costs for creating a fuel-free blackline zone are calculated. For slopes less than 40%, costs are averaged to \$0.3 per m^2. For steeper slopes over 40%, costs rise to \$1.02 per m^2.

- Fuel density factor at cell (a, b):

$$\text{factor}(a,b) = 1 + \frac{\text{fuel density at } (a,b) - \text{average fuel density}}{\text{average fuel density}} \tag{2}$$

The core of the model calculates the costs of constructing blacklines to a specified width, W, integrating both terrain-adjusted costs and fuel density factors. Formulas for blackline construction costs, such as $C^{(1)}_{\text{blackline}}(w)$, are aligned with prevailing wind directions. This method accounts for wind's impact on fire spread, facilitating strategic blackline placement and dimensioning for enhanced efficacy.

– Option 1 (North/South):

$$C^{(1)}_{\text{blackline}}(W) = \sum_{w=1}^{W} \left(\sum_{i=1}^{x} \mathbf{1}_{\{i+w \leq x\}} \cdot f(i+w, w) \cdot \text{factor}(i+w, w) + \sum_{j=1}^{y} \mathbf{1}_{\{j+w<y, j+w \neq w\}} \cdot f(w, j+w) \cdot \text{factor}(w, j+w) \right) \quad (3)$$

where $\mathbf{1}_{\{\cdot\}}$ is the indicator function, equaling 1 if the condition is true, and 0 otherwise.

– Options 2 to 4 are defined for East/West, South/North, West/East directions.

Control lines further enhance fire containment. The costs for these control lines, C_{control}, are established for a fixed width of $W_c = 4$, with adjustments based on their orthogonal orientation to the blackline. This method establishes a buffer zone along directions not influenced by wind.

$$C_{\text{control}} = (\text{Appropriate formula based on fixed width and orthogonal orientation to blackline}) \quad (4)$$

The culmination of this model is the integration of the costs associated with both the creation of a blackline and control line constructions costs. The final cost, $C_{\text{fuelremoval}}(W)$, is found by combining blackline and control line costs up to width W and given by

$$C_{\text{fuelremoval}}(W) = C_{\text{control}} + C^{(o)}_{\text{blackline}}(W) \quad (5)$$

where o is the choice of option based on wind direction.

Following the formulation of the final cost $C_{\text{fuelremoval}}(W)$, Fig. 3 provides a visual representation of the fuel removal cost dynamics. This figure demonstrates an approximate logarithmic growth pattern between cumulative costs and width.

3.2 Penalty Costs for Fire Escape

Penalty costs are associated with both fire escape, bus also for vegetation not burned within the burn unit. For evaluation of penalty costs, the simulation domain S is defined within the bounds $(k_{\max}, l_{\max})$ of the pixels of the image. Each pixel within this domain is denoted by the coordinates (k, l), where k ranges from 1 to $k_{\max}$ and l from 1 to $l_{\max}$. The burn unit is represented by a grid G which is a subset of S, with G embedded within the simulation domain S.

To compute the penalty costs, several functions are introduced. The function $U(k, l)$ is defined to determine the membership of a pixel within the grid G:

$$U(k, l) = \begin{cases} 1 & \text{if } (k, l) \in G \\ 0 & \text{if } (k, l) \notin G \end{cases} \quad (6)$$

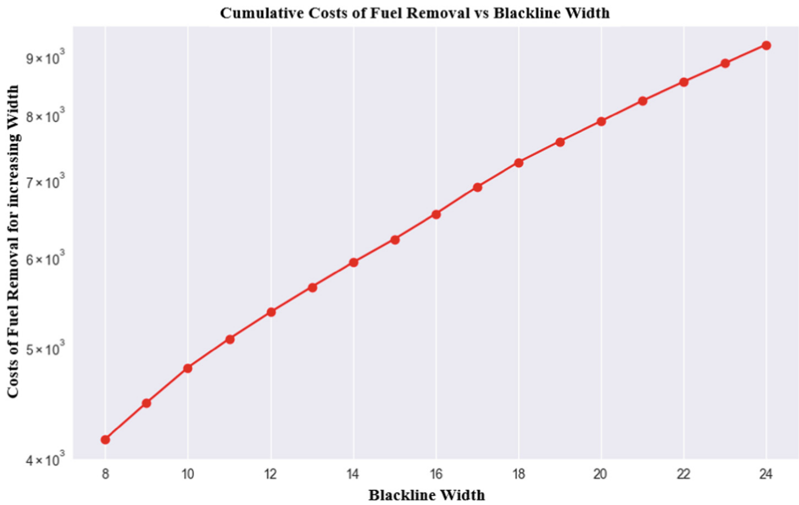

Fig. 3. Comparative analysis of fuel removal costs for blackline and control line constructions up to width W, y-axis is on log scale.

Furthermore, a fuel density evaluation function $B(k, l)$ is defined to ascertain whether a pixel is burnt or unburnt:

$$B(k,l) = \begin{cases} 1 & \text{if fuel density at } (k,l) = 0 \\ 0 & \text{if fuel density at } (k,l) \geq 0 \end{cases} \tag{7}$$

This function is applied over the entire simulation domain S. Additionally, the distance function $R(k, l)$ calculates the Euclidean distance from the center of grid G to each pixel in S:

$$R(k,l) = \sqrt{(x_c - k)^2 + (y_c - l)^2} \tag{8}$$

where (x_c, y_c) represent the coordinates of the center of G.

The penalty for land loss due to fire escape, denoted as $C_{\text{landloss}}(w)$, is calculated across the simulation domain S, encapsulated within the bounds $(k_{\max}, l_{\max})$, and is expressed as:

$$C_{\text{landloss}}(w) = \sum_{k=1}^{k_{\max}} \sum_{l=1}^{l_{\max}} f_w(k,l) \tag{9}$$

The function $f_w(k, l)$ is defined based on the conditions of pixel membership within grid G and the fuel density status of each pixel:

$$f_w(k,l) = \begin{cases} 0 & \text{if } U(k,l) = 1 \text{ and } B(k,l) = 1 \\ C & \text{if } U(k,l) = 1 \text{ and } B(k,l) = 0 \\ \alpha R(k,l) & \text{if } U(k,l) = 0 \text{ and } B(k,l) = 1 \\ 0 & \text{if } U(k,l) = 0 \text{ and } B(k,l) = 0 \end{cases} \tag{10}$$

In this context, α, representing the land value constant at \$1.09 per cell, adjusts the penalty for burnt pixels beyond the designated boundary based on distance. This constant is derived from averaging the 2022 values of United States farm real estate (\$0.9460 per m^2) and cropland (\$1.2572 per m^2) [20]. While this analysis utilizes average prices for concept demonstration, the framework allows for the adjustment of these prices to reflect specific regional values for more localized analyses.

To address the loss of important structures, the model incorporates a secondary penalty function. Each critical structure within the domain is indexed by t and located at pixel (k_t, l_t). The vicinity of each structure incurs an enhanced penalty, modeled by the function $d_t(k, l)$, which is a decreasing exponential function of the distance from the pixel to the structure:

$$d_t(k, l) = e^{-(\beta\sqrt{(k_t-k)^2+(l_t-l)^2})} \tag{11}$$

The decay constant β governs the influence range of the structural penalty in this case 30 m [19], decreasing with increasing distance from the structure. The cumulative penalty impact due to structures at pixel (k, l) is the sum of penalties from all structures t:

$$d(k, l) = \sum_t d_t(k, l) \tag{12}$$

The total penalty cost associated with structural loss, $C_{\text{structureloss}}(w)$, is then given by the sum of individual penalties across the domain:

$$C_{\text{structureloss}}(w) = \sum_{k=1}^{k_{\max}} \sum_{l=1}^{l_{\max}} p_w(k, l) \tag{13}$$

where $p_w(k, l)$ is defined as:

$$p_w(k, l) = \begin{cases} 0 & \text{if } U(k, l) = 1 \\ \gamma d(k, l) & \text{if } U(k, l) = 0 \text{ and } B(k, l) = 1 \\ 0 & \text{if } U(k, l) = 0 \text{ and } B(k, l) = 0 \end{cases} \tag{14}$$

The variable γ represents a constant associated with structural loss. Consequently, the total penalty cost is the sum of the land loss and structural loss costs:

$$C_{\text{penalty}}(w) = C_{\text{structureloss}}(w) + C_{\text{landloss}}(w) \tag{15}$$

Finally, the comprehensive cost for a prescribed burn at blackline width w encompasses both fuel removal and penalty costs:

$$C_{\text{burncost}}(w) = C_{\text{fuelremoval}}(w) + \theta * C_{\text{penalty}}(w) \tag{16}$$

where, θ is the dollar conversion constant that converts the penalty factor to dollar value. In this case, it has been assumed to be 1.

To illustrate the end result of the cosst analysis, Fig. 4(a) shows the spatial distribution of penalty cost factor, while Fig. 4(b) refers to costs associated with land and structure loss due to the fire escape illustrated earlier in Fig. 2(b).

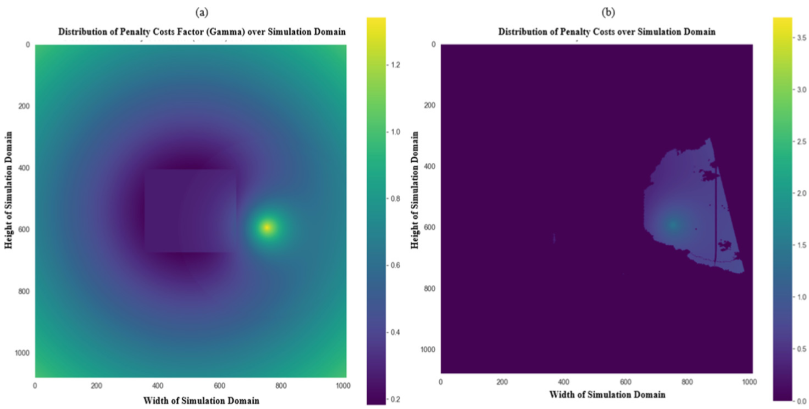

Fig. 4. Visual representation of the simulation domain depicting (a) cost factor and (b) costs calculated from fire escape and structure damage

4 Methodology for Optimization

In the optimization methodology, the cost function $C_{\text{burncost}}(w)$ in (16) can be calculated across a discrete set of potential widths (w) for blackline construction. In addition, variability in anticipated wind speed and wind direction can be used to find either an average or worst-case cost $C_{\text{burncost}}(w)$ and an optimal blackline width could then be chosen by the minimization of $C_{\text{burncost}}(w)$ over w. However, such optimization inevitably tends towards a trivial solution of maximal fuel removal (maximum w) when costs associate to fire escape are large. While such an approach effectively mitigates fire spread, it may not represent the most efficient allocation of resources.

To counter the propensity for trivial solutions, the optimization methodology integrates an additional effort cost component, analogous to regularization parameters in optimization problems. The additional effort cost is given $C_{\text{effort}}(w) = \delta \cdot (w - w_0)^2$, where w again represents the blackline width, w_0 is set to a value of 8 and δ is a coefficient adjusting the impact on the total cost and is set to a value of $\$135/m^2$. This incorporation of an effort cost is intended to ensure a more balanced approach to evaluating strategies advocating for a more judicious and effective deployment of fire management resources.

The cost evaluation has been summarized in Fig. 5. Specifically, Fig. 5(a) illustrates the penalty costs arising from prescribed burn escapes, with cost assessments per blackline width refined by introducing wind direction variations within a $270 \pm 15°$ range. Furthermore, Figure 5(b) reveals a non-linear correlation between total cost and blackline width, suggesting that optimal width aligns with a strategy of maximal fuel removal. Figure 5(c) displays the total costs.

$$C_{\text{fuelremoval}}(W) = C_{\text{control}} + C^{(o)}_{\text{blackline}}(W) + C_{\text{effort}}(W) \tag{17}$$

including the additional effort cost, o is the choice of option based on wind direction.

Given the inherent variability in the simulation outcomes, a deterministic approach to determine the optimal blackline width is not advisable. Instead, a 6th order polynomial function is fitted to the data to capture the nuanced trends and provide a smooth approximation of costs over varying blackline widths. This is mathematically expressed as $C(W) = a_0 + a_1 W + a_2 W^2 + \cdots + a_6 W^6$, where $C(W)$ denotes the cost associated with a blackline of width W, and $a_0, a_1, \ldots, a_6$ are the coefficients determined by the fitting process. The rationale for selecting a polynomial function lies in its flexibility to model the non-linear relationships between the control measures and the resultant costs, thus ensuring a robust optimization process. This polynomial model offers a continuous, differentiable function, crucial for identifying cost minima with gradient-based optimization techniques.

The BFGS algorithm [14] emerges as a formidable quasi-Newton method for local minimization within the basin-hopping framework, crucial for the refined optimization of the cost function $C(w)$. It iteratively adjusts an estimation H of the inverse Hessian matrix alongside the position vector w, in accordance to the update rule $w_{\text{new}} = w_{\text{old}} - \alpha H \nabla f(w_{\text{old}})$, where α denotes the step size, ascertained via a line search adhering to Wolfe conditions. Simultaneously, the approximation H is updated by $H_{\text{new}} = (I - \rho s y^T) H_{\text{old}} (I - \rho y s^T) + \rho s s^T$, with $s = w_{\text{new}} - w_{\text{old}}$ and $y = \nabla f(w_{\text{new}}) - \nabla f(w_{\text{old}})$, encapsulating the changes in position and gradient. This method is integral to the basin-hopping strategy, which conducts a comprehensive exploration for the global minimum of $C(w)$, navigating beyond the barriers of local minima. This methodology offers a systematic way to determine the optimal blackline width, minimizing costs and efforts in prescribed burn operations.

5 Use Case Results

In the results section, findings from the simulation exercises conducted within the Auburn, CA, burn unit scenario are presented. Utilizing the QUIC FIRE simulation tool, a series of simulations were executed with specific parameters: a wind speed set at 32.18 kph, oriented from east to west, and a head fire ignition pattern. These parameters were chosen to simulate environmental conditions influencing wildfire spread in the designated area. An ensemble methodology, involving variations in the width of the black line across different simulations, evaluates the implications on cost and the efficacy of burn operations.

Figure 6 provides a visual sequence that conveys the outcomes of the ensemble simulations conducted within the context of the Auburn, CA, burn unit scenario, ranging from 8 m to 24 m in increments of 2 m, for 270° wind angle. Each depicted scenario offers a distinct visual representation, shedding light on the effect of blackline widths on prescribed burn control. This analysis necessitates minimum black line width to prevent fire escape, while also noting that widening the line beyond this minimum would incur excessive costs.

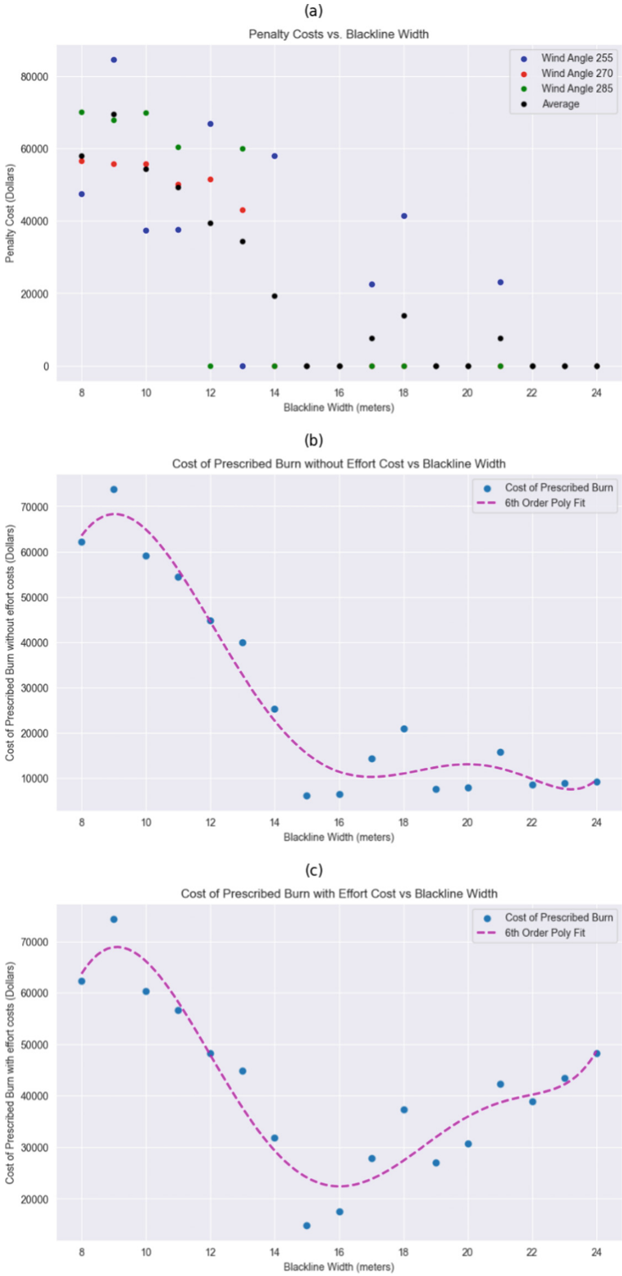

Fig. 5. Cost of Prescribed burn vs width of blackline

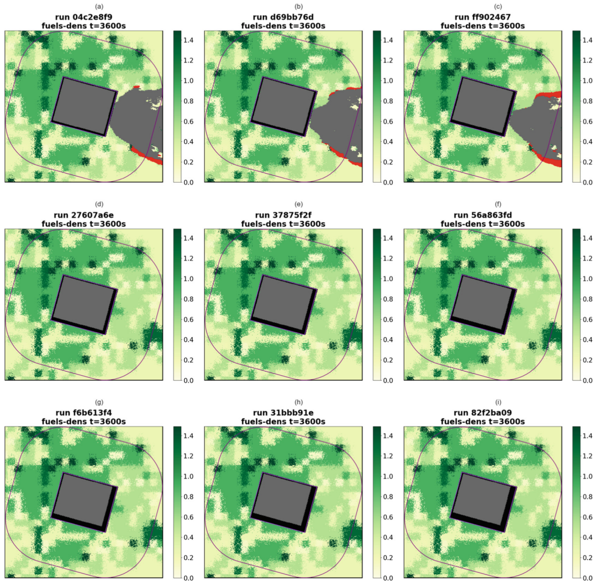

Fig. 6. Impact of Blackline widths on Fire Control in Auburn, CA. Panels a to i display the effects of blackline widths ranging from 8 m to 24 m in 2 m increments on prescribed burn spread for 270° wind angle

Building on the visual insights, Table 1 provides a quantitative assessment, detailing the financial impacts of different blackline widths. This methodical tabulation of burn costs linked to each width level offers a structured basis for informed decision-making in fire management strategies. It is important to consider that altering the blackline width may inadvertently increase local wind speeds, potentially escalating the risk of fire escape, even with wider blacklines.

Finally, Fig. 5 illustrates the crucial balance between the cost of prescribed burns and blackline width, pinpointing the optimal width for minimizing cost, efforts and fire damage. The comprehensive analysis and simulations detailed above culminate in identifying an optimal blackline width of 16 m as the most effective in balancing cost reduction, efforts and enhancing fire control measures for the prescribed burn scenario in Auburn, CA.

Table 1. Comprehensive Cost Analysis for Various Blackline widths Under Simulated Wind Conditions in Auburn, CA.

Blackline width (w)	Penalty Cost Average ($\theta \cdot C_{\text{penalty}}$)	Cost of Fuel Removal ($C_{\text{fuelremoval}}$)	Total Cost (C_{burncost})
8	58024.45	4285.95	62310.41
10	54271.44	6008.94	60280.38
12	39474.50	8737.10	48211.61
14	19334.57	12543.40	31877.97
16	0	17471.02	17471.02
18	13783.91	23588.35	37372.27
20	0.00	30693.04	30693.04
22	0.00	38905.80	38905.80
24	0.00	48205.51	48205.51

6 Conclusions

Embarking on an exploratory journey to unravel the complexities inherent in the planning of prescribed burns, this study has meticulously investigated the optimization of blackline widths, aiming to strike a delicate balance between operational efficacy and cost-efficiency. Through an exhaustive series of simulation exercises conducted within the Auburn, CA, burn unit scenario using the QUIC FIRE simulation tool, we have shed light on the intricate relationship between blackline width, fire control, and economic factors.

The ensemble methodology, exploring varying blackline widths has unequivocally demonstrated that strategic modifications in width can profoundly affect fire behavior and containment. This finding emphasizes the critical need for added precision in the planning and execution phases of prescribed burns. The simulations not only provided a qualitative insight into the impact of varying blackline widths on fire control efforts, but also paved the way for a quantitative analysis that meticulously outlined the financial ramifications.

Leveraging polynomial interpolation and the BFGS optimization algorithm within a basin-hopping framework facilitates the computation of optimal blackline width as a compromise between cost, effort and potential damage from fire escapes. This fusion of computational modeling and economic analysis marks a introduction of a framework in enhancing the effectiveness of prescribed burns as a wildfire management strategy, highlighting the potential of simulation-based optimization in achieving an optimal balance between operational efficiency and cost-effectiveness.

Reflecting on the objectives outlined in the introduction, this research has successfully:

- Established a foundational framework with an aim to advance multi-dimensional control strategies for fireline creation and fuel management.
- Developed a comprehensive cost-based analysis framework for prescribed burns, aiding in resource allocation and strategic planning.
- Introduced financial modeling within prescribed burn management domain by harnessing the capabilities of the QUIC FIRE simulation, thereby refining planning and cost estimation efforts.

This research highlights key opportunities for future work, including the use of computational and data driven technologies to aid prescribed burn strategies. Additionally, a more detailed economic model incorporating broader cost factors could improve prescribed burn planning. By integrating advanced simulations with economic analysis, this study contributes significantly to developing more effective and sustainable wildfire management strategies.

References

1. Achtemeier, G.L.: Field validation of a free-agent cellular automata model of fire spread with fire-atmosphere coupling. Int. J. Wildland Fire **22**(2), 148–156 (2012)
2. Achtemeier, G.L., Goodrick, S.A., Liu, Y.: Modeling multiple-core updraft plume rise for an aerial ignition prescribed burn by coupling daysmoke with a cellular automata fire model. Atmosphere **3**(3), 352–376 (2012)
3. Ager, A.A., Vaillant, N.M., Finney, M.A.: A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecol. Manag. **259** (2010). https://www.sciencedirect.com/science/article/pii/S0378112710000514
4. Arriagada, R.A., Cubbage, F.W., Abt, K.L., Huggett Jr, R.J.: Estimating harvest costs for fuel treatments in the west. Forest Prod. J. **58**(7), 24–30 (2008). https://www.proquest.com/scholarly-journals/estimating-harvest-costs-fuel-treatments-west/docview/214625926/se-2
5. Dennison, P.E., Brewer, S.C., Arnold, J.D., Moritz, M.A.: Large wildfire trends in the western united states, 1984-2011. Geophys. Res. Lett. **41**(8), 2928–2933 (2014). https://doi.org/10.1002/2014GL059576. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2014GL059576
6. Gibbons, P., et al.: Land management practices associated with house loss in wildfires. PLoS ONE **7** (2012). https://api.semanticscholar.org/CorpusID:4677687
7. Graham, R.T., McCaffrey, S., Jain, T.B.: Science basis for changing forest structure to modify wildfire behavior and severity (2004). https://api.semanticscholar.org/CorpusID:140583948
8. Hesseln, H.: The economics of prescribed burning: a research review. Forest Sci. **46**(3), 322–334 (2000). https://doi.org/10.1093/forestscience/46.3.322
9. Ingalsbee, T.: Fuelbreaks for wildland fire management: a moat or a drawbridge for ecosystem fire restoration? Fire Ecol. **1**(1), 85–99 (2005). https://doi.org/10.4996/fireecology.0101085
10. Lemons, R.E., Prichard, S.J., Kerns, B.K.: Evaluating fireline effectiveness across large wildfire events in north-central washington state. Fire Ecol. **19**(1) (2023). https://doi.org/10.1186/s42408-023-00167-6

11. Linn, R., et al.: Quic-fire: a fast-running simulation tool for prescribed fire planning. Environ. Model. Softw. **125**, 104616 (2020). https://doi.org/10.1016/j.envsoft.2019.104616
12. Macarena, O., y Silva Francisco, R., Ramón, M.J.: Fireline production rate of handcrews in wildfires of the spanish mediterranean region. Int. J. Wildland Fire **32**, 1503–1514 (2023). https://doi.org/10.1071/WF22087
13. Mercer-Smith, J.A.: Quic-fire: 3D fire-atmosphere feedback model for wildland fire management (2020). https://doi.org/10.2172/1650598. https://www.osti.gov/biblio/1650598
14. Nocedal, J.: Theory of algorithms for unconstrained optimization. Acta Numerica **1**, 199–242 (1992). https://doi.org/10.1017/S0962492900002270
15. Pardyjak, E.R., Brown, M.: QUIC-URB v. 1.1: Theory and user's guide. Los Alamos National Laboratory, Los Alamos, NM (2003)
16. Penman, T.D., et al.: Prescribed burning: how can it work to conserve the things we value? Int. J. Wildland Fire **20**, 721–733 (2011). https://api.semanticscholar.org/CorpusID:128823603
17. Radeloff, V.C., Helmers, D.P., Mockrin, M.H., Carlson, A.R., Hawbaker, T.J., Martinuzzi, S.: The 1990-2020 wildland-urban interface of the conterminous united states - geospatial data (2023). https://doi.org/10.2737/RDS-2015-0012-4. https://usfs.maps.arcgis.com/home/item.html?id=454bddfa18784660a472685ac7965881. Financial support was provided by the USDA Forest Service under the National Fire Plan and by USDA Forest Service, Northern Research Station. Data obtained from the U.S. Census and USGS National Land Cover Data
18. Singh, B., Hansen, B.S., Brown, M.J., Pardyjak, E.R.: Evaluation of the QUIC-URB fast response urban wind model for a cubical building array and wide building street canyon. Environ. Fluid Mech. **8**, 281–312 (2008)
19. Syphard, A.D., Brennan, T.J., Keeley, J.E.: The role of defensible space for residential structure protection during wildfires. Int. J. Wildland Fire **23**, 1165–1175 (2014)
20. United States Department of Agriculture, National Agricultural Statistics Service: Land values 2022 summary. Technical Report ISSN: 1949-1867, United States Department of Agriculture, National Agricultural Statistics Service (2022)
21. U.S. Bureau of Labor Statistics: Consumer price index for all urban consumers (CPI-U): All items in U.S. city average, all urban consumers, not seasonally adjusted (2023). https://www.bls.gov/cpi/. Series Id: CUUR0000SA0. Data extracted on: February 22, 2024 (3:41:28 AM). Not Seasonally Adjusted
22. Weir, J.R., et al.: Prescribed fire: understanding liability, laws and risk. Technical report, Oklahoma Cooperative Extension Service (2020)
23. Weir, J.R., et al.: Liability and prescribed fire: perception and reality. Rangeland Ecol. Manag. **72**(3), 533–538 (2019). https://doi.org/10.1016/j.rama.2018.11.010. https://www.sciencedirect.com/science/article/pii/S1550742418301283
24. Wollstein, K., O'Connor, C., Gear, J., Hoagland, R.: Minimize the bad days: wildland fire response and suppression success. Rangelands **44**(3), 187–193 (2022). https://doi.org/10.1016/j.rala.2021.12.006. https://www.sciencedirect.com/science/article/pii/S019005282100122X. Changing with the range: Striving for ecosystem resilience in the age of invasive annual grasses