



Comparing contingency fire containment strategies using simulated random scenarios

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Abstract

Contingency firelines can be used to back up primary lines to increase probability of fire containment, decrease fire losses, and improve firefighter safety. In this study, we classify firelines into primary, contingency, and response lines. We design a modeling process to iteratively implement a mixed integer programming model to evaluate contingency strategies under randomly generated fireline breaching scenarios. Our objectives include: (1) gaining conceptual understanding of the effectiveness of using contingency containers in a fireline network, and (2) suggesting future data collection and model improvement directions to support contingency strategy planning. We evaluate the effectiveness of several model generated containment strategies: only responding to observed primary line breaches, being proactive by implementing a system-level contingency plan, or constructing contingency lines to back up a proportion of a primary container. Data from the Ferguson Fire in California are used to derive a set of hypothetical test cases with different fireline breaching risks to support sensitivity analysis. For comparison, we also test a contingency plan inspired by the Ferguson Fire operation. Analyses

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suggest that a contingency plan will provide the greatest benefit when fireline breaching risk is high. This study also suggests there are significant data and knowledge gaps that must be addressed to make the model suitable for operational use.

Recommendations for Resource Managers

- Systems analysis can help evaluate contingency containment plans.
- A contingency plan will provide the greatest benefit when fireline breaching risk is high.
- It is often efficient to strategically locate contingency lines to back up primary lines with high breaching probabilities.
- A good contingency plan may help lower fire loss and save suppression effort under many fireline breaching scenarios.
- Data collection and synchronization are important in supporting future advances in fire containment decisions.

KEYWORDS

fireline contingency, mixed integer programming, risk management, wildland fire suppression

1 | BACKGROUND

Wildfire area burned and associated damages have increased over the past 50 years in the United States. Firefighting expenditures have escalated, as have concerns about public and firefighter safety (Calkin et al., 2005; Gebert and Black, 2012; Liang et al., 2008). This has motivated land and fire management agencies, including the US Forest Service, to research and operationalize strategies to lower fire suppression costs and improve firefighter safety (Calkin et al., 2012; NWCG, 2014). These efforts have resulted in the widespread use of wildfire risk assessment in land management planning (Calkin et al., 2010; Gonzalez-Olabarria et al., 2019; Miller & Ager, 2013; Scott et al., 2013), and growth in the application of similar technologies to support decisions during active fires (Calkin et al., 2011). In contrast, there has been limited development of containment strategy models that leverage information on values at risk and suppression effectiveness to evaluate competing strategies and/or recommend efficient solutions (Thompson et al., 2018a; Thompson et al., 2018b; Thompson et al., 2019).

Uncertainty in a wildfire-management system is derived from the nearly infinite variations from many influencing factors (Finney, 2020), which makes it challenging to prescribe precise



solutions to fire containment and to accurately assess tradeoffs between alternative strategies (Martell, 2015; Thompson, 2015; Thompson et al., 2017). Major sources of uncertainty in containment planning stem from variations in fire spread, fire behavior, and containment effectiveness, and from difficulties of forecasting the driving weather conditions over incident time scales of days to weeks (Duff & Tolhurst, 2015; Dunn et al., 2017; Minas et al., 2012; Plucinski, 2019a, 2019b). Fire managers often mitigate uncertainty by building redundant firelines (Gannon et al., 2020) during large fire suppression. Calkin et al. (2011) show fireline production capacity from the suppression resources dispatched to a large fire can be several times more than the actual fire perimeter length, partially to build redundant lines. Nowell et al. (2017) qualitatively describe the different forms and functions of redundancy in fire suppression.

Many studies from the systems engineering literature examine the pros and cons of different configurations of redundancies for a variety of systems. For example, system elements may be placed in series or parallel to create redundancy (Najafi et al., 2013). In a series system, redundancy may be built at the component level to prevent the failure of each component, or at the system level to prevent the failure of any component in the primary system (Hazra & Nanda, 2014). Despite the common use of redundant firelines in fire suppression to address fireline breaching concerns, past fire suppression optimization models typically assume a fireline will hold once built (e.g., Belval et al., 2016, 2019; Donovan & Rideout, 2003; Fried & Fried, 1996; Hu & Ntaimo, 2009; Wei et al., 2011, 2018, 2019). The study of system redundancy in fire suppression is limited.

Identifying candidate locations for fireline construction has historically been an ad hoc process completed in real-time by fire managers. Recent spatial fire planning efforts in the United States have emphasized pre-identifying operationally relevant control features, such as roads, ridge tops, rivers, or other lower fire intensity line features to delineate the landscape into fire planning units called Potential fire Operational Delineations (PODs; O'Connor et al., 2016; Thompson et al., 2016; Thompson et al., 2018b). The operationally relevant boundaries make POD a useful spatial unit for large fire containment planning. For example, POD delineation was used to plan for control opportunities and assign strategic response (i.e., protect, maintain, or restore) before the Pinal fire ignition in Arizona (O'Connor & Calkin, 2019). Previous studies have optimized the aggregation of PODs into a large fire response container with mixed integer programming (MIP) models (e.g., Wei et al., 2018, 2019). Using PODs to support containment planning often better reflects large fire operation decisions than raster-based containment models (e.g., Belval et al., 2016, 2019; Wei et al., 2011; Zhou & Erdogan, 2019).

In this study, we introduce a conceptual framework to describe fireline contingency planning using the concepts of primary, contingency, and response lines; we build hypothetical test cases by synthesizing data from a recent large fire event to illustrate this framework. Those test cases reflect the complexity in real-world large fire operations, that is, heterogeneous landscape, fireline breaching uncertainty, and the dynamic decision process. We prototype an analysis process that extends the MIP model from Wei et al. (2018, 2019) to evaluate the effectiveness of different fire containment strategies. The enhanced MIP model allows for coarse-scale fire arrival time tracking to help managers strategically depict fire spread and distribute suppression efforts. We create and test a set of stochastic fireline breaching scenarios that include both fireline construction decisions and the impact from stochastic fireline breaching events. Our objective is to provide conceptual understanding of how redundant firelines may be used to mitigate the uncertainties from fireline breaching. We also hope to provide suggestions for future fire suppression data collection and modeling needs to promote research in large fire containment decisions.



2 | A CONCEPTUAL DESCRIPTION OF PRIMARY AND CONTINGENCY STRATEGIES

Fire suppression activities are often classified as either direct attack or indirect attack (NWCG, 1996). Direct attack is implemented directly on the fire's edge by knocking down the flames. It generally works best on low-intensity fires. Indirect attack builds a fireline from certain distance to the fire edge along natural (i.e., river and ridge top) and human-made (i.e., roads, trails or fuel breaks) barriers and is mostly used to contain high-intensity fires. In this study, we focus on indirect attack planning during large fire suppression. The objective is to form fire containers.

We define “primary container” as the closest contiguous firelines constructed around a wildfire. Additional layers of back up firelines can be built beyond a primary container to lower the risk of loss should primary lines breach. We refer to back up lines built proactively—that is, before we could observe which primary lines will breach—as “contingency lines.” An alternative strategy is to build back up lines to directly compensate for observed line breaches, which we refer to as “response lines”. Building proactive contingency lines may provide managers additional flexibility in selecting the time and locations to safely construct higher quality lines, thus increasing holding probability (e.g., wider lines having lower breaching probability; Mees et al., 1993). However, if the primary lines targeted by the contingency lines do not breach, those contingency lines would not contribute to fire containment (unengaged). Past studies show the length of unengaged fireline sometimes exceeds 50% of the fireline constructed during large wildfires in the western United States (Thompson et al., 2018b). In contrast, response lines would be more likely to engage with fire. However, waiting to first observe a breach may leave less time for managers to construct higher quality lines in desirable locations.

Contingency firelines can be planned along POD edges to provide backup for either the entire primary container or for a portion of the container. Figure 1a shows an example of a separate contingency container (solid red lines) built to back up each of the three primary lines in case of any primary line breach. Figure 1b provides an example of a contingency plan that is targeted at backing up two of the three primary lines (solid blue lines). Figure 1c depicts a set of connected contingency lines that provide “system-level” redundancy in case any of the primary lines breach. Each of the three contingency plans has pros and cons. For example, the three separate contingency containers (Figure 1a) provide the best protection because any fireline breach may be contained within one of the containers, but this plan requires the most line construction effort. In contrast, the system-level redundancy in Figure 1c provides backup for all primary lines with one container, which requires less line construction comparing with Figure 1a but may result in burning all areas inside the contingency container if any of the primary lines breached. Figure 1b shows a case of using contingency lines to add “partial” redundancy to the system, which could save on contingency line construction, but also leaves vulnerabilities that may need to be addressed with response lines.

A more realistic fire containment and breaching example is shown in Figure 2. This example demonstrates how POD boundaries (thin black lines) may be used as candidate locations to build fireline. When a fire starts in one POD or a group of PODs, managers can identify a primary container that reflects their ideal strategy for controlling the fire and minimizing fire loss; in Figure 2, the primary firelines are depicted by thick blue lines (either solid or dashed). To mitigate the risk of a primary fireline breach, managers may build contingency lines aimed at backing up some primary lines. In Figure 2, only primary line 1 is backed up by contingency lines (thick red lines). In a hypothetical fireline breaching scenario shown here, both primary

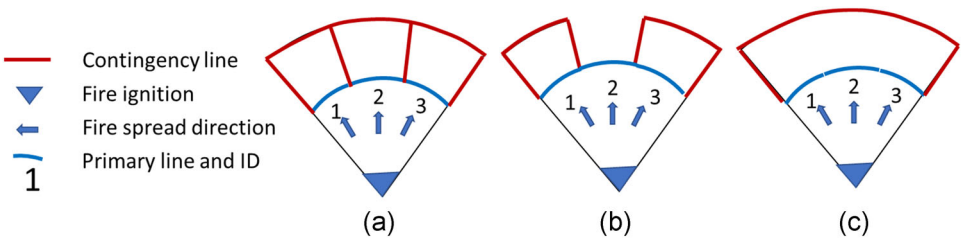


FIGURE 1 A conceptual description of three potential contingency plans to minimize the consequences of primary line breaches: (a) separate contingency container for each of the three primary lines, (b) contingency containers targeted at a subset of primary lines (line 1 and 2), and (c) a complete system-level contingency plan

lines 1 and 2 breach (dashed blue lines). The breach of line 1 could be stopped by the contingency lines. However, any fire escaping line 2 would need to be addressed by building response lines (thick green lines), presumably along the POD boundary *A*. In Figure 2, line *A* breaches as well. In this example, fire is finally contained by the set of unbreached primary, contingency, and response lines. The scenario shown here is just one realization of many possible line-breaching scenarios. To account for the uncertainties of fireline breaching, we need to model and compare the effectiveness of contingency strategies through many stochastic scenarios.

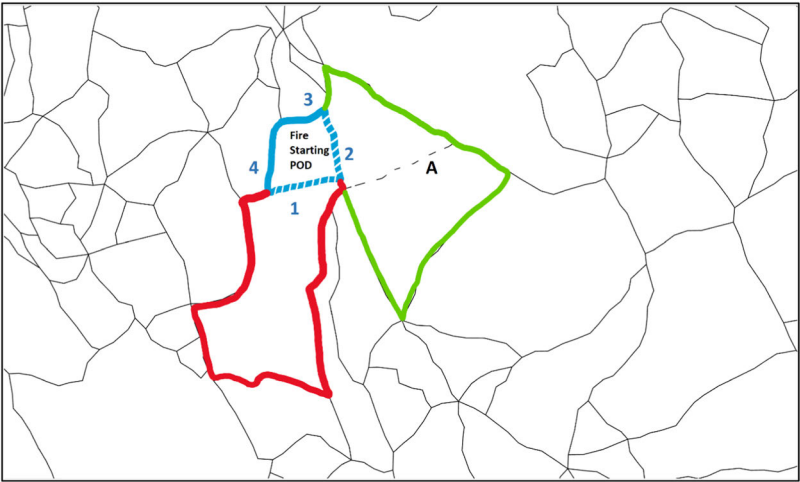


FIGURE 2 A hypothetical case depicts a fire origin and candidate fireline locations along POD boundaries (thin black lines). The blue lines depict the primary container. A contingency container (thick red lines) is built to back up only primary line 1 and it will hold upon the breach of line 1. Both lines 1 and 2 breached under this random scenario; a response line *A* (dashed black) was built to stop the escaped fire, but it also breached in this scenario; the other response lines (solid green lines) were then built and finally held. The final fire footprint is enclosed by the solid red, green, and blue lines. POD, Potential fire Operational Delineation



3 | AN MIP MODEL TO BUILD FIRE CONTAINERS

The MIP model used in this study was designed to form a large fire response container (referenced as “fire response PODs,” or rPOD) by aggregating multiple preidentified PODs. A set of bookkeeping variables and formulations are added into the MIP formulations from Wei et al. (2018, 2019) to implement the minimum travel time (MTT; Finney, 2002, 2007; Hof et al., 2000) algorithm to dynamically track the fire arrival time to the centroid of each POD as a result of both fire spread and fireline constructions (Constraints 11 and 12). Model notations for the MIP model are provided in Table 3.

$$\text{Max } \sum_i \text{NVC}_i \times X_i - w_1 \times V_t \quad (1)$$

subject to

$$X_i = 1 \quad \forall i \in I^0, \quad (2)$$

$$F_i = 0 \quad \forall i \in I^0, \quad (3)$$

$$T_i = 1 \quad \forall i \in I^0, \quad (4)$$

$$\sum_t Y_{(i,j),t} \leq 1 \quad \forall (i,j), \quad (5)$$

$$\begin{cases} X_i - X_j \leq \sum_t Y_{(i,j),t} & \forall (i,j), \\ X_j - X_i \leq \sum_t Y_{(i,j),t} & \forall (i,j), \end{cases} \quad (6)$$

$$B_{(i \rightarrow j)} \leq X_i \quad \forall (i \rightarrow j), \quad (7)$$

$$X_j \leq \sum_i B_{(i \rightarrow j)} \quad \forall j \notin I^0, \quad (8)$$

$$\begin{cases} B_{(i \rightarrow j)} \leq 1 - \sum_t Y_{(i,j),t} & \forall (i \rightarrow j) \text{ when } i < j, \\ B_{(i \rightarrow j)} \leq 1 - \sum_t Y_{(j,i),t} & \forall (i \rightarrow j) \text{ when } i > j, \end{cases} \quad (9)$$

$$\begin{cases} F_j \leq F_i + M \times (1 - B_{(i \rightarrow j)}) + 1, \\ F_j \geq F_i - M \times (1 - B_{(i \rightarrow j)}) + 1 \end{cases} \quad \forall (i \rightarrow j), \quad (10)$$

$$T_j \leq T_i + M \times \sum_t Y_{(i,j),t} + s_{i \rightarrow j} \quad \forall (i \rightarrow j), \quad (11)$$

$$\begin{cases} t \times Y_{(i,j),t} \leq T_i, \\ t \times Y_{(i,j),t} \leq T_j \end{cases} \quad \forall (i,j)', t, \quad (12)$$

$$V_t = \sum_{(i,j) \in (I,J)_t} l_{(i,j)} \times Y_{(i,j),t} \quad \forall t = 1 \text{ to } T, \quad (13)$$

$$\begin{cases} V_t \leq (1 + f) \times V_{t+1}, \\ V_t \geq (1 - f) \times V_{t+1} \end{cases} \quad \forall t = 1 \text{ to } T - 1. \quad (14)$$



The objective function (Equation 1) maximizes the total net value change (NVC) within an rPOD when fire is contained. Positive NVC represents potential fire benefit; negative NVC represents potential fire loss. This objective function also includes minimizing the weighted (w_1) total crew hours. Equation (2) ensures that all fire-starting PODs would be part of the selected rPOD. Equation (3) assigns a pseudoburn sequence number of zero to all fire-starting PODs. Equation (4) assigns a fire arrival time of one to each fire-starting POD. Constraint (5) assumes that fireline along each rPOD boundary would be constructed during one suppression period (e.g., 1 day). Constraint (6) ensures that containment effort is needed at the boundary between PODs i and j to stop fire spreading between them if and only if one of them is burned. In addition, Constraint (6) reflects an assumption that fire will spread between two adjacent PODs i and j without suppression. Constraint (7) ensures that fire can spread out from POD i only after that POD has burned. Constraint (8) ensures that if fire reaches POD i , it must have spread into it from one of its adjacent PODs unless i is a fire-starting POD. Constraint (9) reflects the assumption that a fireline between two PODs would stop fire from crossing the boundary of them. Constraint (10) updates the pseudosequence F_i by which POD i would be added into the rPOD. This pair of constraints is required to build the rPOD as a contiguous patch. Without those constraints, the model may select multiple disconnected patches as the rPOD. F_i does not necessarily reflect the true sequence that a fire enters each POD; instead it is a model generated number to enforce all PODs to be connected when forming an rPOD. Constraint (11) calculates the upper bound of the fire arrival time T_j to the centroid of POD j using the MTT algorithm. Starting from the ignition PODs, a fire can spread into POD j from any of its adjacent PODs i . The earliest possible time a fire would reach the centroid of j from any of its adjacent PODs is recorded as the upper bound of fire arrival time to POD j . Parameter $s_{i \rightarrow j}$ is the fire travel time from the centroid of POD i to the centroid of j . In the case that fireline is built along the boundary between i and j , a large positive number (represented by the big M in the equation) is added to the fire travel time. Like other MTT formulations used in an MIP model (e.g., Hof et al., 2000), the model reported value of T_j may take a smaller value than its upper bound if doing this does not increase the total fire loss or crew hours. Constraint (12) uses T_j to determine whether a fireline can be built along an edge (i, j) during period t . In this example, we assume fireline can be built at edge (i, j) during any period before fire arrives the centroid of POD i or j . Other forms of time restrictions for fireline construction could be formed based on T_j if desired. Constraint (13) uses bookkeeping variable V_t to track the total resource effort (i.e., hand crew hours) spent during the suppression period t . Constraint (14) allows the crew hours spent on each suppression period fluctuating within a range of $(1 - f, 1 + f)$ from the next fire day. Increasing the value of f would relax this constraint.

In this study, to model the uncertainties in fireline breaching, we run this MIP model iteratively to form fire containers under different fireline breaching scenarios. To reflect fireline construction decisions and fireline breach events, we will dynamically add new constraints into the model to capture those effects. We illustrate this process later through the test cases.

4 | TEST CASES AND PROCESS

A flowchart (Figure 3) is provided to describe the data preparation and analysis processes. We use fire records from the Ferguson Fire and other relevant fire risk analysis data to form a baseline test case to reflect the landscape heterogeneity and uncertainties often encountered during real-world large fire suppression operations. We then create additional hypothetical test cases by varying those baseline assumptions to study how various fire containment strategies

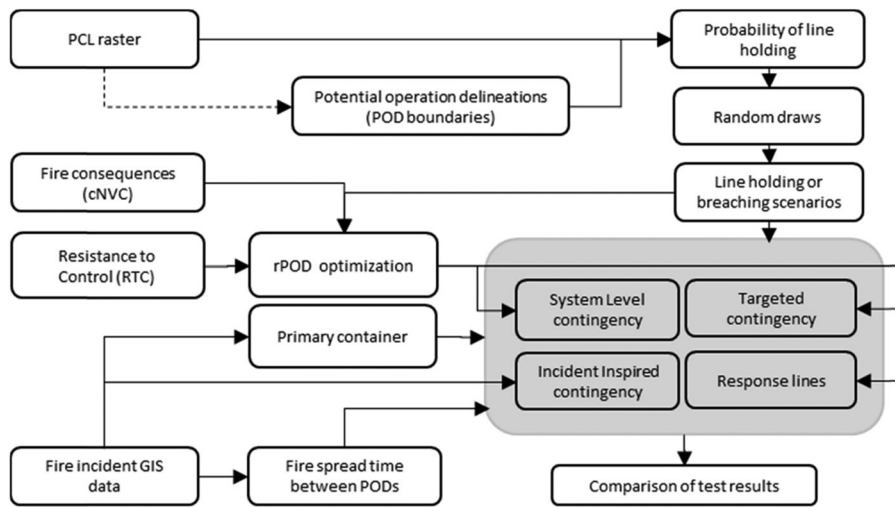


FIGURE 3 A flowchart describing how data and information are aggregated to build test cases to analyze the efficiency of different contingency plans. Boxes with shaded gray background represent the contingency strategies tested in this paper. A dashed arrow represents an alternative way of using PCL surface (instead of using natural or human-made boundaries) to delineate PODs. cNVC, conditional net value change (referred as NVC in this paper); GIS, geographic information system; PCL, Potential Control Line; POD, Potential fire Operational Delineation; rPOD, response POD

could perform differently under different line-breaching conditions. We evaluate several fireline containment strategies (in the shaded boxes in Figure 3) using those test cases.

4.1 | The Ferguson Fire

Our test cases are derived from the 2018 Ferguson Fire (Figure 4a) that burned 39,200 ha in the Sierra National Forest, Stanislaus National Forest, and Yosemite National Park in California, USA. GIS data on completed firelines were collected from the Wildland Fire Decision Support System (WFDSS; Noonan-Wright et al., 2011). The landscape was divided into 662 PODs; these delineations were developed using major roads, rivers, ridges, and most of the constructed firelines from the Ferguson Fire operation (Figure 4b). Including actual firelines constructed during the incident allows us to mimic incident fireline construction decisions. For testing, we classify firelines built during the fire operation into two categories (Figure 4c): (1) firelines that formed the closest contiguous internal container are assumed as the primary lines, and (2) firelines outside of the primary container are assumed to be the “Incident Inspired” contingency plan, which will be evaluated later by comparing it with model constructed contingency plans.

We use an NVC surface (Figure 4b) from a wildfire risk assessment conducted before the fire to represent spatially heterogeneous fire losses or gains across the landscape that should motivate fire containment efforts. NVC in each raster cell is a relative fire loss index calculated as a function of predicted fire intensity, the presence of fire-sensitive resources or assets, and quantitative functions describing fire loss or gain by intensity level (Finney, 2005; Scott et al., 2013). This risk assessment included infrastructure, habitat, timber, watersheds, and vegetation. Fire intensity distributions were modeled with FSim (Finney et al., 2011) under a range of

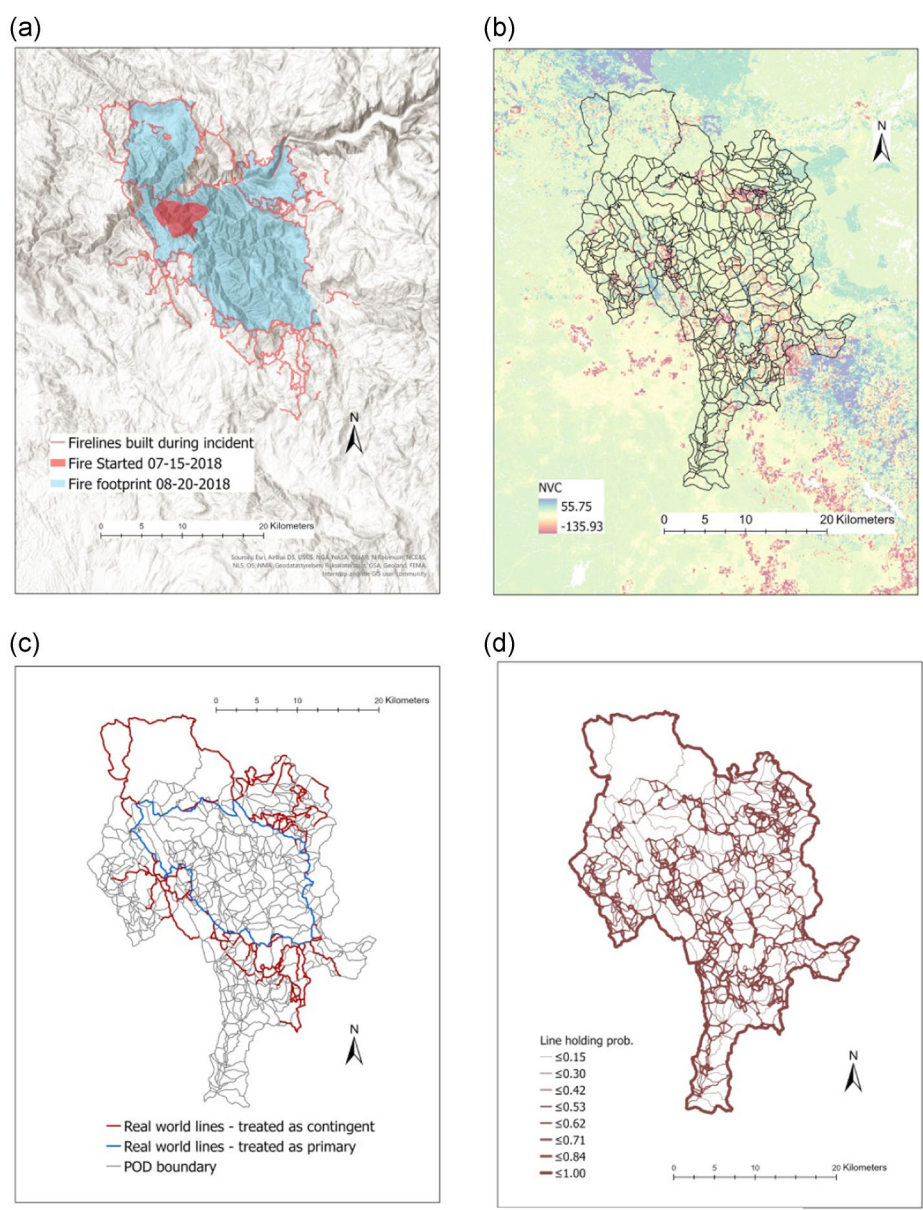


FIGURE 4 (a) The Ferguson Fire footprints and firelines built during the incident; (b) POD boundaries are candidate line locations; (c) we reclassify the firelines built during the incident into either primary lines or contingency lines depending on their relative positions, which is used for testing purpose; (d) displays the estimated probability of each fireline would hold once built along a POD edge; we assume all firelines along the study site boundaries will hold once built. NVC, net value change; POD, Potential fire Operational Delineation

representative fire weather conditions. Hence, the modeled NVC surface likely varies somewhat from the realized effects of the Ferguson Fire due to differences in weather and fire intensity, but it provides a reasonable representation of the direction and magnitude of effects should the fire burn part of the landscape.



4.2 | Fireline holding and breaching

Probability of containment at a linear control feature could be quantified either using theoretical models (e.g., Mees et al., 1993) or empirical models (e.g., Syphard et al., 2013; Wilson, 1988), but these models do not capture many of the factors that influence containment probability across diverse landscapes. Recent research has pivoted towards modeling raster surfaces of Potential Control Line suitability (PCL; O'Connor et al., 2017) and Suppression Difficulty Index (SDI; Rodríguez et al., 2014, 2020) using empirical data or expert evaluation. PCL is the modeled probability of containing fire in each pixel based on the statistical association between historical fire interior and perimeter locations with predictor variables related to fire behavior (at 90th percentile fire weather conditions), topography, distance to natural and anthropogenic barriers to fire spread, resistance to control (RTC), and travel cost. PCL has been demonstrated to explain up to 69% of historical fire perimeter locations in a diverse landscape (O'Connor et al., 2017) and has been used to develop predictive models of potential control locations across fire-prone landscapes of the Pacific Northwest of the United States (Dunn et al., 2020). SDI is an expert weighted index accounting for potential fire behavior (flame length and heat per unit area), density of roads and other fire break features, and fire responder mobility (O'Connor et al., 2016; Rodríguez et al., 2014, 2020). A higher SDI corresponds with a higher suppression difficulty (Rodríguez et al., 2014).

To build baseline test cases, we developed a logistic regression model to estimate the probability a fireline will hold (0 = breached, 1 = held) using operational data from six large wildfires in the western United States (South Umpqua Complex, Meyers, Sunrise, Lolo Peak, Rice Ridge, and Milli fires). The fireline and fire perimeter data came from the National Interagency Fire Center. Raster surfaces of PCL and SDI were developed by the authors using forecasted weather conditions to support decision-making by the incident managers. The firelines were first classified as breached, held, or not engaged based on their position relative to the final fire extents and perimeters (Gannon et al., 2020). Each breached or held fireline was buffered by 30 m from each side of the line to extract the average, minimum, and maximum of PCL and SDI. After testing several model formulations (see Appendix A), we selected a simple model using only two predictors: the minimum PCL (denoted as *MinPCL*) and the area of fireline buffer (denoted as *Area*). *MinPCL* reflects the most vulnerable location for fire breaching along a line and *Area* is proportional to the fireline length. A longer fireline should have a higher probability of breaching than a shorter fireline all else being equal. The coefficients for the selected variables and descriptors of model performance are presented in Table 1. Due to small sample size, this prototype regression model is only aimed at building baseline test cases. We recommend that future studies validate the model form and fit with data from additional fires.

The results of the model applied to POD boundaries are presented in Figure 4d and are used to build the baseline test cases (Table 2), in which the average holding probability from all firelines is 0.556, which means that firelines by average have a slightly less than 50% of chance to breach when engaged with a fire. We refer to this case as the “*lower line holding probability*” or *LowHP* case; it represents a system with high fireline breaching risk. To test model sensitivity, we arbitrarily double the estimated probability for each fireline to create a “*higher line holding probability*” or *HighHP* test case with an average line holding probability of 0.875. Testing both the *LowHP* and *HighHP* cases allows us to compare contingency plan effectiveness between fire suppression systems with different levels of fireline breaching risk.

TABLE 1 A logistic regression model selected to estimate the probability of each fireline holding

	Intercept	MinPCL	Area of line buffer
Coefficients	1.044	0.715	−0.00002262
z Value	12.088	2.302	−10.070
Significant level	0.001	0.01	0.001
AIC		3205	
AUC		0.669	

Abbreviations: AIC, Akaike Information Criterion; AUC, Area Under the ROC curve; MinPCL, Minimum Potential Control Line.

4.3 | Fireline production rate and fire travel time

Although large fire suppression typically requires collaboration among multiple resource types (Katuwal et al., 2016), for the purpose of this study we use hand crew hour alone to measure fire

TABLE 2 The list of fireline construction strategies tested, fireline holding probability level assumptions, and contingency line holding probability assumptions in this study

Description of line construction strategies
• <i>Primary only:</i> a. No proactive contingency lines built to back up the primary container. b. All breaches will be compensated by response lines built on the fly. • <i>System Level:</i> a. Contingency lines form a contiguous container outside of the primary container. b. Contingency lines are not built between the primary and contingency containers. • <i>Incident inspired:</i> a. Inspired by the Ferguson Fire operation, in which all firelines built outside of the inner fire container (primary container) are considered as contingency lines. b. Contingency lines do not always form a complete container. c. More contingency lines are built outside of the primary container comparing with the <i>System-Level</i> plan. • <i>Targeted:</i> a. Systematically back up a subset of primary lines with holding probability lower than certain preselected thresholds.
Fireline holding probability sensitivity tests
• <i>Lower line holding probability (LowHP):</i> a. Fireline holding probability is predicted based on a selected logistic regression model. b. It represents a system with higher line-breaching risk level. • <i>Higher line holding probability (HighHP):</i> a. Fireline holding probability is doubled from the <i>LowHP</i> case. b. It represents a system with lower line-breaching risk level.
Contingency line holding probability sensitivity tests
• Doubled contingency line holding probability (<i>DoubleCHP</i>): a. Fireline holding probability is doubled when built as a contingency line. • Other holding probability assumptions: a. Fireline holding probability is either 1.5 times higher (1.5×) or the same (1.0×) when built as contingency lines.



TABLE 3 The list of notations used in the MIP-based rPOD optimization model to configure large fire containers

Indices and sets	
I^0	The set of ignition PODs
i or j	Indices for PODs
(i, j) or (j, i)	Index of the boundary between a pair of adjacent PODs i and j with the first subscript smaller than the second subscript so that each boundary is represented by only one pair of PODs
$(i, j)'$	Index of POD boundaries in which fireline construction time will be restricted
$(i \rightarrow j)$	Index of fire spread direction, from POD i to its adjacent POD j
t	Index of suppression period (i.e., day) from 1 to $t_{\max}$
Decision variables	
X_i	0/1 variable; 1 if POD i is selected as part of the rPOD
$Y_{(i,j),t}$	0/1 variable; 1 if fireline is constructed along the boundary (i, j) during suppression period t
$B_{(i \rightarrow j)}$	0/1 variable; 1 if fire spreads from POD i to j ; 0 if not
F_i	A variable tracking the pseudo sequence each POD being included into the rPOD. Following this sequence, this model can form a contiguous rPOD starting from a set of fire-starting PODs
T_i	Dynamically tracked fire arrival time to the centroid of POD i
V_t	Bookkeeping variable used to track the total resource time (i.e., crew hours) for line construction during period t
Parameters	
NVC_i	Potential net fire loss in POD i ; positive value represents net fire benefits; negative value represents net fire losses within each POD
M	A large positive constant (big M)
$l_{(i,j)}$	Expected resource time (i.e., crew hours) needed to build containment lines along boundary (i, j)
w_1	A selected weight in the objective function to penalize resource use (i.e., total crew hours) in building firelines
$s_{i \rightarrow j}$	Fire travel time from the centroid of POD i to j
f	Allowed suppression effort fluctuation rate between periods

Abbreviations: MIP, mixed integer programming; NVC, net value change; POD, Potential fire Operational Delineation; rPOD, response POD.

suppression effort. We estimate the hand crew hour requirements ($l_{(i,j)}$ in Constraint 13) along each POD boundary based on the average RTC measurement within a 30-m buffer from each side of it. RTC reflects the average fireline production rate (chains/hour) by a 20-person hand crew on each of the 40 fuel models (Dillon et al., 2015; Scott & Burgan, 2005). To build the MIP model, we assume that the total crew hours available during the entire suppression is 5000-h, which provides enough crew hours to contain the simulated fire even if the fireline breaching risk is high. We also restrict the crew hours spent in each fire day to be between half and twice of the crew hours spent in the next fire day to balance suppression workloads.

The MTT formulation (11) in the MIP model tracks fire arrival time to the centroid of each POD based on the estimated fire travel time $s_{i \rightarrow j}$ from the centroid of POD i to j . To estimate $s_{i \rightarrow j}$, we calculate the average distance between the two Ferguson Fire perimeters on July 15 and July 21, 2018, which coincides with the fastest fire spread period, and divide the average distance by the 6-day burn



period. This provides a rough estimate of 276 m/day for the average fire spread rate. This speed is used to populate and test the MTT formulation for purpose of the proof of concept.

4.4 | Alternative containment strategies

Four types of hypothetical fireline construction strategies are tested in this study. We first identify a primary fire container using the innermost set of continuous firelines built during the Ferguson Fire operation. Without a contingency plan, this container represents a “*Primary Only*” strategy (Figure 4c); the remaining firelines built during Ferguson Fire are considered as the “*Incident Inspired*” contingency lines (Figure 4c). For comparison, we also test other two types of contingency strategies. The first is referred to as the “*System-Level*” contingency, which is designed by running the rPOD model to recontain the fire after assuming all primary lines breach (except for those built along the study site boundaries). w_1 is set at 2000 in the objective function so that the rPOD model would build a contingency container with more emphasis on crew hour savings (Figure 6a). We then create and test another set of contingency strategies by running the rPOD model to build contingency lines to back up a portion of the primary lines (partial redundancy from Figure 1b) with holding probabilities lower than the following thresholds: 0.8, 0.6, 0.4, 0.2, and 0.1. We call these “*Targeted*” contingency plans. These test cases are summarized and briefly described in Table 2 and the flowchart in Figure 3. These rPOD model generated contingency strategies are considered “optimal” under the set of assumptions used to build the models. We recognize there are substantial uncertainties within the system and we evaluate each containment plan using many stochastic fireline breaching scenarios described next.

4.5 | Fireline breaching scenarios

Many factors, such as wind shifts, line quality, resource effectiveness, and spotting, may influence the ability of firefighters to effectively control a fire. We start our tests using the baseline estimates of fireline holding probabilities from the selected regression model in Table 1. We then adjust those probabilities systematically to create other test cases for sensitivity analyses. Each test case is evaluated using random line-breaching events, so we can account for variability in outcomes when comparing contingency strategy efficiencies.

For each of the fire containment strategies identified (Figure 3), we evaluate its efficiency by testing it against 60 randomly constructed line-breaching scenarios under each of the two line-breaching risk level test cases (*HighHP* or *LowHP*). For each scenario, we iteratively conduct random draws to determine whether a built fireline would breach; we then run the MIP model to build response lines to compensate for those breaches. Multiple iterations are often required to simulate the random line construction and breaching sequence for each scenario until the fire is fully contained. The iterative steps for each random scenario are described here and illustrated in Figure 6.

1. Select PODs to form a fire container using the rPOD model; all firelines built to contain the fire are recorded. If this is the start of the iterative process for a scenario, all primary lines and contingency lines would be “built” first. For each iteration, new response lines are built to compensate for breached lines.
2. Simulate whether each “newly built” line would breach or hold. We draw one random number r between 0 and 1 for each built line at the start of each iteration; we then calculate



the average of r and $1 - r$ as suggested by Ross (1996) and evaluate whether it is greater (line breached) or less (line held) than the probability of holding for that line. Proactively constructed contingency fireline is assumed to have a doubled line holding probability in the baseline test cases, but we also vary this assumptions in other test cases.

3. All built firelines deemed “held” from Step 2 are kept in all future iterations; all built but breached firelines from Step 2 are removed from all future iterations.
4. The iteration stops when there is no breach from all newly built lines; otherwise, the gaps from breached lines will need to be compensated by building additional response lines selected by the rPOD model. Under the latter case, we will go back to Step 2 to start a new iteration.
5. After the iteration stops, we sum the NVCs of all PODs within the final container and the total crew hours spent on building all firelines, including both held and breached lines from all the iterations.

5 | TEST RESULTS

5.1 | Iterative simulation of fire containment

Fireline construction and breaching can be simulated at coarse scale through a POD network for each modeled random scenario until full containment is achieved. In our test cases, all PODs within the primary container are assumed to be fire-starting PODs. Our test cases assume fire would continue to spread between adjacent PODs at a rate calculated from the fastest 6-day spread period of the Ferguson Fire. Fire spread can be slowed or stopped by held firelines, which is modeled through the MTT formulation in the MIP model. Held fireline delays fire arrival times for nearby areas outside the fire perimeter because fire is forced to take longer spread paths around the line. On the basis of this set of assumptions, Figure 5 shows an example of the MTT reported fire arrival time to the centroid of each POD at the end of one tested iteration. Fire arrival time can be used to guide crew hour distribution between fire days during a suppression operation.

Figure 6a–d shows an example of the constructed and breached firelines through multiple iterations under one tested random scenario when both the primary container and *System-Level* contingency container are implemented. In response to any fireline breaching event(s), managers can back off from those breached lines and build new response lines along the next available set of POD boundaries to fill the gaps left by the breached lines from the previous iteration. This iterative process will continue until all newly built lines hold, or until the fire reaches the boundary of the study site (an arbitrary ending condition). Figure 6e–h shows a similar iterative process from a *Primary Only* scenario if only the primary container is built. For this pair of examples, the final fire container is smaller when contingency firelines were constructed (Figure 6d). In this example, it takes a total of eight iterations until the fire is contained for the *System-Level* contingency scenario. For comparison, it takes 18 iterations to reach full containment if no contingency plan is implemented.

5.2 | Compare contingency plans across random scenarios

To evaluate the variable suppression effectiveness, we run the iterative simulation process for 60 random scenarios under each containment strategy for both levels of line holding

FIGURE 5 An example of the MIP model reported fire arrival day to the centroid of each POD at the end of a tested iteration. Fire arrival day for the assumed fire-starting PODs is set to be one. The minimum travel time formulation reports the upper bound for the fire arrival day. MIP, mixed integer programming; POD, Potential fire Operational Delineation

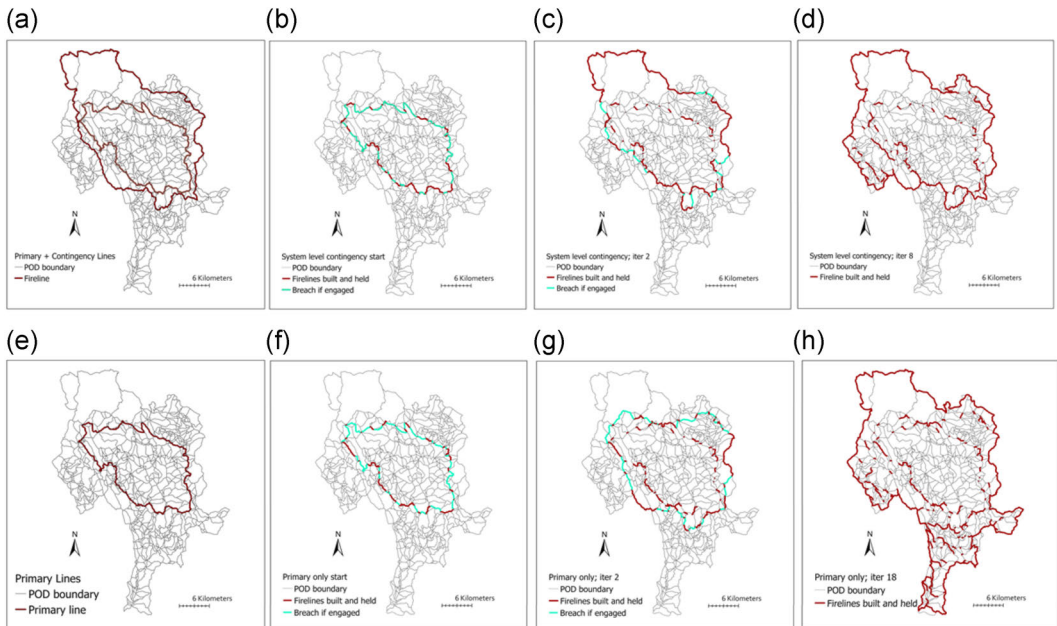
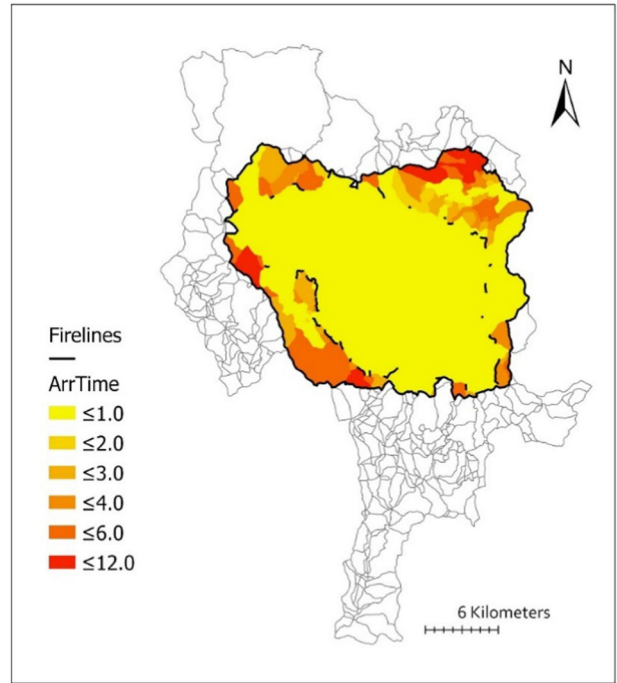


FIGURE 6 Demonstrate a sequence of iterations, including both fireline construction and breaching until the final containment. (a–d) An example with both primary container and the system-level contingency container; (e–h) an example with only primary container built. Note that although some firelines inside the fire container may not breach after engaged a fire, they could be engulfed by the fire and cannot be part of the final *r*POD container. POD, Potential fire Operational Delineation; *r*POD, response POD



probability. We record the total NVC inside the final fire container and the total crew hours needed to build all firelines for each scenario (Figure 7). We start our tests under the *low fireline holding probability (LowHP)* assumption. Both the *Incident Inspired* and the *System-Level* redundancy plans yield significantly lower fire losses (Table 4). The *Incident Inspired* contingency plan requires significantly more crew hours than both the *Primary Only* and the *System-Level* plans. The *System-Level* contingency plan performs reasonably well under the *LowHP* assumption as it requires significantly fewer crew hours than the *Primary Only* plan.

Scatter plots in Figure 7 display the total NVC in the final container and total crew hours needed to suppress fire for every random scenario tested. Due to the uncertainties around fireline breaching events, no individual contingency plan can always guarantee a lower fire loss than the *Primary Only* plan. In other words, no containment strategy would always perform better than the response only strategy. However, we often observe lower fire loss from a subset of random scenarios when contingency plans are in place. Specifically, about one-sixth of the tested random scenarios under the *System-Level* contingency plan leads to lower fire loss and require fewer crew hours at final fire containment when compared with the *Primary Only* plan. The crew hour requirement from the *Incident Inspired* contingency plan is typically higher than the other two fire containment strategies, but more than half of the tested random scenarios under the *Incident Inspired* contingency plan result in lower fire losses when compared with the *Primary Only* plan.

5.3 | Contingency plan effectiveness in a less risky system

In a set of follow-up tests, we analyze containment plan efficiencies under a *higher fireline holding probability* assumption (referred to as “*HighHP*” in Table 2). We again evaluate the three fire containment strategies: *Primary Only*, *System-Level*, and *Incident Inspired* contingencies (Figure 7). Test results show no significant decrease in total fire loss from either the *Incident Inspired* or the *System-Level* contingency plan as compared with the *Primary Only* strategy. However, there are significantly more crew hours spent to build all firelines when implementing either contingency plan comparing with the *Primary Only* strategy. This suggests that when the overall risk of fireline breaching is low in a POD network, managers may be able to efficiently contain a fire by simply responding to less frequent fireline breaches. In addition, we observe smaller variances (Figure 7) regarding both fire loss and crew hour requirements across all random scenarios in the *HighHP* test cases; this is likely due to the lower levels of uncertainty that resulted from a system with lower fireline breaching risks.

5.4 | Impact from contingency line quality

Tests presented so far (shown in Figure 7) assume that contingency lines would be more likely to hold than the other line types under otherwise same conditions due to either more time, safer operation condition, or better preparation. Unfortunately, we currently do not have a model to quantify such a phenomenon. Instead, we start from a baseline assumption that the probability of holding a contingency line is twice of a primary line when building along the same POD boundary. This assumption is then varied by lowering the contingency line holding probabilities. We rerun the “*LowHP*” (Table 2) test cases under those varied assumptions for the three fire containment

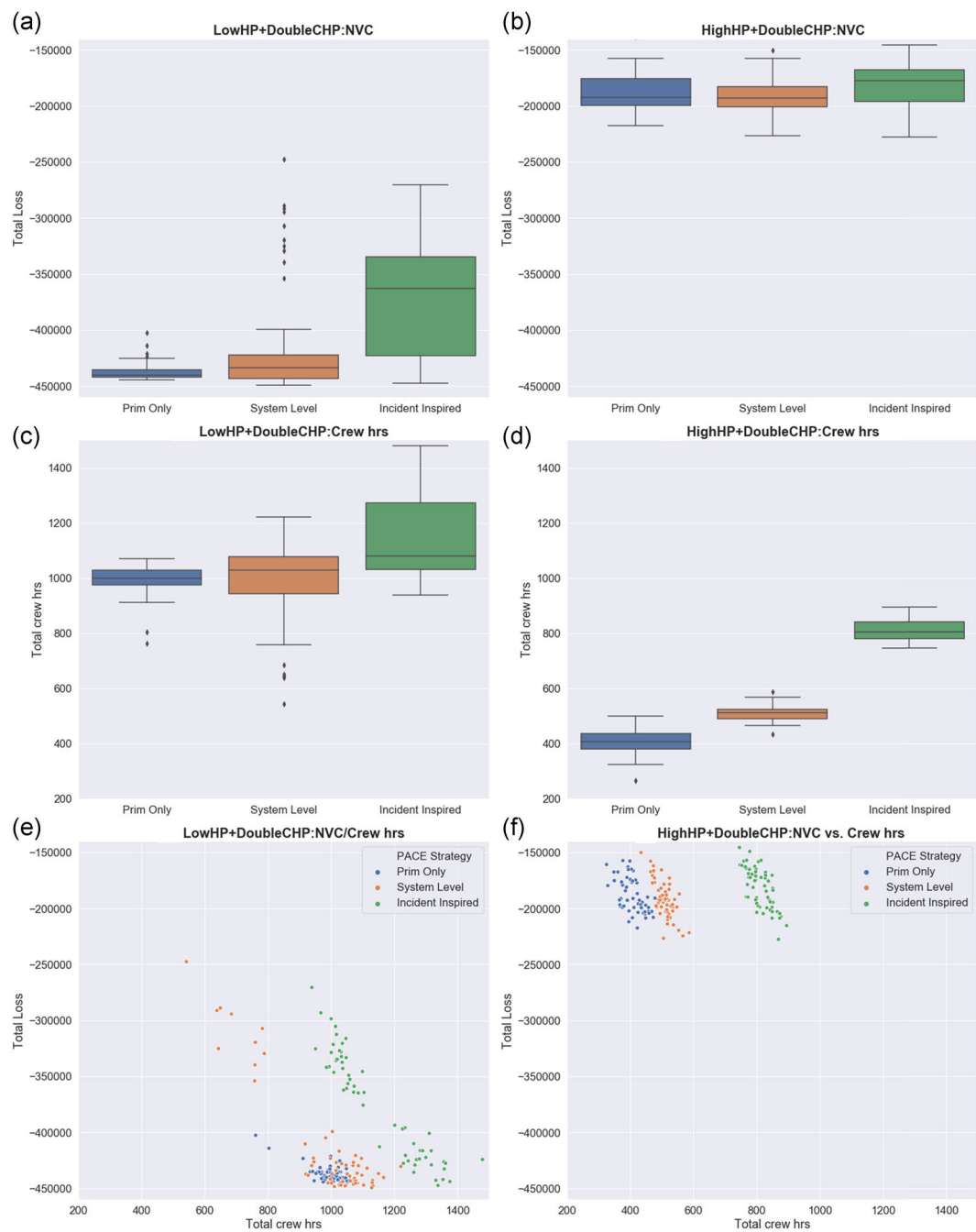


FIGURE 7 Comparison of the total NVC and total crew hours needed for three containment strategies under both the *Low* line holding probability (*LowHP*; represented by the three panels on the left) and *High* line holding probability (*HighHP*; represented by the three panels on the right) assumptions. DoubleCHP, doubled contingency line holding probability; NVC, net value change



TABLE 4 The *t*-test used to compare the total NVC, or the total crew hour spent on line construction between fireline construction strategies (comparing the plan listed in each row to the plan listed in each column) either from the *LowHP* test case (nonshaded cell) or from the *HighHP* test case (shaded cells)

	<i>Primary only</i>	<i>System Level contingency</i>	<i>Incident Inspired contingency</i>
Total NVC			
<i>Primary only</i>		$t = -3.56$ $p = 0.0007^{***}$	$t = -10.29$ $p = 0.0000^{***}$
<i>System level contingency</i>	$t = -1.28$ $p = 0.2046$		$t = -4.57$ $p = 0.0000^{***}$
<i>Incident inspired contingency</i>	$t = 2.1531$ $p = 0.0337^*$	$t = 3.39$ $p = 0.0010^{***}$	
Crew hours			
<i>Primary only</i>		$t = 0.37$ $p = 0.7122$	$t = -7.6819$ $p = 0.0000^{***}$
<i>System Level contingency</i>	$t = 15.43$ $p = 0.0000^{***}$		$t = -5.98$ $p = 0.0000^{***}$
<i>Incident inspired contingency</i>	$t = 55.62$ $p = 0.0000^{***}$	$t = 51.53$ $p = 0.0000^{***}$	

Significance level: * 0.05, *** <0.001

Abbreviations: HighHP, High line holding probability; LowHP, Low line holding probability; NVC, net value change.

strategies: *Primary Only*, *System-Level*, and *Incident Inspired* contingencies. Without surprise, we discover that the benefits of building contingency lines to lower fire loss decline when the probability of a contingency fireline holding decreases (Figure 8).

5.5 | Targeted contingency plans

Our test cases show that *System-Level* contingency could be effective in lowering fire loss in a POD network when fireline breaching risks are high. When there are not enough suppression resources to complete a *System-Level* contingency container, an alternative method is to implement a *Targeted* contingency plan (Table 2) to back up only those primary lines with lower holding probabilities while relying on the response lines to manage other line-breaching events. We conduct a set of sensitivity tests to evaluate the effect of different levels of *Targeted* plans. Specifically, we assume only primary lines with less than the 0.1, 0.2, 0.4, 0.6, or 0.8 holding probability threshold are backed up by contingency lines. Increasing the threshold means

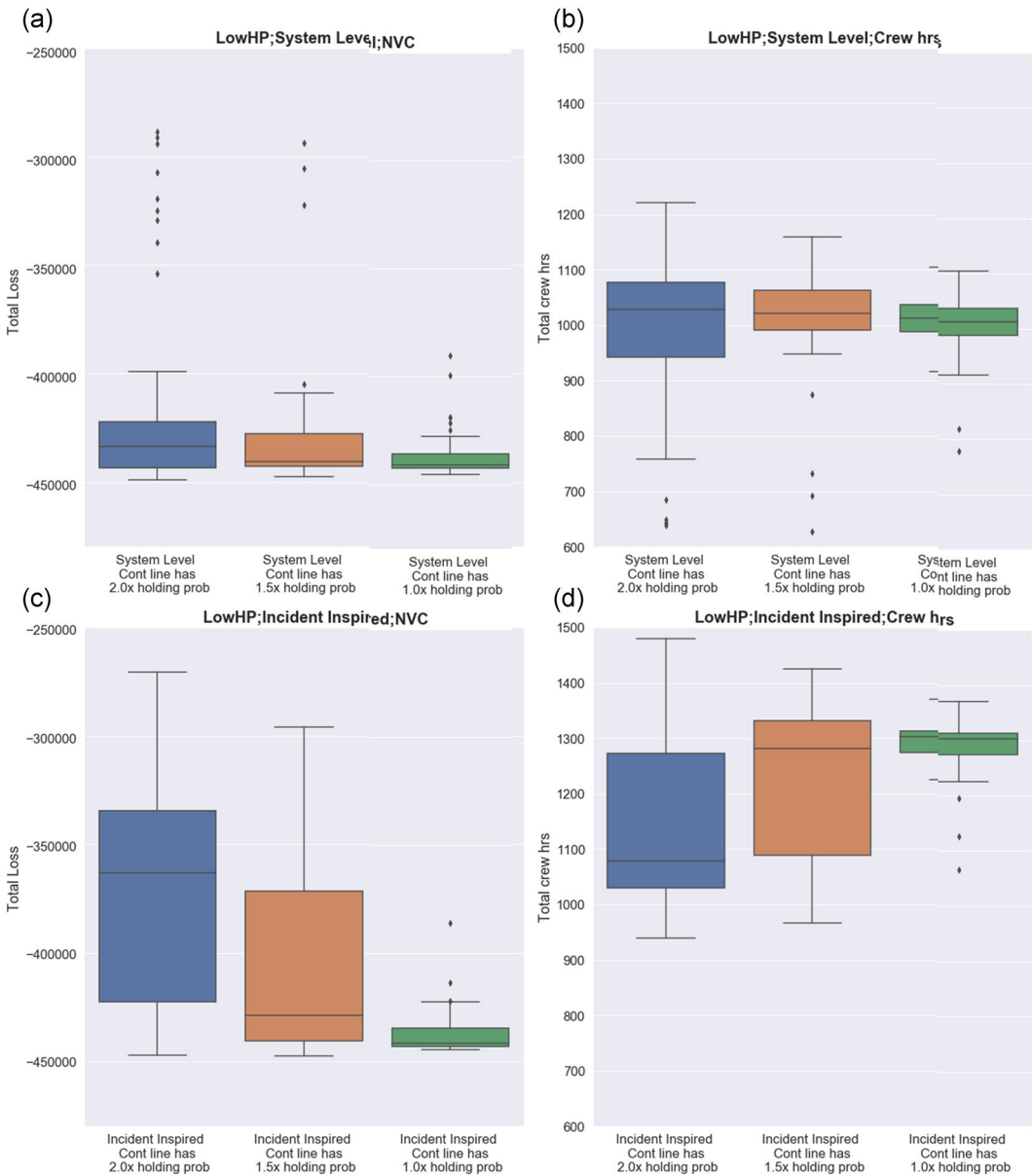


FIGURE 8 Test the impact of contingency line holding probability assumptions. Panels (a) and (b) illustrate results under the *Low line holding probability (LowHP)* assumption; Panels (c) and (d) illustrate results under the *High line holding probability (HighHP)* assumption. Tested multiple assumptions are: if a fireline were built as a contingency line, its probability of holding would either be doubled (*2.0×holding probability*), 1.5 time higher (*1.5×holding prob*), or equal to (*1.0×holding prob*) its probability of holding if it were built as primary or response lines. NVC, net value change

backing up more primary firelines. Tests (Figure 9) demonstrate the benefits of *Targeted* contingency are low until about one-third of the highest risk primary lines is backed up. *Targeted* contingency approaches the protection benefit of *System-Level* contingency when the primary line holding probability threshold is increased to 0.8.

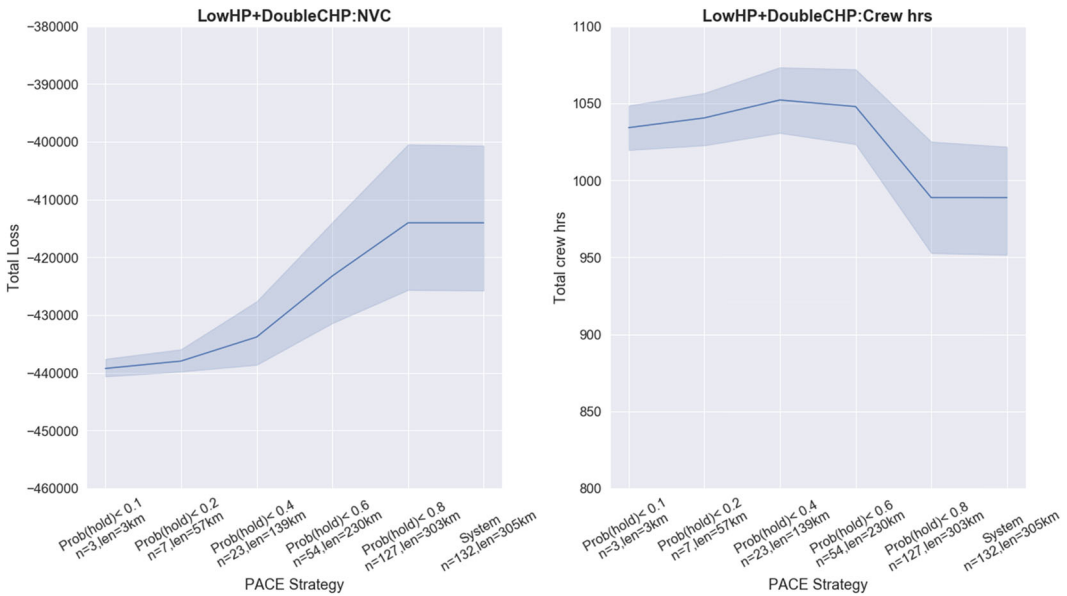


FIGURE 9 Comparison of the NVC (left panel) and crew hours (right panel) needed for contingency plans ranging from the *System* level to several *Targeted* plans. For example, the Prob(hold)<0.8 represents a contingency strategy in which we build contingency containers to target all primary lines with <80% of chance being held (n denotes the number of primary lines supported by contingency lines; len = 303 km denotes total length of primary lines backed up by contingency lines). NVC, net value change

5.6 | Computation time for the MIP model

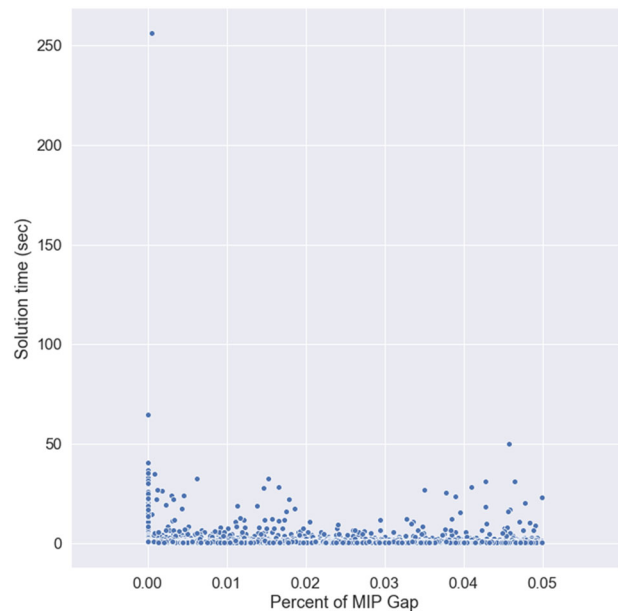
Extensive computation time requirement is a common concern with MIP models. Although running an MIP model to find the optimal solution is certainly desired (Minas et al., 2012; van der Merwe et al., 2015), finding good feasible solutions are often a practical compromise when we need to model a wildfire suppression system with nearly infinite variations (Finney, 2020). Because our rPOD model must be run over many scenarios and potentially multiple iterations for each scenario, each single MIP run must be run relatively quickly. Therefore, we set up the allowed maximum relative MIP gap to be 5% for all model runs for all test cases. The scatter plot of the MIP solution times and relative gaps (Figure 10) for the test cases shows that most of the MIP runs finished within 1 min with a solution value of no less than 5% of the upper bound on a potential optimal solution.

6 | CONCLUSION AND DISCUSSION

This study focuses on an important but less studied large fire contingency plan decision problem. We introduced a systems analysis conceptual framework to evaluate contingency plans and studied the tradeoffs between fire loss and suppression effort by adding redundancy into a POD-based fireline network. Given the risk of fireline breaching, managers can respond retroactively to observed line-breaching events by building response lines, or they can proactively build contingency lines before an observed line-breaching event. Building proactive contingency lines may give managers more time to build higher quality lines under safer working conditions, which may



FIGURE 10 Reported MIP relative gap and the computer solution time for all MIP model runs for the *Primary Only*, *Systems Level*, and *Incident Inspired* contingency plans in the *LowHP+DoubleCHP* test cases. The MIP relative gap is set to be no more than 5% during all runs. DoubleCHP, Doubled contingency line holding probability; LowHP, Low line holding probability; MIP, mixed integer programming



subsequently increase fireline holding probabilities. However, building contingency lines often requires additional suppression effort; some contingency lines may not engage with the fire.

In this study, we compare the effectiveness of three types of contingency plans and the response only strategy, that is, an *Incident Inspired* plan from the Ferguson Fire operations, a *System-Level* contingency plan to back up all primary lines, and plans *Targeted* at a portion of the primary container. We simulate random fireline breaching events to create hypothetical random scenarios and compare their variances in fire loss and crew hours spent. The *System-Level* plan includes a single layer of contingency firelines outside of the primary container. Its advantage is fire breached from any part of the primary container would encounter the contingency container. The *Incident Inspired* contingency plan includes an almost complete contingency container outside of the primary container, plus extra firelines between the primary and contingency containers; it is effective in reducing fire loss but requires more crew hours. We compare contingency plans at two levels of hypothetical fireline breaching risk. A set of test cases show that, if the breaching risk in a fireline network is high, it could be more efficient to build contingency lines to back up a larger portion of the high-risk primary container. We also found that no contingency strategy could outperform the other strategies in all random scenarios. Fire managers may select different containment strategies based on their risk preference, sensitivity to resource costs, suppression resource availability, or firefighter safety concerns. Understanding the variability in suppression costs and benefits from implementing different strategies would help managers make better-informed decisions.

Much work remains to improve models like this for future operational use. Our model sensitivity to assumptions about the magnitude of breaching risk suggests this is a high priority research area. As noted in the methods, the logistic regression model used to predict probability of line holding based on minimum PCL and line length is based on a small sample size and has lower accuracy than desired for operational use. This line-breaching model could be improved by investigating finer-scale and better-synchronized data on fire weather and fire suppression activities, and its application could be improved by tailoring predictions to the changing conditions throughout the duration of the



incident. For example, the likelihood of spotting is part of the PCL calculation. However, to explicitly model spotting risk, we should collect more detailed data, such as spotting locations, timing, and synchronized weathers. We could calculate a separate spotting index and use it together with PCL to fit prediction models. Similar improvements could be made to better align our NVC, fireline production rates, and predicted travel times to the realities of the incident using forecasted weather conditions and resource availability. None of these data improvement requests is new, but the process of collecting high-quality data and using them to support fire weather forecasting, estimating fire spread, and support suppression decisions is difficult and requires significant investment.

POD boundaries used in this study are natural or human-made barriers that serve as candidate fireline locations for safer and more effective suppression. Using PODs allows us to build models that are more relevant to the real-world fire operations (O'Connor & Calkin, 2019; O'Connor et al., 2016; Thompson et al., 2016; Thompson et al., 2018b). We test the concept of using the MTT formulation in an rPOD MIP model to dynamically track coarse-scale fire arrival times. Preliminary model results show that MTT can capture the influence of firelines on fire spread and fire arrival time. However, PODs are often in irregular shapes. Large PODs are not ideal for tracking fire spread. Future research should focus on refining the use of MTT within a POD network. For example, we believe that fire spread can be modeled more accurately at finer resolutions with smaller POD sizes.

Realistically predicting fireline breaching events represents another major challenge in fireline effectiveness analysis for large fire suppression. Our current test cases assume independent fireline breaching events with each of them occurred according to an estimated line holding probability. The occurrence of fireline breaching would likely be much more complicated. For example, when managers are determined to stop a fire from destroying a community or entering a nearby private land, they may put more efforts into building higher quality lines to improve the line holding probability. In other cases, managers may abandon a held line if they anticipate that fire will circle around it. Fireline breaching probability would also vary by fire spread directions, or the direction a fire engaging a line. To support tactical fire suppression operation, studying the joint or conditional probabilities of multiple fireline breaching and holding would be important. Ideally, we want to develop models to dynamically update fireline breaching probabilities across a POD network using updated weather forecasts and suppression resource availabilities.

Our study tests a conceptual modeling process to evaluate strategic contingency line construction plans and derive general rules to improve those plans. From a broader fire risk management aspect (Rodríguez-Martínez & Vitoriano, 2020; Thompson et al., 2019), adding redundant lines into a fire suppression system would reduce the overall system risks and improve the safety and effectiveness of fire operations. While future research is still needed to improve data quality, achieve better data synchronization and improve model resolution, we believe developing a systems analysis approach and using them to support fire risk management may yield new knowledge to support better fire risk management.

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AUTHOR CONTRIBUTIONS

Yu Wei designed modeling procedure to compare contingency plan efficiencies; wrote computer code to process data and conducted the tests; drafted and edited the manuscript.

Matthew P Thompson defined and selected the research problem for contingency plan evaluation; organized the data collection process; provided suggestions to the model design and testing procedure; reviewed and revised the manuscript.

Erin Belval provided suggestions to the testing method; reviewed test results; revised and edited the draft manuscript.

Benjamin Gannon provided data to support the logistic regression model to estimate fireline holding probability; reviewed the test results; revised and edited the draft manuscript.

David E Calkin helped to define, select, and approve the research direction; managed the USFS funding to support this project.

Christopher D O'Connor provided spatial data (PCL, NVC, SDI, and RTC maps) to support the analysis; provided suggestions of the analysis method and results.

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APPENDIX A

We tested several logistic regression models based on 2770 firelines by using different combinations of the following fireline attributes:

- *MinPCL and MeanPCL*: The lowest and average PCL of all raster cells along the buffered area of a fireline.
- *MaxSDI and MeanSDI*: The highest and average SDI of all raster cells along the buffered area of a fireline.
- *Area*: The buffered area along each fireline.

The summary statistics of the fireline attributes are given in Table A1, the performance of some of the tested candidate logistic regression models is given in Table A2, and the impact of sequentially adding each predictor variable is displayed in Table A3.

TABLE A1 Fireline attribute data used to estimate fireline holding probabilities

	Min.	Max.	Mean	Std.
MaxSDI	0	1.7783	0.5161	0.3999
MeanSDI	0	1.4542	0.3271	0.2992
MinPCL	0.0067	0.9963	0.2064	0.1523
MeanPCL	0.0067	0.9966	0.2931	0.1722
Area buffered along each line	73	415,457	14,678	29,641
# Of lines from each fire	Lolo Peak, 419; Meyers, 66; Milli, 83; Rice Ridge, 376; South Umpqua Complex, 1541; Sunrise, 285			
Line status	Breached, 827; Held, 1943			

Abbreviations: PCL, Potential Control Line suitability; SDI, Suppression Difficulty Index.



TABLE A2 The tested logistic regression models used to estimate the probability of fireline holding

Model seq.	Candidate model	Model coefficients and performance measures				
1	Line holding probability = f (MinPCL, Area)	Estimate	Std. Error	z Value	Pr(> z)	
	(Intercept)	1.042e + 00	8.647e - 02	12.05	<2e - 16***	
	MinPCL	7.382e - 01	3.114e - 01	2.37	0.0178*	
	Area	-2.267e - 05	2.249e - 06	-10.08	<2e - 16***	
	Null deviance: 3377.4 on 2769			Degrees of freedom		
	Residual deviance: 3192.2 on 2767			Degrees of freedom		
	AIC: 3198.2					
2	Line holding probability = f (MinPCL, MaxSDI, Area)	Estimate	Std. Error	z Value	Pr(> z)	
	(Intercept)	9.737e - 01	1.072e - 01	9.086	<2e - 16***	
	MinPCL	7.974e - 01	3.165e - 01	2.519	0.0118*	
	MaxSDI	1.211e - 01	1.128e - 01	1.073	0.2831	
	Area	-2.310e - 05	2.292e - 06	-10.080	<2e - 16***	
	Null deviance: 3377.4 on 2769			Degrees of freedom		
	Residual deviance: 3191.1 on 2766			Degrees of freedom		
	AIC: 3199.1					
3	Line holding probability = f (MeanPCL, MeanSDI, Area)	Estimate	Std. Error	z Value	Pr(> z)	
	(Intercept)	0.9321420	0.1118020	8.337	<2e - 16***	
	MeanPCL	0.3970310	0.2600494	1.527	0.12682	
	MeanSDI	0.4844609	0.1552924	3.120	0.00181**	
	Area	-0.0000235	0.0000022	-10.681	<2e - 16***	
	Null deviance: 3377.4 on 2769			Degrees of freedom		
	Residual deviance: 3187.2 on 2766			Degrees of freedom		
	AIC: 3195.2					

(Continues)

TABLE A2 (Continued)

Model seq.	Candidate model	Model coefficients and performance measures				
4	Line holding probability = f (MinPCL, MaxSDI)	Coefficients:				
		(Intercept)	Estimate	Std. Error	z Value	Pr(> z)
		MeanPCL	0.9656	0.1072	9.006	<2e - 16***
		MaxSDI	0.1098	0.2479	0.443	0.65787
			-0.2733	0.1045	-2.616	0.00889**
		Null deviance: 3377.4 on 2769				
		Residual deviance: 3369.7 on 2767				
		AIC: 3375.7				
					Degrees of freedom	
					Degrees of freedom	

Note: The 1st model (highlighted as bold) is selected due to its lower AIC estimator value and the correct sign of each predictor variable (e.g., a positive coefficient for MinPCL and a negative coefficient for Area). Although the 2nd and the 3rd model both have an AIC value close to the 1st model, the sign of their coefficients for SDI is wrong (higher SDI should decrease the probability of a fireline holding), which indicate potential autocorrelations between SDI and PCL measurements.

Abbreviations: AIC, Akaike Information Criterion; PCL, Potential Control Line suitability; SDI, Suppression Difficulty Index.

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.



TABLE A3 Use the anova() function from R to analyze the table of deviance

Analysis of deviance table Model: binomial; link: logit Response: Outcome							
Terms added sequentially (first to last)							
	Df.	Deviance	Resid.	Df.	Resid.	Dev.	Pr(>Chi)
Null				2769	3377.4		
MinPCL	1	33.497		2768	3343.9	7.136e − 09	***
Area	1	151.650		2767	3192.2	<2.2e − 16	***
MeanPCL	1	4.902		2766	3187.3	0.02682	*
MaxSDI	1	0.876		2765	3186.5	0.34917	
MeanSDI	1	19.001		2764	3167.5	1.306e − 05	***

Note: The table shows significant drops in deviance when adding MinPCL and Area. Adding the other variables has less significant impact.
Abbreviations: PCL, Potential Control Line suitability; SDI, Suppression Difficulty Index.
Signif. codes: '***' 0.001 '**' 0.05 '*' 0.1.