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Wildfire Response Decision Making, Risk, and Interactions with Fuels Management in
California

By

Andrew Swan Johnson

A dissertation submitted in partial satisfaction of the
requirements for the degree of

Doctor of Philosophy

in

Environmental Science, Policy, and Management

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Scott Stephens, Co-Chair

Professor Brandon Collins, Co-Chair

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PhD Stephen Fillmore

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Abstract

How Wildland Fuels Management Influences Decision Making and Risk During Wildfire

Response

by

Andrew Swan Johnson

Doctor of Philosophy in Environmental Science, Policy, and Management

Professor Scott Stephens, Co-Chair

Professor Brandon Collins, Co-Chair

Decisions made during and in preparation for wildland fires are dictated by many factors including the existing fuel profiles that determine fire behavior and fire perimeter access, both of which influence the decision space available to practitioners, safety concerns, and the ability to control fire spread. The following four chapters provide insight into how preventative management of wildland fuels impact operational decision making and quantified risk across large areas.

First, I examine linear fuel breaks, a common fuel treatment type designed to be used by firefighters. Linear fuel breaks are constructed for landscape fire management and to protect highly valued resources when staffed by firefighters. Despite common implementation, controversy exists due to negative externalities and lack of clearly demonstrated effectiveness. Using input from practitioners, I determine how fuel breaks are planned, used, and how the outcomes they provide shape future implementation. I distributed a questionnaire to fire and fuels managers in California to determine end-user considerations during planning, construction, and fire response to provide detail to their diverse fire management applications. I created a descriptive decision-making framework for managers using fuel breaks that includes themes related to planning, construction, uses, outcomes, mediating factors, and general attitudes towards fuel breaks. Evaluations are determined by managers' attitudes towards fuel breaks, which is influenced by previous experiences and landscape considerations, influencing future treatment design. During planning, environmental factors and preferred uses are incorporated into construction. While using fuel breaks, managers leverage altered fire behavior to increase first responder safety and the number of plausibly initiated tactics due to the reduced risk profile, varied temporal considerations, and altered fire trajectories. Based on our findings, I propose alternative methods of measuring fuel break efficacy and discuss the placement of linear treatments in broader land management strategies.

Second, I quantify the risk reductions provided by fuel breaks. This study presents a framework to assess how fuel break configuration, arrangement, and firefighter tactics influence control opportunities using a new spatial metric for Uncontrollable Wildfire Risk (UWR). UWR

combines outputs from fire modeling software widely available to fire and land management practitioners with suppression difficulty weights derived from previous literature. Fire spread simulations were conducted across four case study fuel break configurations in Southern California: Single Segment, Branching Network, Enclosed Network, and Multiple Segment Network. Three leverage scenarios representing different levels of suppression intervention (unstaffed, firebreak, and firing operations) were applied to each landscape. Linear mixed effects models and spatial analysis quantified the effects of distance from treatment, wind alignment, topography, treatment width, length, sinuosity, and proximity to other treatments on UWR. Results showed that increased leverage intensity consistently reduced UWR, while treatment geometry and spatial arrangement influenced risk reduction in some models. Notably, in some instances unstaffed fuel breaks increased burned area due to changes in fuel characteristics and subsequent fire behavior. This research highlights the importance of selecting appropriate outcomes for wildfire modeling evaluations of fuel break placement and operational utilization.

Third, I investigate the tactical decision factors, processes, and outcomes on the 2021 Caldor Fire. The Caldor Fire destroyed 1,003 structures while costing \$1.2 billion USD for suppression and recovery. Although these losses were substantial, statements from state and federal firefighting agencies indicate the worst potential impacts were avoided because of effective pre-fire fuels management and incident response. I interviewed fireline supervisors to investigate incident response decisions and the use of fuel treatments on the Caldor Fire. I conducted event-centered interviews using an ArcGIS Online map application as a visual-elicitation tool to determine: 1) What were the tactical decision-making processes and their contributing factors, and 2) how fuel treatments were incorporated into decisions. Based on interviews, I outlined a framework for tactical decision-making beginning with five criteria: operational, environmental, resource, risk, and institutional factors. Factors fed into three decision processes: sequencing actions, reactive or anticipatory, which were in pursuit of three primary objectives: protection of property and life, perimeter control, and holding pre-established containment line. Treatment characteristics and local knowledge determined whether fuel treatments were incorporated into tactical decisions. When incorporated, treatments increased containment effectiveness, resource efficiency, and firefighter safety. This work adds to the body of knowledge on incident decision making, indicating how time pressure, uncertainty, and pre-fire mitigation influence the planning and sequencing of tactical actions.

Fourth, I explore how the decisions outlined in chapter 3 changed over time on the 2021 Caldor Fire. Operations on the Caldor Fire were complicated by extreme fire behavior and threats toward valuable resources. Outcomes varied over time, reflecting the influence of incident management. To examine how decisions on the Caldor Fire changed over time I describe the sequence of fire management operations in detail, eliciting detailed information on changing decisions and outcomes. I segmented the fire into four Operational Phases using fire progression and official documentation. I then conducted event-centered interviews using an ArcGIS Online map application as a visual-elicitation tool to determine how decisions changed over time. Changing decisions over time demonstrated how incident management decreased uncertainty for tactical decision makers. Reactive decisions dominated during early phases of the fire when there were notable impacts on the community of Grizzly Flats when the incident was being managed locally, and the fire grew rapidly. When extreme fire behavior occurred over a week later, after an Incident Management Team had been in place for a week, interviewees generally continued to

make anticipatory decisions. The analysis of decision making over time demonstrates how fire governance can improve large fire management outcomes and where more structured decision making could improve future outcomes.

For my family and friends. For those who do the work.

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1 INTRODUCTION

Wildfire maintains most North American ecosystems by returning periodically to reduce competition and stimulate reproduction (Hagmann *et al.*, 2021). While often framed as a natural process, modern research including the incorporation of Traditional Ecological Knowledge has shown that the frequency of ignitions necessary to maintain many historical ecosystems was likely not possible from naturally occurring ignitions alone (Bowman *et al.*, 2020; Hagmann *et al.*, 2021). In modern times, beneficial fire cycles have been replaced by less frequent, large wildfires, often featuring adverse impacts on ecosystems and human values (Calkin *et al.*, 2005; Bowman *et al.*, 2020). This paradigm is also a product of human action, leading to increased ignitions during adverse weather conditions, fire exclusion via the removal of Indigenous burning and fire suppression, and climate change (Stephens and Ruth, 2005; Keeley and Syphard, 2025). The contemporary and historical wildfire regimes of North America are therefore not free from human influence, or at least they have not been for many millennia (Bowman *et al.*, 2020). Rather they are an attempt by society to manipulate ecosystems to maximize services, and therefore are best explained as a linked human-natural system (Thompson, 2013).

This explains the motivation of this dissertation, which focuses on fire management in California. Modern fire management encompasses numerous institutions and practices with the goal of managing landscapes, preventatively reducing wildfire risk, and improving wildfire response (Stephens and Ruth, 2005; North *et al.*, 2015). In California, federal and state policies occasionally clash, and sometimes complement one another (USDA, 2020). The state (CAL FIRE) and federal (Forest Service, National Park Service, Bureau of Land Management, Fish and Wildlife Service, Bureau of Indian Affairs) agencies both practice proactive fuels management while managing wildfire response in distinctly different ways (Starrs *et al.*, 2018).

In this dissertation, I focus primarily on CAL FIRE and the US Forest Service. Both agencies must navigate complex regulatory environments to achieve their goals, such as the federal National Environmental Policy Act and its state-level equivalent, the California Environmental Quality Act, which mandate environmental review for land management projects (USDA, 2020; Kooistra *et al.*, 2021). While the federal agencies manage federal land, CAL FIRE is responsible for fuels reduction on private and state lands. Both agencies tend to conduct fuels management for the same objectives, to reduce wildfire risk and restore ecosystems (Starrs *et al.*, 2018; Kooistra *et al.*, 2021).

Linear fuel breaks are one type of fuel treatment commonly selected to achieve these objectives, although evaluations of their success must be in accordance with their objectives (Green and Schimke, 1971; Green, 1977). While linear treatments are always constructed with wildfire containment during incident response as an objective, in formerly frequent fire forested systems, linear fuel breaks may be constructed through forest thinning, offering a co-benefit of restoration to historical tree densities (Green and Schimke, 1971; Baijnath-Rodino *et al.*, 2023). In shrub systems, fuel break construction imposes some well-established negative ecological impacts, such as vegetation type conversion and the introduction of invasive species (Merriam *et al.*, 2006; Keeley, 2006; Shinneman *et al.*, 2019). Despite these known negative externalities and moderate effectiveness in halting fire spread (often measured just below 50%), land management

agencies continue to construct these treatments (Syphard *et al.*, 2011; Gannon *et al.*, 2023). Therein presents important questions which are the subject of chapter 1 – Why do land managers employed by state and federal agencies construct fuel breaks? How do they think about them? And what benefits do they provide? Chapter 2, extends the theories described in chapter 1 to the quantitative realm. There, I use fire spread modeling and categorized fuel break configurations to examine how fuel breaks, when used or “leveraged” in different ways, or are unstaffed by firefighters, influence fire risk?

Fuel breaks exemplify the human-natural systems intersecting fire management and the contentions they pose. Through exploring their meaning and use to fire management personnel, we may begin to understand the complex tradeoffs required to manage wildfire under the often-conflicting goals land managers face when tasked with ecosystem restoration and community protection. While my investigations of fuel breaks shed light on these questions, they are more thoroughly explored in the context of large wildfire management in my final two chapters.

Large wildfires typical of contemporary fire regimes are responsible for approximately 95-98% of the area burned in an average year (Calkin *et al.*, 2005). These conditions are the consequence of a “fire paradox”, where we have become so adept at extinguishing wildfires that the fires escaping initial containment efforts are much more likely to become devastating due to the conditions under which they occur (Kreider *et al.*, 2024). Once initiated, large wildfires require complex management approaches by multiple stakeholders as they impact different jurisdictions and threaten diverse ranges of valuable resources (Thompson, 2013; Dunn *et al.*, 2017; Fillmore *et al.*, 2024). Large wildfire strategy, whether to fully suppress or manage wildfires for multiple objectives, is well studied under rational choice and humanistic approaches (Calkin *et al.*, 2013; Wibbenmeyer *et al.*, 2013; Fillmore *et al.*, 2024). Of interest in the following chapters are the tactical decisions made by on-the-ground supervisors during large fire management and how these decisions are impacted by incident management and the presence of fuels reduction projects. Fireline supervisors must process large amounts of information to make decisions. While there are currently a large number of digitalized decision support tools to assist in this process, it is of particular interest regarding what cues managers use to make decisions, how these cues interact with uncertainty during response, and how these dynamics change over time.

The breadth of the writing below is the product of an honest effort towards understanding the multiple definitions and lenses through which the wildfire problem is viewed. Predominant research methodologies take a purely social or physical approach to this problem. Interdisciplinary approaches, while time consuming and labor-intensive, may shed more light on these complex phenomena, providing needed information for researchers and managers addressing problems that will impact the lives and livelihoods of many in California.

2 LEVERAGING AN OPEN-ENDED QUESTIONNAIRE TO CREATE AN EXPLORATORY DECISION-MAKING FRAMEWORK FOR MANAGERS USING FUEL BREAKS IN CALIFORNIA

2.1 INTRODUCTION

Globally, increased occurrences of catastrophic wildfires linked to climate change and land management practices have caused ecological harm and the destruction of assets (Bowman *et al.*, 2020; Jones *et al.*, 2022). In the Western US, past management and fire exclusion have amplified the problem by altering wildland fuels (Keeley *et al.*, 2009; Hagmann *et al.*, 2021), while fire seasons have become longer, warmer, and drier (Abatzoglou and Williams, 2016), contributing to unprecedented workforce attrition (Granberg *et al.*, 2023; Belval *et al.*, 2024). Responsive pledges to increase preventative management have spurred recent investments at the federal and state levels (US Department of Agriculture and State of California, 2020; Ager, 2022; The White House, 2023). Recent federal legislation such as the Bipartisan Infrastructure Law and the Inflation Reduction Act fund policies that expedite treatment implementation including the Wildfire Crisis Strategy Landscapes and the Collaborative Wildfire Risk Reduction Program (US Department of Agriculture, 2024). Concurrently, state governments have increased their capacity for fire mitigation with new initiatives, including leveraging of existing funds (US Department of Agriculture and State of California, 2020; Kooistra *et al.*, 2022).

Managing wildland fuels requires the context-dependent selection of fuel treatment types to match desired outcomes, such as resilience or risk reduction (Agee and Skinner, 2005; Collins *et al.*, 2010; Vorster *et al.*, 2024). One option, linear fuel breaks, are strips of flammable fuels permanently converted to lighter fuels at strategic locations to increase ease of fire control, provide access to firefighting resources, and improve safety (Green, 1971; Green, 1977). These treatments are implemented across different fuel types although the intended purpose remains the same. Shaded fuel breaks, typically constructed in historically frequent-fire forested systems retain some canopy cover to maintain ecosystem function following treatment (Green, 1971; Agee *et al.*, 2000). Other options for forested systems include ‘green belts’, where heavily managed strips of broad-leaved evergreen tree species with high fuel moistures and reduced surface fuels mitigate fire behavior (Wang *et al.*, 2021), or complete overstory removal (Green, 1971). Fuel breaks in crown-fire adapted shrub systems frequently involve complete removal of existing vegetation cover and type conversion to annual or perennial grasses (Green, 1977; Pellant, 1994; Monsen, 1994). Despite their long history of use, installing and maintaining linear fuel breaks can be controversial, particularly where the post-treatment vegetation condition does not align with the natural range of variability (Keeley, 2006; Shinneman *et al.*, 2019). While managers may select a single treatment type, recent prioritization of risk reduction in the wildland-urban interface promotes a model of integration (US Department of Agriculture, 2024), using fuel breaks as a point from which to expand other treatments (North *et al.*, 2021; Moritz *et al.*, 2022; Thompson *et al.*, 2022).

Previous examinations of fuel break effectiveness have explored treatment capacity to halt fire perimeter expansion and avoid losses. Southern California fuel breaks stop fires in 22-47% of measured instances depending on utilization by responding resources and fuel break condition (Syphard *et al.*, 2011; Gannon *et al.*, 2023). A similar study without fire response data

found a 58% success rate in the Great Basin (Weise *et al.*, 2023). Investigations of avoided losses have noted positive reductions in fire size, burn probability, exposure to structures, and ecological implications, albeit at a high ratio of area treated to avoided losses (Gray and Dickinson, 2016; Oliveira *et al.*, 2016; Aparicio *et al.*, 2022). Studies of shaded fuel breaks may examine the post-fire effects in a treatment's vicinity to determine the ability to limit severe wildfire impacts (Agee *et al.*, 2000; Baijnath-Rodino *et al.*, 2023). Additional research has assessed economic implications and optimization strategies such as encompassing the maximum number of structures (Davis, 1965; Grah and Long, 1971; Massada *et al.*, 2011). Renewed interest in fuel break implementation and integration into larger land management strategies necessitates holistic investigations of fuel break use and effectiveness.

To fill this gap, process-oriented examinations of the decisions that dictate fuel break selection and resulting outcomes are a relevant area for future research and the focus of this application. Previous fire management decision-making investigations belong to two complementary categories: prescriptive and descriptive research (Thompson, 2014). Prescriptive studies assume rationality and utility maximization, while deviations from these assumptions explain flawed decisions (Gigerenzer, 2020). This research has found managers to exhibit biases of loss aversion, discounting, and tending towards the status quo, resulting in heightened risk of employee exposure, suppression costs, and property loss (Wilson *et al.*, 2010; Calkin *et al.*, 2012; Wibbenmeyer *et al.*, 2013; Hand *et al.*, 2015). Conversely, descriptive studies avoid most binding assumptions by investigating manager decision making through procedurally focused investigations at the group or individual level and are frequently conducted in time constrained, high pressure environments (Lipshitz *et al.*, 2001; Klein *et al.*, 2003). Taynor *et al.*, (1990) studied fire managers in this context, finding individual decisions during wildfire management utilize pattern matching and mental simulation while decisions distributed across multiple decision-makers frequently occur relative to other high-pressure environments. Subsequent descriptive research has assessed fire management decisions by compiling relevant factors derived from interviews and investigated how managers use decision support tools in the field relative to their intended purposes (Rapp *et al.*, 2020; Fillmore and Paveglio, 2023; Fillmore *et al.*, 2024).

In the current application, we examine decisions around fuel breaks by assessing how managers think about, implement, and use these treatments. Our objectives are to understand:

- 1) Managers' attitudes and beliefs about fuel breaks.
- 2) Why fuel breaks are selected to reduce risk.
- 3) Manager preferences for planning and construction of fuel breaks.
- 4) Fuel break uses during fire response and subsequent outcomes.
- 5) Factors mediating fuel break effectiveness, according to managers.

To that end, we distributed an online questionnaire to managers in California, where intersecting risk factors have led to a common and historied practice of fuel break implementation (Pyne, 2016).

2.2 METHODS

2.2.1 Questionnaire

We distributed an online questionnaire via Qualtrics (Qualtrics, 2021) to fire and fuels managers in California responsible for fuel break administration or operations. The survey included closed-ended questions about fuel break characteristics, demographics, fire intersections, and locations or spatial data. Open-ended questions asked managers for construction and planning preferences, observations of altered fire behavior, perceptions of effectiveness, uses during fire response, risk reduction, changed resource efficiencies, and desired changes to existing treatments. Inquiries were constructed to assess attitudes and beliefs about fuel breaks and record end-user experiences at different stages throughout the life cycle of a single treatment.

Participants were instructed to answer all questions for a familiar fuel break and a single corresponding fire-fuel break interaction. If the fuel break had not intersected with a wildfire, respondents would skip the section on fire-fuel break operations to questions about general perceptions. Additionally, we asked participants to provide spatial data or fuel break locations and fire names to visualize fire fuel-break intersections. Archival data from the US Forest Service Forest Activity Tracking Systems (FACTS) and CAL FIRE was used to extract fuel break polygons using respondent-provided locations.

The questionnaire was distributed using a modified snowball sampling method in the Spring of 2021. Snowball sampling uses a small number of initial contacts who then share information about the study with their social network as well as provide researchers further potential contacts (Parker *et al.*, 2019). We leveraged researcher connections to enroll participation through initial contacts with the US Forest Service Region 5 fuels program and CAL FIRE Foresters. Respondents enrolled via initial contacts were asked to share the questionnaire with other fire and fuels managers in California responsible for fuel break administration or operations, creating a chain of participants. Additionally, the California Fire Science Consortium (<https://www.cafirescience.org/>) advertised the questionnaire via social media to enlist participants who would not be reached through state or Forest Service connections. Prior to distributing the survey, we raised awareness for the project by informing agency contacts, presenting to professional groups, and distributing an online video through the California Fire Science Consortium.

2.2.2 Analysis

We report on demographic data, fuel break characteristics, spatial data, and open-ended questions. Questionnaires were filtered based on a total completeness threshold of 66% and completion of open-ended answers. Demographic and fuel break characteristic data are presented descriptively, while some spatial data is presented relative to respondent descriptions of fire-fuel break intersections. Respondent position descriptions were broadly categorized and a responsibility level of fire engine operator was established as a lower threshold for inclusion in analysis (Table 1).

Qualitative analysis was completed with Nvivo 14 (Lumivero, 2014) using principles of grounded theory and an iterative three-stage coding process to reveal concurrent patterns throughout the data. Grounded theory provides a systematic process and theoretical foundation for researchers to construct theory from empirically observed qualitative data. The principles of grounded theory we used include inductive reasoning, constant comparison, iteration, abductive reasoning, and memo-writing (Glaser *et al.*, 1968; Charmaz, 2014). Our three-stage coding process began with topic coding. The data were then grouped into themes, which were reorganized and collapsed during the analytic coding stage (Boyatzis, 1998). Inductive and deductive logic were used to assign data to thirteen topic codes representing broad categories reflective of question topics and other patterns across responses. Deductive topic codes were derived from questions and assigned to responses with closely linked subject matter. Themes were induced by assigning the data under each topic code into eighty-nine categories, revealing detailed patterns across the data. Analytic coding was completed inductively by reorganizing topic codes and themes into an interconnected framework. Similarities revealed by comparison reduced the number of topic codes to 6 and themes to 23, while relationships between different topics were established from dependencies described in the data. Inter-coder consistency was assessed through periodic discussions establishing agreement and explaining variations in coding at each stage of the process (Thomas and Harden, 2008; O'Connor and Joffe, 2020).

2.3 RESULTS

2.3.1 Respondent and fuel break descriptions

A total of 89 questionnaires were completed, including thirty-five that met our criteria for analysis. Respondent employers included CAL FIRE, the US Forest Service, private industry, and City or County fire departments (Table 1). Respondents were distributed throughout the state with concentrations in Southern California, the western Sierra Nevada foothills, and the southern coast (Figure 1). Respondents provided information about the vegetation composition of 33 fuel breaks. Fuel break vegetation type included hardwood and conifer forests, shrubland, and grasses (Table 2). Most fuel breaks ($n = 25$) included multiple vegetation types.

2.3.2 Framework

We synthesized topics and themes discussed by respondents into a descriptive decision-making framework. The framework explores the cycle of how attitudes and beliefs about fuel breaks affect how fuel breaks are used in fire response, the outcomes of which then affect attitudes and beliefs (Figure 2). After making the decision to create a fuel break, a variety of factors influence the planning stage before managers construct and then maintain fuel breaks. When a fire approaches managers choose how to use the treatment to produce a specific outcome. Uses and outcomes are mediated by fire response and physical environment characteristics. Finally, this cycle feeds into how managers evaluate fuel breaks for future implementation. Evaluations, which consist of attitudes, beliefs, and landscape considerations, influence managers' willingness to select fuel breaks in the future and are combined with external factors and objectives to make future planning decisions (Table 3).

2.3.3 Planning

During fuel break planning managers consider the surrounding physical and social environment and determine design features (Figure 2, Table 3). Approximately two-thirds of managers stated that placement choices should be relative to factors that align to influence fire behavior. This includes locating treatments on topographic features where fire behavior naturally mitigates, like ridgetops or flat areas, but also considering interactions between these factors. For example, one manager stated that fuel breaks in areas with frequent strong winds required heavier fuel reduction, and others noted linear treatment should be placed at perpendicular angles to the prevailing wind direction. Other topographic variables frequently considered by respondents were aspect and slope steepness, with a few managers mentioning that north aspect placement improved outcomes.

About one-third of managers mentioned external influences from the public, policy, and other stakeholders on fuel break placement and construction. Some respondents viewed the public as a hindrance to completing and maintaining treatments. For example, multiple respondents described perceived aesthetic losses post-construction. However, some managers experienced positive public engagement when collaborating across land ownerships or found opportunities to engage the public by enrolling assistance in “adopt a highway”-like maintenance projects. Policy hurdles included restrictions intended to decrease environmental impacts, which made widening or maintaining fuel breaks challenging, potentially compromising community protection goals. Other managers wished for more inter and intra-agency collaboration to complete projects to decrease barriers from jurisdictional boundaries and funding limitations.

Incorporating fuel breaks into pre-suppression planning to improve fire response was mentioned by about one-third of managers. Several stated it was desirable to include design features that increased firefighter safety, such as pre-established safety zones and vehicle turnarounds. One respondent described their strategy to identify sites for water tanks at appropriate distances for pumping systems so that this time-consuming task was not performed during an incident. Other respondents emphasized planning for firefighter intervention by establishing well-placed access points, strategic placement for firing operations, or planning fuel breaks for use by specific resource combinations, such as with aircraft and ground forces. Multiple respondents also mentioned placement around roads due to implications for access and where ignitions are likely to occur. Tactical placement aligns with the recommendation from many managers that risk reduction is best achieved by strategically placing fuel breaks near structures, surrounding areas with high ignition risks, and dividing communities and landscapes from high fire risk zones. Other managers stressed that fuel break locations should be included in pre-attack maps, which can be shared with firefighters who may not be familiar with the area.

2.3.4 Construction and Maintenance

During the construction and maintenance stage managers execute plans by treating fuels and determining maintenance intervals based on ecosystem knowledge and previous experience (Figure 2, Table 3). Specific fuel treatment descriptions provided by approximately one-third of respondents included preferred treatment methods, preferences for fuel continuity disruption, and the conversion to fuels light enough for use by firefighting resources. Treatment methods included thinning, mastication, chipping, herbicide, broadcast burning, and pile burning.

Prescribed fire was frequently referenced with some acknowledgment that it was not always appropriate and would need to be combined with other methods to complete treatments. Others only discussed mechanical methods, frequently combined with specific objectives for fuel removal in various strata, emphasizing intense understory fuel removal and canopy disruption. Specific criteria for fuel continuity disruption differed by manager and respective fuel types with some favoring reductions in lighter fuels to slow fire spread, canopy disruption to increase aircraft effectiveness, removal of ladder fuels, or all three. Overall, it was implied that fuels should be light enough for firefighters to easily manage fire behavior, a point specifically mentioned by several respondents.

Over two-thirds of these managers emphasized the importance of maintenance for continued fuel break efficacy and expressed preferences for specific fuel break widths. Maintenance was the most frequently mentioned theme during this stage. Many respondents stated that maintenance, either lacking or regular, was the single reason for failure or success. There was widespread acknowledgment that without regular maintenance, the presence of a fuel break did not matter. However, one manager described successful use despite a lack of maintenance on a particular break. Generally, managers preferred wider treatments than currently exist due to improved firefighter protection and easier management of fire behavior.

2.3.5 Uses

Fuel break uses during fire management may be broadly categorized as leveraging strategic placement and altered fire behavior to improve safety and support firefighting tactics (Figure 2, Table 3). Contributions to safety include aiding evacuations, access/egress to the fire's edge, and increased visibility. Safety was seen as the product of having a "safe place to work from" produced by adequate fuel reduction and placement. Access and egress for firefighters were frequently mentioned because fuel breaks may act as safe corridors to deliver personnel to advantageous locations or provide escape routes. Similarly, fuel breaks support public evacuations in two ways: by attenuating fire behavior when placed across roadways, which allows community members to evacuate safely, and by delaying fire arrival, which increases the time available for escape. Other respondents noted that increased visibility of ground resources on a fuel break was useful for aerial resources and firefighters in lookout positions.

About two-thirds of respondents mentioned firefighting tactics typically used to leverage fuel breaks including indirect attack, structure protection, and direct attack. About half of these managers discussed using fuel breaks for indirect options such as firing operations, which were enhanced by strategic placement and the ability to begin well before the arrival of the main fire or adverse weather conditions due to reduced fuels. Other respondents described how fuel breaks near communities helped firefighters perform point protection by providing an altered fuel profile and improved access near structures. Notable was the infrequent (about one-fifth of these respondents) mention of direct line construction inside of fuel breaks. In these limited situations, firefighters capitalize on decreased fire behavior inside the treatment to construct a fireline against the fire's edge. Importantly, managers described these tactics as not mutually exclusive; the same fuel break could be used for multiple purposes, but adequate access was consistently a key factor.

Accordingly, fuel breaks are used by specific resources and resource combinations to increase effectiveness. A few respondents stated that combining fuel breaks and aircraft can functionally increase treatment width when water or retardant is applied on the lee side, increasing the chances of success for direct and indirect tactics performed by ground forces. Others noted that fuel breaks are generally used with specific combinations of resource types to increase effectiveness such as aircraft, bulldozers, and engines.

Other managers noted that decreased fire behavior in a fuel break was useful because it provided more options when engaging the fire. Respondents reported that reduced fire behavior and improved access granted opportunities for anchoring fireline construction to the fuel break or to use the treatment as a line's start and end point. If a fuel break was breached, a fire's flanks could be accessed and direct line construction could begin from the break, progressing into untreated fuels while using "one foot in the black" tactics where already consumed fuels act as a safety zone. Well-placed anchor points such as fuel breaks minimize the likelihood of a fire crossing the fireline's point of origin and outflanking firefighters as they progress along the fire's perimeter. Treatments can also contribute to escape routes if the circumstances become unmanageable for ground personnel while implementing direct tactics. Descriptions of fuel breaks as "a starting and stopping point" for line construction imply that the fire had been held at the break during firing operations or other indirect and parallel tactics.

2.3.6 Outcomes

Consequential outcomes are changes to the operational and fire environment produced by fuel break uses including increased operational effectiveness, altered temporal considerations, and mitigated risk (Figure 2, Figure 3, Table 3). These themes contain combinations of actual fuel break outcomes and perceived possible outcomes from respondents. Specific outcomes described by two-thirds of managers involve increased decision space, firefighter efficacy, and reduced risk to Highly Valued Resources or Assets (HVRAs). Respondents felt they had increased flexibility, i.e., decision space, when fuel breaks allowed them to complete tasks in less time or with fewer resources. For example, if a fuel break is present, suppression resources need to remove less vegetation before implementing indirect tactics. Additionally, since fire behavior is easier to manage inside a fuel break, the marginal effectiveness of deployed resources improves, and fewer resources are needed for a given operation. Respondents described that increased decision space expanded the number of tactics managers could apply effectively and promptly.

Approximately one-third of managers described reduced risk through altered fire trajectories or changes in direction or rate of spread as a favorable outcome of utilizing fuel breaks in fire response. While most of these respondents described fuel breaks positively when they halted fire spread at the fuel break, some managers experienced operational benefits when fire progression slowed at the fuel break, even if the fuel break was ultimately breached. These benefits include the increased availability of safe anchor points for fireline construction and delayed fire arrival times increasing the probability of success for nearby operations, such as structure protection. Reduced risk from altered trajectories was widely acknowledged to increase the likelihood of achieving HVRA protection objectives. These managers communicated experiences where fuel break use resulted in fewer structures lost or described a counterfactual scenario where fewer homes would have been lost if a fuel break were present.

2.3.7 Mediators

The factors that mediate how fuel break uses influence fire outcomes include the fire environment, fire response, and fire behavior (Figure 2, Table 3). Nearly two-thirds of managers discussed how fuels, topography, and weather influenced the efficacy of fire response using fuel breaks. In particular, weather was viewed as the factor with the highest degree of uncertainty. Respondents described experiences when weather characteristics like high winds and low humidities aligned with fuel and topographic conditions to produce fire behavior that compromised fuel break utility. Relatedly, fire behavior factors, such as spotting potential and the impact of the fire on the break, were crucial variables. Some managers shared experiences of treatments as more effective when they intersected with backing and flanking fires, rather than with head fire spread rates.

One-third of managers discussed mediating factors related to firefighting resources including availability, response size, and time until arrival. Many managers noted that fuel breaks were ineffective without resources present in sizeable numbers including air and ground forces. Multiple respondents acknowledged the response timing was a key uncertainty but highly influential to success. As one participant described: “It is more of a ‘Right response at the right time’ kind of business. All the pieces have to be in place for us to fight fire effectively and provide for employee safety.”.

2.3.8 Evaluation

Managers evaluate the utility of fuel breaks based on their landscape context and personal experience. Evaluations are a product of specific landscape constraints and attitudes, which are influenced by affect (i.e., negative or positive emotions) and beliefs derived from previous experiences (Figure 2, Table 3). Over three-quarters of respondents indicated generally positive feelings towards fuel breaks. Those with a positive affect frequently indicated that fuel breaks can improve coordination, reduce risk, and increase resource efficiency. In comparison, those who had a negative affect toward fuel breaks described their inability to improve outcomes, especially during extreme fire weather. Two managers described how fuel breaks may be used to halt fire progression, but these fires would be stopped by initial attack forces anyway and the outcomes of fast-moving fires would be unchanged.

When asked about previous fuel break experiences directly, fewer than a third of participants stated they would change the treatment in question. When asked about preferred changes, several themes emerged: nearly all the respondents favored improvements to planning processes and fuel management including increased width, size, maintenance, improved stakeholder engagement, incorporation into pre-suppression, and better design for resource use such as enhanced access. A few managers reflected on changes to operational use including timing of response, specific tactics, or using different types of resources.

Approximately two-thirds of managers described how fuel breaks fit into a broader landscape treatment strategy, and the trade-offs of construction. While these respondents noted that fuel breaks should be incorporated into broader treatment plans, there was little consistent agreement on how. Some thought incorporation into a larger network of fuel breaks was preferable, and others described expanding landscape scale or community-level fuel treatments implemented by mechanical means or with prescribed fire. Respondents acknowledged trade-offs

between factors such as acres treated and maintained vs. cost, labor, and environmental impact. Additionally, some managers noted that environmental and landscape restrictions made fuel breaks the only allowable treatment option, as opposed to more expansive fuel reduction efforts, e.g., large-scale thinning or prescribed fire.

2.4 DISCUSSION

The multi-stage decision framework we constructed from manager perceptions and experience highlights that fuel breaks provide options, flexibility, and reduced uncertainty during fire response. This process begins with the decision to implement a fuel break and ends with evaluation, a cognitive concept describing respondents' views as a function of their attitudes, environmental determinants, and previous experiences (Ajzen, 1991). Evaluations influence treatment selection and guide planning, where the local setting and objectives influence placement and design considerations. While constructing fuel breaks, managers select treatment methods and intensities dependent on ecosystem characteristics, natural resource protection constraints, and utilization objectives, as laid out in the planning stage. This influences use efficacy during fire response, where fuel breaks can increase firefighter safety, support tactics, and impact fire behavior. These functions contribute to diverse outcomes beyond halting forward spread by attenuating fire behavior, including decreased risk to personnel and HVRAs, altered temporal considerations, and increased firefighting effectiveness. Social and environmental mediators such as fire weather and resource response variables influence outcomes, which determine future fuel break evaluations.

Our questionnaire was distributed to individuals employed in a range of positions in fire and fuels management who are familiar with, but may not be responsible for, the decisions made throughout the life cycle of a fuel break. Therefore, the constructed framework comprises various decision factors that are distributed across multiple managers and firefighters, which determine the selection and use of a single treatment. The following discussion will address how the role of fuel breaks on the landscape and in fire management decision making hold implications for how we understand successful outcomes.

2.4.1 Fuel Breaks on the Landscape

Managers described the variety of ways landscape considerations play an important role in fuel break placement and utilization. Research to enhance fuel break placement has used algorithmic approaches including optimization (Wei *et al.*, 2008; Ager *et al.*, 2023) and circuit connectivity (Gray and Dickson, 2016; Buchholtz *et al.*, 2023), suitability mapping (Syphard *et al.*, 2011), structure enclosure (Massada *et al.*, 2011), and qualitative recommendations, i.e., ridgetop placement (Green, 1977). These applications typically prioritize using metrics useful to land managers, such as HVRA protection, fire behavior, and economic trade-offs, that may not consider how first responders utilize a treatment. Important considerations for managers when placing fuel breaks were aligning factors influencing fire behavior, high-density ignition locations, HVRA protection, and resource use. Fire alignment, referring to the dynamics between fuels, topography, weather, and fire, is nominally poorly addressed in the literature relative to the frequency of use in the fire management vocabulary. This concept may be imperfectly captured with operational fire modeling, which risks underprediction, leading to error propagation in other fire behavior metrics (Cruz and Alexander, 2013). Fire modeling outputs and other considerations important to managers may be used with algorithmic and suitability mapping

approaches to fuel break placement, but data limitations and variable selection necessitate caution. Optimization approaches may consider risk factors relevant to managers and regulation so that these trade-offs can be spatially displayed. Noticeably absent from previous research is the incorporation of variables advantageous for fire management personnel, like access points or proximity to water refill sites. Tools developed to assist managers in placing fuel breaks have typically assumed that fuel break/fire intersection is the singular desired outcome of fuel break placement (Syphard *et al.*, 2011; Gray and Dickson, 2016; Ager *et al.*, 2023; Buchholtz *et al.*, 2023). Our framework shows that intersection is a key consideration, but incorporating other characteristics important to managers would increase the usefulness of scientifically developed tools.

Our framework provides evidence that managers consider the place of fuel breaks in broader management strategies and prefer incorporation into pre-suppression planning during evaluation and planning stages. Managers discussed larger management strategies facilitated by fuel break implementation when used as points to expand further treatments from, synergistic with various fire management frameworks. While not specifically mentioned by our respondents, the Potential Operational Delineation (PODs) planning tool categorizes landscapes according to consequences of fire exposure, simplifying decisions regarding fire engagement by identifying exclusion zones, areas where fire may be beneficial, and control lines (Thompson *et al.*, 2022). Potential Control Locations, the linear holding features that constitute POD boundaries, if not already treated fuel breaks, may be targeted for treatment upon identification (Buettner *et al.*, 2023). Decision support tools like PODs aid managers in making risk-informed decisions by identifying areas where mitigation has been completed, in agreement with how our respondents evaluated and planned fuel breaks (Thompson *et al.*, 2022). See North *et al.*, (2021) and Moritz *et al.*, (2022) for additional frameworks that include linear fuel treatments. Interestingly, while the existence of treated areas was found to be a decision factor for managers when making decisions around managed wildfires (Fillmore *et al.*, 2024), our findings did not include references to this specific practice. This may be due to a lack of direct questioning on this subject, fuel break locations, and the protection oriented objectives behind linear fuel break construction.

The environmental externalities of fuel breaks were not salient to most managers when completing our questionnaire outside of barriers from regulations created to prevent ecological harm from land management. The concept of a risk trade-off for fuel breaks, where environmental damage is exchanged for benefits, has been acknowledged by some authors who have advocated for thorough cost-benefit analysis (Shinneman *et al.*, 2019). Ecological harm has been well documented in some vegetation types, with findings of invasive species introduction (Merriam *et al.*, 2006; Germino *et al.*, 2024), reductions in plant species diversity (Gruppenhoff and Molinari, 2021), habitat alteration (Hobson and Kardynal, 2019), and edge effects (Shinneman *et al.*, 2019). We explicitly asked managers about planning considerations and fuel management, but not environmental harm, which could explain the lack of this theme's saliency among respondents. In fire response, firefighter and public safety are the top priority for all fires (USDI, USDA, 2022). However, pre-fire planning, including fuel break planning and implementation, can include the prioritization and explicit consideration of a wide variety of risks and impacts. While several studies have examined how fire managers trade off risks in hypothetical fire response scenarios (Wilson *et al.*, 2011; Calkin *et al.*, 2012; Wibbenmeyer *et*

al., 2013; Hand *et al.*, 2015), less is known about how managers navigate risk-risk tradeoffs for fuel treatments.

2.4.2 Redefining Fuel Break Effectiveness

Fire response is a challenging decision environment. Managers must identify a proper course of action during situations characterized by changing conditions and considerable risk and uncertainty (Thompson *et al.*, 2017). Fuel breaks assist managers with mitigating risk and uncertainty during fire response by facilitating a variety of tactical choices, improving safety, and creating opportunities to leverage decreased fire behavior. To that end, fuel breaks can be important for a risk management approach to fire response that emphasizes safe, effective response and does not over-emphasize suppression at the smallest possible size (Thompson *et al.*, 2018a).

Previous research has acknowledged the role of fuel breaks in decreasing fire risk (Oliveira *et al.*, 2016; Aparicio *et al.*, 2022), contributing to the cessation of fire spread, increasing firefighter safety, and providing access (Green, 1977; Syphard *et al.*, 2011; Shinneman *et al.*, 2018; Gannon *et al.*, 2023; Weise *et al.*, 2023). However, empirical effectiveness evaluations have defined fuel break success as the cessation of perimeter expansion (Syphard *et al.*, 2011; Gannon *et al.*, 2023; Weise *et al.*, 2023), which lies in the range of 22-58% depending on fuel type. Despite this moderate effectiveness in the conventional sense, managers generally indicated positive attitudes toward linear treatments and described multiple uses and outcomes beyond halting forward spread. Common construction may be explained by overconfidence and acceptance of high thresholds of breaching, however, respondents described alternative outcomes that provide insight into why fuel breaks are frequently selected.

According to managers while contributing to containment line is a linear break's primary purpose, moderating fire behavior along a strategically located corridor provides additional advantages. This calls into question the narrow definitions of success employed during previous investigations. Managers described various methods of fuel break utilization and scenarios where fuel breaks breach and still act as partial containment lines, points of access, safety enhancement, aids for structure defense, and anchor points. Protecting human life including the public and first responders is the primary objective of fire management in the United States, while safeguarding property and resources is second (USDI, USDA, 2022). Considering our findings, an index of how fuel breaks reduce risk along multiple parameters would be a more appropriate assessment of efficacy. At a minimum, such an index could include use for access, fire line intersections with the fuel break, proximity to structures, structure condition, and distance past the fuel break at which fire progression ceased.

Another potential measurement of operational fuel break effectiveness could use decision-making analysis to examine how fuel breaks influence operational uncertainty during fire response. The incalculable factors that define uncertainty force managers to employ fast-and-frugal decision-making heuristics in time-compressed environments with limited information (Rapp *et al.*, 2021; Rapp and Nelson, 2024). While this uncertainty may be managed with computer based decision support tools, required expertise and computation time are barriers to effective use for fast-paced decisions (Rapp *et al.*, 2020; Fillmore and Paveglio, 2023). Conversely, known fuel breaks immediately provide managers with information about fire behavior in beneficial locations. Comparing how this knowledge is contextualized in the larger fire environment using prior experience versus how decision support products are used and the

expediency and characteristics of subsequent decisions would advance and deepen understanding fuel break effectiveness. Our framework shows that fuel breaks increase decision space by affecting the temporal factors related to fire management. Due to the limited scope of this study, there may be additional contributions to an uncertain environment beyond the faster access, improved safety, pre-established containment lines, heightened probabilities of success for multiple objectives, and increased resource efficiency we described. Exactly how these advantages are incorporated into heuristics employed by first responders is an area for future study.

While decision support tools such as quantitative wildfire risk assessments may incorporate fuel treatments into calculations of expected net value change (Scott *et al.*, 2013), in-depth investigations of how suppression resources interact with fuel breaks are limited (Syphard *et al.*, 2011; Gannon *et al.*, 2023). Detailed information regarding efficacy in arresting fire spread across multiple ecosystem types, resources present, and temporal factors including time until resources arrive on scene and time until containment would be required for the correct incorporation of fuel breaks into similar decision support tools. Quantifying fuel break success will be challenging considering the poor but improving quantity and quality of data describing wildland fire response (Thompson *et al.*, 2018). Using new data sources to provide improved measurements of fuel break efficacy may yield better outcomes for agencies and the public by increasing safety and aiding in developing informed fire management plans.

2.4.3 Limitations

We acknowledge limitations to generalizability due to our use of snowball sampling, open-ended written questions, and relatively small sample size. Established best practices while implementing grounded theory include theoretical sampling (Glaser *et al.*, 1968), however, snowball sampling was chosen due to practical limitations. Open-ended survey questions do not allow for elaboration or clarification compared to interviews limiting topic exploration and probing. We acknowledge that the decision to construct a single treatment is often distributed across multiple individuals, including groups such as US Forest Service District Rangers, who are not represented in this study. Another limitation is the lack of employer diversity in our sampling pool, which does not have representation from tribes and other federal land management agencies in California that may administer fuel breaks. Finally, our thirty-five respondents' locations represent much of the variation in fuel types where fuel breaks are frequently constructed in California, however, we caution readers that the small representation of our total sampling frame may limit the generalizability of this framework.

2.5 CONCLUSION

Fuel breaks are a frequently selected treatment to reduce fire risk and aid management efforts in California. We have established a framework for how fire managers think about, evaluate, and use linear fuel breaks including planning, implementation, and function, and how outcomes influence their thoughts about future treatments. Fuel breaks help fire managers and first responders manage risk and support decision-making in previously unacknowledged ways. Favorable outcomes are more likely when the local context and users' preferred objectives are incorporated into the construction of treatments. Though fuel breaks are not without costs and drawbacks, we encourage more consideration of the myriad ways managers value fuel breaks when evaluating their effectiveness and appropriateness on a landscape.

2.6 TABLES

Agency Position Title	Number of Participants
CAL FIRE	
Chief	8
Forester	7
Forestry Assistant II	2
Supervisory Wildland Firefighter	2
City or County	
Fire and Fuels Manager	4
Private	
Industry Professional	2
USDA Forest Service	
Fire Management Officer	3
Fuels Manager	3
Supervisory Wildland Firefighter	4

Table 1: The position title and employing agency of fuel break questionnaire participants surveyed in 2021, providing input to develop the fuel break decision making framework, and categorized by employing agency and position title. Position categories encompass multiple job titles. CAL FIRE chiefs are unit, battalion, and assistant chiefs. Foresters are Forester I and II. Supervisory wildland firefighters are engine captains and engineers. City or County Fire and Fuels Managers are in planning and management positions. Private industry professionals are in management and coordination positions. US Forest Service Fire Management Officers are in assistant, district, and forest level positions. Fuels managers are in technician, specialist, and battalion positions. $n = 35$.

Vegetation Type	Proportion of Fuel Breaks
Conifer forest	37%
Hardwood forest	29%
Grass	46%
Shrub	77%

Table 2: Proportion of samples fuel breaks containing each vegetation type. 25 fuel breaks were composed of multiple vegetation types and two respondents did not include information describing the underlying fuel type of their fuel break. $n = 33$.

<u>Planning</u>	<u>Construction and maintenance</u>	<u>Uses</u>	<u>Outcomes</u>	<u>Mediators</u>	<u>Evaluations</u>
Public perceptions and regulations	Fuel management based on local conditions	Improved safety: evacuations, access/egress, visibility	Increased decision space and firefighting effectiveness	Fuels, topography, and weather	Positive and negative attitudes
Placement relative to factors influencing fire behavior	Preference for large widths	Tactical options: indirect and direct attack, structure protection	Reduced risk to HVRAs	Resource availability and size of response	Changes to previous projects
Design for firefighter use	Maintenance dictates success or failure	Specific resources or resource combinations	Altered fire trajectories: perimeter changes, slowed progression	Timing of response	Incorporation into a broader treatment strategy
Pre-attack planning products	-	Options for fireline placement	-	Fire behavior, spotting, part of fire intercepted	Uncertainty management
-	-	-	-	-	Consideration of trade-offs

Table 3: Themes from the different stages of the fuel break decision making framework. Tabulated themes were compiled from thematic analysis of questionnaires completed by California fire and fuels managers during Spring 2021. Themes describe the managerial rationale for employing fuel breaks.

2.7 FIGURES

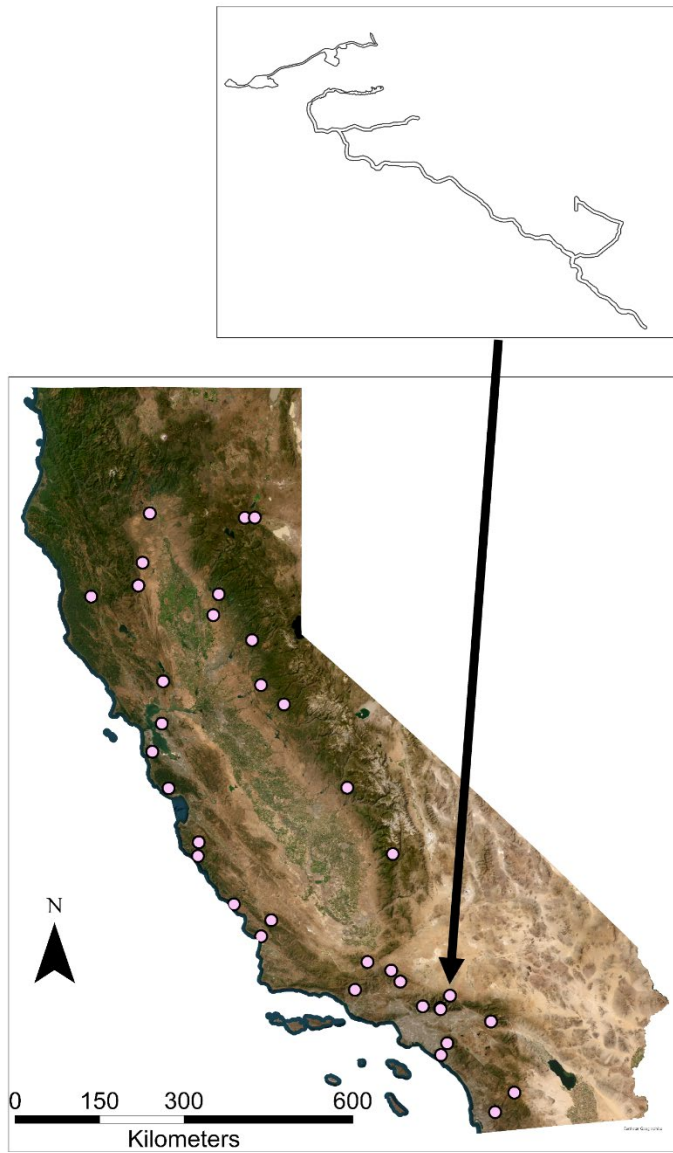


Figure 1: Map of fuel break locations created from survey participant provided data and approximate fuel break locations.

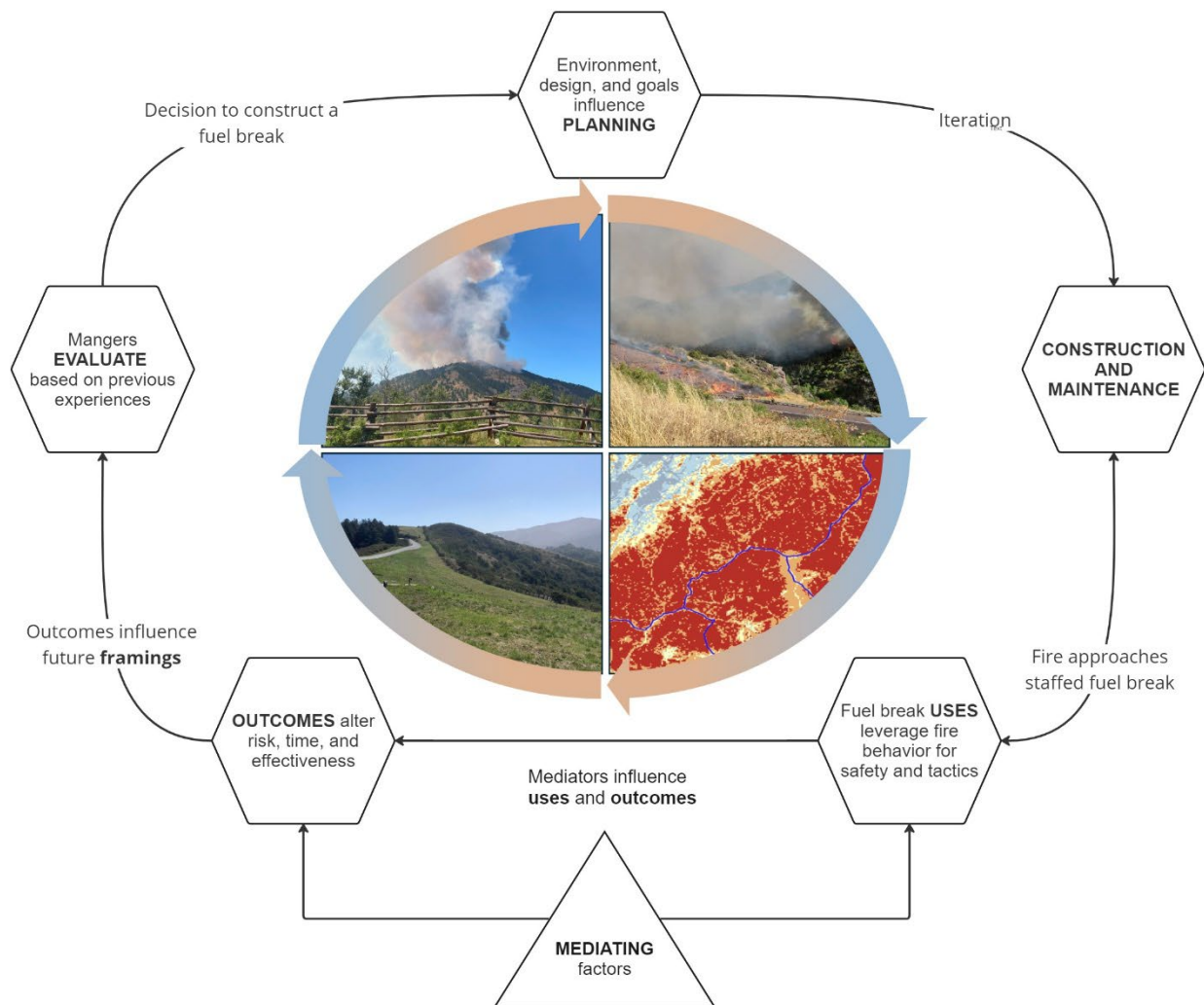


Figure 2: Fuel break decision making framework constructed from thematic analysis of open-ended question data. Photographer credit: Andrew Johnson.

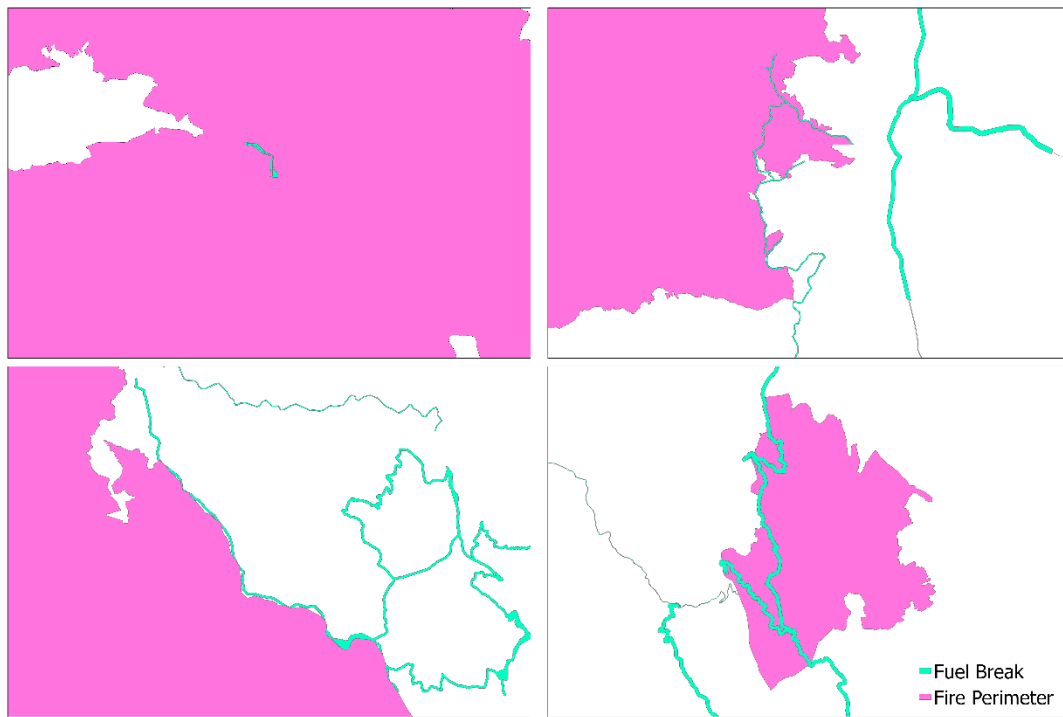


Figure 3: Maps of fuel break intersections with fires where participants described treatments as contributing toward fire management objectives. Starting in the top left and moving clockwise, these fuel breaks were used on the Thomas Fire in 2017, August Complex in 2020, Soberanes Fire in 2016, and Cuesta fire in 2015.

3 **TRANSITION**

Understanding linear fuel break decisions is integral to performing quantitative measurements of fuel break effectiveness. The fuel break decision cycle, how they are thought of, planned, constructed, used, and their outcomes, provides information to develop relevant risk metrics for the evaluation of treatments constructed to assist fire suppression. Due to the limitations of current fire modeling inputs, researchers must make assumptions when selecting fuel models to represent fuel treatments or fire suppression actions. Using information synthesized in the first chapter and from a thorough literature review on linear fuel break research, in the next chapter I develop a risk metric and use this metric to evaluate different fuel break configuration case studies. The risk metric in question reflects the risk of uncontrollable wildfire, fire modeling inputs are manipulated to reflect recently constructed treatments under different conditions of suppression “leverage”, or, how a fuel break might be used during fire management.

4 CONFIGURATIONS OF FUEL BREAK NETWORKS INFLUENCE LANDSCAPE-LEVEL FIRE-RISK IN CALIFORNIA

4.1 INTRODUCTION

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

To achieve fire management objectives, practitioners pre-emptively construct strategically placed linear fuel treatments, hereafter Fuel Break Networks (FBNs), in locations where firefighters are likely to place containment lines (Green 1977; Agee *et al.*, 2000). Fuel breaks are constructed and maintained along natural and anthropogenic features that moderate fire behavior and provide access and holding locations for firefighters, such as ridges, valleys, and road systems. (Green 1977; Syphard *et al.*, 2011; Gannon *et al.*, 2023). In shrub systems, construction involves fuel type conversion by partially or completely removing or rearranging dense surface and canopy fuels (Green 1977). Construction methods include mechanized equipment (crushing and mastication of vegetation), or hand tools, and prescribed fire. Initial treatment is sometimes followed by seeding of less flammable herbaceous species (Green and Schimke, 1971; Green, 1977). Maintenance schedules vary by location and are influenced by local vegetation productivity (Green, 1977; Aubard *et al.*, 2020). Establishment methods depend on site conditions and objectives but may promote erosion, fragmented wildlife habitat, or invasive species spread (Merriam *et al.*, 2006; Shinneman *et al.*, 2019). These ecological consequences must be weighed against the benefits of a reduction in wildfire risk afforded by a well-designed and effectively used FBN (Shinneman *et al.*, 2019).

Generally, Southern California fuel breaks are effectively leveraged to contain wildfires in 22-47% of cases (Syphard *et al.*, 2011; Gannon *et al.*, 2023). Effectiveness is dependent upon treatment placement, maintenance, intensity, width, the presence and type of firefighting resources, fire behavior and weather (Omi 1977; Green, 1977; Agee *et al.*, 2000; Syphard *et al.*, 2011; Gannon *et al.*, 2023; Ortega *et al.*, 2024; Young *et al.*, 2024; Johnson, *in prep*). Firefighters using linear treatments may conduct direct (constructing fireline on the burning edge) and indirect suppression tactics (allowing fire to reach a distant fireline or firing operations) (Plucinski, 2019). When firefighters are present to conduct fire control or "leverage" the reduced fuel profiles and fireline intensities in FBNs, fuel break effectiveness, or the likelihood of successful containment and improved firefighter safety, increases (Green 1977; Syphard *et al.*,

2011; Gannon 2023; Young 2024). The concept of fuel treatment “leverage” originates from comparisons of ratios of fuel treatment area to avoided burned area, damages, and suppression costs (Loehle 2004; Boer *et al.*, 2009; Price *et al.*, 2015; Thompson *et al.*, 2017). Leverage uniquely suits the objectives of fuel break construction and is used hereafter to describe various wildland firefighting tactical FBN uses (Young *et al.*, 2024). Fuel breaks left unleveraged are “unstaffed” by firefighters during treatment-fire intersections. In southern California unstaffed treatments are almost always ineffective in limiting fire size, however, additional consequences of this phenomenon are poorly understood (Syphard *et al.*, 2011).

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

In operational wildland fire research, the agreed upon definition of risk generally includes fire likelihood, fireline intensity, and effects on social, ecological, or economic systems at varying levels (Scott, 2006; Miller and Ager, 2012). Wildfire effects are wide ranging and variable. Impacts on ecosystems may be positive or negative depending on ecological history and current conditions (Stephens *et al.*, 2013). Conversely, impacts on the built environments and human safety are generally considered to be negative (Plucinski, 2019). Accounting for every variable may increase workflow complexity, decreasing the flexibility of applications (Thompson and Calkin 2011). Previous examples focusing on firefighter safety and fuels hazard include Integrated Hazard (IH) and Wildfire Hazard Potential (WHP) (Scott *et al.*, 2012; Dillion *et al.*, 2015). IH is the product of fire likelihood and fireline intensity. Wildfire Hazard Potential (WHP) advances this concept by combining fire likelihood, and fire intensity weighted line production rate derived control difficulty (Dillon *et al.*, 2015). Due to the complexity of analysis, managers using WHP rely upon experts to update the nationally mapped version of the product periodically at 270m spatial resolution (Dillon *et al.*, 2023). Consequently, WHP cannot be used for fine-scale sensitivity testing of planned fuel treatment effects on fuel hazard. While a version of IH is available for managers conducting counterfactual analysis using the Interagency Fuel Treatment Decision Support System (IFTDSS) (Drury *et al.*, 2016), a need exists for managers assessing the influence of planned treatments on the intersection of risk and explicit risks to fire control likelihood and firefighter safety.

Recent research has focused on landscape level evaluations, which includes outside of treatment area effects. These relationships often lack rigorous empirical evaluation due to the challenges associated with data collection and analysis. The lack of data-driven analysis of landscape treatments, like FBNs, is a critical gap in our knowledge regarding fuel treatment effectiveness (McKinney *et al.*, 2022; Ott *et al.*, 2023; Urza *et al.*, 2023). The evaluation of landscape level fuel break effectiveness is pressing considering increased investments in fuel treatments on private and public lands in the United States (Knight *et al.*, 2022). Additionally, the incorporation of fuel breaks within comprehensive land management frameworks such as Potential Operational Delineations (PODs), which segment landscapes by fire response objectives, make landscape level fuel break effectiveness an important subject for further investigation (North *et al.*, 2021; Thompson *et al.*, 2022). The strategic placement of linear treatments may aid managers by reducing local and landscape risk, which may be leveraged to increase the effectiveness of control efforts. However, questions persist regarding their effectiveness under extreme weather conditions, in different configurations, and under various conditions of suppression leverage (Gannon *et al.*, 2023; Young *et al.*, 2024; Nguyen *et al.*, 2024).

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

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

4.2 METHODS

4.2.1 Study System

Southern California's variable topography, elevation, and climate support diverse vegetation communities including mixed conifer forest, shrublands, and grasslands (Van De Water and Safford, 2011). Except for the Sonoran and Mojave deserts, which are beyond the scope of this study, the region's vegetation is shaped by its Mediterranean climate, elevation gradients, and associated fire regimes (Stephenson and Calcarone 1999; Keeley and Syphard 2018). At low and mid elevations, the region's expansive wildland urban interface frequently borders crown-fire adapted chaparral communities dominated by flammable chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylos* sp.) and ceanothus (*Ceanothus* sp.) (Van De Water and Safford, 2011). At higher elevations, fire suppressed pine dominated forests historically shaped by frequent and low severity fire persist (Stephenson and Calcarone 1999). The area is bounded by the Pacific Ocean to the west and the Mojave and Sonoran Deserts to the

east (Figure 4). Average annual precipitation in the region varies from 15 - 44cm fueled by periods of heavy rain during the winter. Average temperatures during the May to October fire season range from 19- 23C (NOAA, 2024). Anthropogenic sources provide 95% of the region's ignitions and can fuel fires occurring during Santa Ana winds in the fall and winter, accounting for the majority of the region's burned area (Keeley and Syphard, 2018)

4.2.2 Fuel Break Network Categories

Data on thirty fuel breaks were collected from a survey of California fire managers distributed during Spring 2021 (Johnson, *in prep*). Snowball sampling, a purposive chain-referral method where subjects recruit additional participants through their networks, was used to distribute the survey (Parker *et al.*, 2019). Survey data represents treatments throughout California, with twenty-five treatments in the shrub, grass and oak woodland dominated Central California Foothills and Coastal Mountains, Southern California Mountains, and Southern California/Northern Baja Coast ecoregions (Supplementary Materials Figure 6; Supplementary Materials Table 12) (Omernik and Griffith 2014). The other five fuel breaks were in conifer systems and did not represent meaningfully different configurations from the rest of the data. Linear treatment data was provided directly by respondents or mined from the USDA Forest Service, Forest Activity Tracking System (FACTS) Hazardous Fuel Treatment Reduction dataset (USFS, 2020) and the California Department of Forestry and Fire Protection's (CAL FIRE) treatment database CalMAPPER (CAL FIRE, 2021). FACTS polygons were identified through project names and general locations collected through the survey. We also collected information on nearby treatments, which served two purposes: increasing certainty of association with survey responses and including adjacent treatments intended for simultaneous use during incident management.

Treatment designs were examined relative to topography, roads, and communities using ArcGIS Pro basemaps (ESRI, 2024). Design characteristics were recorded and non-exclusive treatment categories were established to group the dataset into four configurations: Single Segments, Branching Networks, Enclosed Networks, and Multiple Segment Networks (Figure 5). Branching Networks feature segments branching from primary ridge systems down sub-ridges or valleys (Omi 1977). Enclosed Networks surround high risk or strategic areas such as highways or continuous expanses of vegetation (Oliveira *et al.*, 2016). Multiple Segment Networks feature multiple discontinuous segments of varying shapes distributed across a landscape. Single Segments are individual, non-sinuous treatments. We selected case study examples from each category for evaluation in a fire modeling environment: Limestone Ridge (Segment), Boundary Ridge (Branching), Mount Lowe (Enclosed), and North Mountain (Multiple Segment). Treatment categories are not mutually exclusive; therefore one treatment might belong to multiple groups. For example, a treatment featuring characteristics of a Branching Network could be classified as a Multiple Segment Network.

Southern California is a crucial location for fuel break research (Syphard *et al.*, 2011; Gannon *et al.*, 2023; Young *et al.*, 2024; Nguyen *et al.*, 2024). Case study fuel breaks were selected exclusively from this region to facilitate treatment performance comparisons. The case study examples represent the EPA Level III Ecoregions most representative of the categorized fuel break data set described above – Southern California Mountains (Boundary Ridge and North Mountain), Southern California/Northern Baja Coast (Limestone Ridge), Central California

Foothills and Coastal Mountains (Mount Lowe) (Omernik and Griffith 2014) (Figure 4). These ecoregions feature similar Mediterranean climates, a preponderance of chaparral shrub communities, and fire regimes (Stephenson and Calcarone 1999). However, key vegetation differences exist, such as concentrations of oak woodlands in the case studies in the Southern California Mountains and Central California Foothills and Coastal Mountains and coastal sage scrub in the Southern California Coast landscape (Griffith *et al.*, 2016).

The Boundary Ridge, Mount Lowe, and North Mountain polygons were collected from FACTS using a combination of respondent-provided documents and locations. The Boundary Ridge respondent submitted a post-fire assessment of the 2009 Sheep Fire including images of treatments. The Mount Lowe fuel breaks were located using respondent-provided aerial imagery. The North Mountain respondent provided an approximate location (North Mountain System near Beaumont, CA), which was used to identify linear treatments near Beaumont with North Mountain in the project name. All FBNs were implemented or maintained between 2015 and 2020. Treatment data for Limestone Ridge was provided as a line shapefile, which was buffered according to the survey-reported width. A construction date for Limestone Ridge was not provided, but the treatment was successfully used in 2020 on the Silverado Fire. Below, we describe locations and adjacent vegetation using LANDFIRE Existing Vegetation Type (LANDFIRE, 2016).

The Limestone Ridge Single Segment fuel break (Figure 5A) was constructed across Limestone Ridge Road, which runs along a northeast angled ridge located east of Limestone Canyon in Limestone Canyon Regional Park. The treatment extends from the intersection with Santiago Canyon Road, west of the Williams Canyon community. The treatment covers 18ha, is 3.9km long, and approximately 46m wide. The primary pre-treatment vegetation type inside and surrounding the treatment is California coastal scrub. The fuel break was used to defend nearby communities during the 2020 Silverado Fire.

The Boundary Ridge Branching FBN (Figure 5B) consists of two separate treatments totaling 28km in length with an average width of 100m on the San Bernardino National Forest. One treatment, constructed in Southern California Dry-Mesic Chaparral, is on a primary ridge, with three lateral treatments following east angled sub-ridges. The North Fork of Lytle Creek is to the southwest and Lone Pine Canyon lies to the northeast. The second treatment separates Lone Pine Canyon to the southeast and the town of Wrightwood to the northwest, extending across a ridge and crossing Lone Pine Canyon road. Adjacent and interior vegetation is Mesic Mixed Conifer Forest and Woodland and Southern California Dry-Mesic Chaparral. The FBN was used during containment operations on the 2009 Sheep Fire.

The Mount Lowe Enclosed FBN (Figure 5C) consists of 4 separate segments northeast of San Luis Obispo, surrounding part of Highway 101 in the Santa Lucia Mountains. The treatments are constructed primarily on northwest to southeast angled ridges around Highway 101 and the community of Thyle in the Los Padres National Forest. Surrounding and interior vegetation is primarily Northern and Central California Dry-Mesic Chaparral and Coastal Live Oak (*Quercus agrifolia*) Woodland and Savannah. Total treatment length covers 43km with an average width of 35m, although widths are variable between treatments. Survey results indicate the fuel break was unsuccessfully used during the 2015 Cuesta fire.

The North Mountain Multiple Segment FBN (Figure 5D) consists of 6 segments totaling 35.4km in length with an average width of 35.7m. The FBN is constructed in Southern California Dry-Mesic Chaparral and lies west of Highway 243 and east of Hemet, CA. The fuel breaks partially surround the community of Poppett Flats on public land managed by the San Bernardino National Forest and Bureau of Land Management. Managers reported the FBN has been used for wildfire management, but did not include the incident name(s). Please see Supplementary Materials Tables 10 and 11 for additional description of case study fuel breaks characteristics (Scott and Burgan 2005).

4.2.3 Wildfire Simulations

Fuel break assessments were conducted using Flammap 6.2, which allows users to simulate fire behavior and growth across landscapes for thousands of fires under static wind and fuel moisture conditions (Finney, 2006). First, we modified treatment polygons using ArcGIS Pro to represent three fuel break leverage scenarios, ordered by increasing intensity: unstaffed (treatments in place, but no barrier to fire spread), firebreak (unburnable linear surface through treatment impedes fire growth but is susceptible to spot fires), and firing operation (200m wide unburnable surface from fuel break center impedes fire spread and limits spot fires).

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

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

Single wind directions and fuel moisture conditions were calculated from 97th percentile Energy Release Component conditions (Deeming *et al.*, 1977). Remote Automatic Weather Stations (RAWS) and associated identification numbers were located for each landscape using the IFTDSS Map Viewer. Weather from May 1 to October 31 for the previous 10 years was selected to reflect fire season conditions and avoid extreme wind events, which distort weather

variable distributions (NWCG, 2025) (Supplementary Materials Tables 1-2). Fire Family Plus 5.0 was used to create fuel moisture and wind files required for Flammap 6.2 (Jolly and Heinsch, 2024).

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

All inputs were identical for the four simulations on an individual landscape (control, unstaffed, firebreak, firing operation), but different between landscapes to reflect local climatological influences on fire behavior (Supplementary Materials Tables 1-2). Fire locations from control simulations were used in subsequent processing of leverage scenarios, limiting stochastic differences in outputs. A 2km buffer was implemented on FBN landscapes to decrease edge effects, allowing fires to burn into and out of study areas. The segment landscape was trimmed further to increase the treated proportion, aiding comparison between fuel break configurations. Final outputs consisted of 30m resolution BP (Burn Probability), Flame Length Probability files to create 30m CFL (Conditional Flame Length), and fire size lists.

4.2.4 Suppression Hazard Metric

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

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

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

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

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

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

Suppression difficulty has a positive relationship with fireline intensity due to the width, quality, and construction rate of fireline needed to halt tall flames (Burgan, 1979; Plucinski, 2019). Hand crews alone are typically ineffective beyond 1000 kW/m, larger resources capable of producing wider containment lines more quickly, such as bulldozers, are ineffective beyond 3000 kW/m, and aircraft applying retardant can reduce fire behavior for ground resources to contain fire spread up to 5000 kW/m (Burgan, 1979; Loane and Gould, 1986; Budd *et al.*, 1997). Fireline intensity was converted to flame length using Byram's (1959) equation and hazard weights were assigned via relationships between flame length categories and resource types required for suppression (Table 4). Generally, the relationship between fireline intensity and suppression hazard follows an S-shaped logistic growth curve, where suppression occurs with relative ease at low flame lengths, and beyond a certain threshold difficulty increases rapidly before plateauing at intensities where suppression becomes ineffective (Burgan, 1979). In the equation below, ϕ_1 equals the maximum hazard weight value, while ϕ_2 is the intercept and ϕ_3 is the coefficient of a logit model created from assigned hazard weights and suppression effectiveness thresholds (Figure 9, Equation 3, Table 4).

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

UWR at location j is the natural logarithm of the summed product across flame length categories (i) of the Flame Length Probability (FLP), flame length category midpoint (FL), hazard weights associated with each flame length category (W), and the probability that a cell will burn (BP_j). A constant is derived from the minimum logged UWR value of a landscape (c_l) and added to ensure values are above 0 (Equation 4). Weights representing hazardous flame length categories were derived from Equation 3. The logarithmic transformation was applied to limit exponentially decreasing values, increasing map readability and interpretability of subsequent analysis.

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

UWR is a dimensionless metric for mapping the risk of uncontrollable wildfire. Across landscapes, values ranged from <0.01 to 13.58 and 95% of the data fell between 0.61 and 12.65. UWR values map closely to CFL while greater dispersion is visible in relation to BP values (Supplementary Materials Figure 1). The metric should be interpreted in the context of the associated risk definition, and high values may represent locations where fire is likely to challenge control efforts due likely fire spread or high CFL values, with the metric weighted towards the latter condition. Therefore, a relatively high UWR value may be associated with a location where higher flame lengths are predicted, but burn probability is low, while the inverse is possible, it is less common (Figure 7).

4.2.5 Analyses

4.2.5.1 Descriptive Statistics

UWR may be interpreted at multiple scales including individual pixels or summarized across regions to assess suppression hazard at the landscape scale. We calculated multiple UWR and fire size statistics for each case study modeling scenario to understand changes in landscape level fire characteristics. Measurements include mean UWR, percent change from untreated, and the difference of mean UWR between untreated and leverage scenarios multiplied by a normalization metric (ratio of treated area to landscape size), facilitating comparison between case studies. Fire size statistics included change from a uniform distribution of fires in the untreated landscape and total burned area per treatment hectare. We divided fires into 5 equal size classes (quintiles) for untreated landscapes and calculated shifts in the uniform distribution to compare change in the number of fires per size class across leverage scenarios. Fire size lists were summed to total burned area, facilitating calculations of reduction in burned area per treatment hectare.

4.2.5.2 Sampling and Variable Production

Systematic sampling and variable creation were conducted using the Terra and sf libraries in R (Pebesma and Bivand, 2023). Raster extractions were completed in NAD 1983 and vector relationships were calculated in UTM WGS 1984 to avoid pixel distortion. Our sampling protocol placed sample points in systematic grids with 120m spacing to limit spatial autocorrelation (Ver Hoef *et al.*, 2001). The distance of each sample to the nearest point on a treatment polygon boundary was calculated and each sample point was assigned to the nearest treatment. These boundary locations were used to determine treatment Topographic Position Index (TPI), width, wind alignment, sinuosity, area treated, adjacent treatment proximity, and length for attribution at nearest samples. TPI was calculated by subtracting the average elevation of an individual cell's "neighborhood" with a 9x9 moving window, selected after comparing multiple dimensions. High TPI values correspond to ridges, while low values indicate valleys (Weiss, 2001). Treatment width was calculated at 10m intervals along treatments by intersecting a line positioned orthogonally to the angle between two neighboring perimeter points. This method produced anomalous values (<2m and >800m), which were excluded from subsequent analysis. We calculated a wind alignment metric from the cosine of the difference of the azimuth between a sample point and nearest fuel break and the landscape's static wind direction. Values of 1 indicate complete alignment with wind direction and are therefore on the leeward side, -1 indicates upwind direction, and 0 indicates points positioned orthogonal to treatments and static wind directions. Sinuosity measures deviation from a straight line path and was measured by dividing fuel breaks into 500m sections. Low values indicate straightness while higher values reflect waviness (Ager *et al.*, 2023). The relative proximity index reflects the clustering (low values) or isolation (higher values) of treatments and was calculated by dividing the distance to nearest treatment at 10 meter intervals along treatment boundaries by total treatment perimeter (Gustafson and Parker, 1992). Approximate linear treatment length was calculated by halving total perimeter lengths and sample points were assigned the length value of the closest treatment section.

4.2.5.3 Linear Mixed Effects Models

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

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

UWR for the j th pixel location is equal to the intercept, the summed product of the 11 main effect coefficients, 7 interaction terms, and random intercept (Supplementary Materials Table 3). Our models uses mean untreated UWR as the intercept (β_0). The main effect coefficients represent the marginal relationships between predictor variables and average risk on untreated landscapes (βX_{ij}), while interaction terms capture how these relationships change across the i leverage scenarios ($\beta(X_{\text{scenario},i} \cdot X_{(k-10),i})$). Interactions were modeled for all variables except fuel model and slope, facilitating clear interpretation of how fuel break leverage may alter these relationships. Model coefficients quantify the influence of each predictor on mean response holding other variables constant. The primary coefficients of interest are from interaction terms, however, these should be interpreted as additive to main effects. For example, the coefficient β_9 , (*wind x scenario* interaction) is added to β_4 (main effect of *wind*). Finally, a random intercept for plot locations ($b_{\text{plot}(i)}$) was included to account for repeated measurements under different leverage scenarios.

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

We checked model validity by comparing residual variance to independent variables and predicted risk with scatter and box plots to check for residual heteroscedasticity and patterns. Variograms of residuals were assessed to detect unacceptable levels of spatial autocorrelation. Model performance was evaluated using ten-fold cross validation with the cv package in R, which performs leave-one-out cross validation and calculates Mean Squared Error (MSE) to measure model performance (Fox and Monette, 2024). Data simulations were conducted to visualize assumed model relationships. To assess the variance in the data explained by the model,

conditional and marginal R^2 were calculated. Conditional values represent variance explained by fixed and random effects, while marginal values capture only the fixed effects (Nakagawa and Schielzeth, 2013).

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

4.3 RESULTS

4.3.1 Landscape Fire Modeling Summaries

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

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

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

scenarios, respectively. In the firebreak and firing scenarios fire counts in the 1st quintile (0.9-278 ha) grew by 11 and 158.

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

The 22,500 ha North Mountain–Multiple Segment Network contains 3,239 ignitions, southwest winds, and the highest average UWR of all untreated landscapes. A continuous high-risk patch with multiple linear treatments spans the center, east, and southeast regions. This landscape exhibited the largest absolute and relative influence from firebreak and firing fuel break leverage, with UWR decreasing linearly with intensity. Total burned area and median fire size increased in the unstaffed scenario, although 3 fewer fires were in the 10th quintile (2,260-4,290 ha) and the 1st quintile (0.09-545 ha) grew by 11. Fire size distributions shifted left for firebreak and firing leverages, with the 10th quintile shrinking by 70 and 150 and the 1st quintile increasing by 12 and 124 fires, respectively. The firebreak scenario produced the greatest reduction in area burned per treatment hectare and normalized UWR.

4.3.2 Statistical model results

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

The number of parameters included in models are 36 and 28 for the FBN and Single Segment models, respectively. Parameters include main effects and interaction terms between factored scenario and continuous variables, and a random effect for repeated measurements at sample locations across leverage scenarios. The untreated scenario and grass fuel model were selected as baseline variables in all models. Main effects should be interpreted as the relationship between the independent and dependent variables in question at baseline conditions, holding other values at their means. Interaction terms are additional to the main effect, i.e. a main effect of 0.05 and an interaction of -0.02 should be interpreted as 0.03. See supplementary materials for all model results, performance, and validation metrics (Supplementary Materials Tables 7-8).

4.3.2.1 Landscape Effects

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

Main effects of distance vary dependent upon the placement of fuel breaks relative to areas of risk on a landscape (Segment: 0.14; Enclosed: -0.15; Branching: 0.07; Multiple: -0.58). Lower main effect coefficients indicate homogeneous risk, while higher values suggest changing conditions toward landscape boundaries. Positive values indicate increasing risk with distance from treatment locations and negative values indicate treatments were placed in relatively high-risk areas. Positive interaction coefficients represent lower UWR values adjacent to treatments under a given leverage condition relative to the baseline, which rise to levels observed on untreated landscapes as distance increases (Figure 7). Only the Branching FBN predicted changing risk over distance when unstaffed (0.01). All FBN models include positive interaction terms for the firebreak scenario (Enclosed: 0.03; Branching: 0.03; Multiple: 0.05), an effect that strengthened with the firing operation leverage (Segment: 0.16; Enclosed: 0.13; Branching: 0.24; Multiple: 0.22) (Figure 9).

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

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

4.3.2.2 Configuration Effects

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

under firing operations across FBN models (Enclosed: 0.08; Branching: -0.03; Multiple: -0.07). Notably, main effects for the Branching FBN are positive while the Multiple Segment and Enclosed models are positive. Therefore, the relationship should be interpreted as weakening for Branching and Enclosed and strengthening for Multiple Segment configurations.

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

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

4.4 DISCUSSION

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

4.4.1 Uncontrollable Wildfire Risk

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

dimensionless metric that should be interpreted as the likelihood of fire behavior in the context of controllability, similar to UWR. Complex WHP calculations challenge reproducibility for fire and fuels management planners and researchers (Scott *et al.*, 2012; Dillon *et al.*, 2015). Conversely, UWR is easily produced at 30m and relies on fire modeling software widely available to managers and researchers. Therefore, UWR enables wildland fuels managers to evaluate the efficacy of treatments in aiding wildfire control at the treatment and landscape scale through counterfactual analysis (Green, 1977; Agee *et al.*, 2000; Drury *et al.*, 2016).

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

4.4.2 Fuel Break Network Configurations

Establishing common fuel break configurations provides information on tailored approaches to target location-specific risk, while allowing us to investigate the effectiveness of treatments implemented in a barrier laden environment. Managers must consider the challenges to complete construction fuel break networks face while planning treatments, such as limited resources, land management policy, and public opinion (Reinhardt *et al.*, 2008; Collins *et al.*, 2010; Reiner *et al.*, 2014; Urza *et al.*, 2023). Our classification approach produced four configurations, which influenced risk differently across leverage scenarios: Branching Networks, Enclosed Networks, Multiple Segment Networks, and Single Segments. While the explicit objectives and limitations of individual fuel break projects are beyond the scope of our study, inferences may be made when considering adjacent and intersecting landscape features, treatment extent, and continuity.

Single Segment (Figure 5A) and Multiple Segment (Figure 5D) fuel breaks typically surround or abut roads and ridges while individual treatments are frequently adjacent to Highly Valued Resources and Assets (HVRAs). The small extent and isolation of individual treatments suggest the existence of incomplete extensive treatment networks, targeted protection of HVRAs from specific fire spread directions, connection to adjacent areas unavailable for treatment, or where treatments are deemed unnecessary (Collins *et al.*, 2010; Massada *et al.*, 2011; Scott *et al.*, 2013; Oliveira *et al.*, 2016; Tubbesing *et al.*, 2019). Relative to the other configurations we examined, these arrangements produced greater normalized risk reductions when leveraged with firebreaks or firing operations, and produced larger burned areas when unstaffed. Multiple Segment FBNs provide strategic options across landscapes, and treatment discontinuity can be used advantageously, disrupting growth along the heel and flanks of individual perimeters where fuel breaks are known to be most effective (Finney, 2001; Young *et al.*, 2024). Single Segments

provide fewer opportunities, but orthogonal placement relative to wind direction and proximal to fire spread barriers such as downwind roads acting as secondary firelines interacted to increase the likelihood of fire intersection and reduce fire size (Finney, 2007). While assessments of isolated treatments are rare, our results reinforce successful leverage by first responders can limit negative wildfire outcomes when placed respective of probable spread directions, near HVRAs, with access and appropriate treatment intensity (Syphard *et al.*, 2011; Massada *et al.*, 2011; Collins *et al.*, 2013; Oliveira *et al.*, 2016).

Branching Networks (Figure 5B) are situated in topographically complex areas, where lateral fuel breaks extend from treatments on primary ridges down into valleys and along sub-ridges. Empirical studies show probability of successful use is highest for primary treatments, whereas safety concerns and placement may limit operations on lateral breaks, which often involve longer travel distances to safety zones (Omi, 1977; Syphard *et al.*, 2011; Young *et al.*, 2024). The Branching FBN landscape contained the highest proportion of treated area (1.04% unstaffed) and was the only configuration to decrease burned area when unstaffed. Exclusive ridge top placement enhances the treatment's ability to disrupt fire spread by combining the influence of landform with a fuel type exhibiting lower flame lengths, increasing likelihood of extinguishment (Holsinger *et al.*, 2016). Additionally, lateral treatments offer managers strategic opportunities to integrate fuel breaks into broader risk reduction planning by providing access for landscape treatments activities within key portions of watersheds (North *et al.*, 2015; 2024).

Enclosed Fuel Break Networks (Figure 5C) surround areas with high ignition potential, such as highway corridors, or areas prioritized for fire exclusion, such as communities (Massada *et al.*, 2011; Oliveira *et al.*, 2016; Aparício *et al.*, 2022). Relative to other configurations, Enclosed Networks frequently follow mid-slope roads until roads intersect with ridges, exemplified in the case study treatment. Extensive Networks planned in Portugal limited cross-boundary transmission of fire, decreasing fire size, likelihood, and building exposure in simulation analyses (Oliveira *et al.*, 2016; Aparício *et al.*, 2022). Poor performance in our case study analysis likely results from the relatively lower landscape risk, small width, and the amount of mid-slope treatment (Van Wagtenonk *et al.*, 1996; Holsinger *et al.*, 2016; Zong *et al.*, 2021).

4.4.3 Fuel Break Leverages

Increased burned area and average fire size on unstaffed fuel break landscapes is potentially attributable to vegetation conversion (represented by fuel model) inside treatments, which included the replacement of roads with herbaceous fuels. Inspecting the proportion of pretreatment polygon interiors containing unburnable fuel models (Segment: 0.5%, Branching: 12%, Enclosed: 18%, Multiple: 10%) suggests road removal is not the sole driver of this phenomenon (Supplementary Materials Table 10). Depending on pre-existing vegetation and treatment type, fuel manipulations may introduce continuous light fuels and remove tall vegetation, elevating surface winds, which increase fire spread rates and overall fire size but not fire intensity (Cochrane *et al.*, 2012; Cochrane *et al.*, 2013). Therein lies a tradeoff where fire spreads more rapidly, while the risk of crown fire and long-range spotting is reduced (Albini and Baughman 1979; Cochrane *et al.*, 2012; Cochrane *et al.*, 2013). This compromise is captured by cumulative landscape-level evaluations with UWR, where lower risk from decreased flame lengths in and adjacent to treatments compensated for higher burn probabilities (Table 5).

Accurately evaluating cumulative landscape-level fuel break effects requires ecological context, such as historical fire regime and current vegetation type. In ecosystems adapted to frequent fire, area burned does not indicate meaningful ecological or human impacts from wildfire (Stephens *et al.*, 2013; North *et al.*, 2015). However, in crown-fire adapted systems, such as Southern California chaparral, the management paradigm has been to limit fire size due to the consequences of frequent burning on native vegetation and HVRAs (Keeley and Brennan, 2012; Halsey and Syphard, 2024). Empirical studies show fuel breaks in this region are frequently unstaffed during fire intersections, and that burned fuel breaks can spread invasive species further into wildlands (Merriam *et al.*, 2006; Syphard *et al.*, 2011). If an additional consequence is larger fires, then including firebreaks, which aid local objectives by increasing firefighter safety and decreasing average fire size, are a logical management recommendation (Thompson *et al.*, 2021). Our evaluation of burned area per treatment hectare indicates fuel breaks leveraged with firebreaks may improve cost-benefit ratios and limit the negative externalities from larger treatments, subject to the cost and environmental consequences of road construction relative to treatments (Table 5) (Boston, 2016; Shinneman *et al.*, 2019). Accompanying firebreaks decrease fire size and may delay impact times to areas targeted for fire exclusion even when unstaffed (Young *et al.*, 2024). In these cases, well timed aerial ignitions with piloted or unmanned aircraft may be used to increase the likelihood of either containment or slowing spread when ground operations are deemed unsafe (Lawrence *et al.*, 2023).

Firing operations leveraging fuel breaks consistently contributed to the greatest absolute reductions of landscape-level risk. Unsurprisingly, simulating fuel breaks as unburnable surfaces leads to improved outcomes in terms of fire spread and transmission (Oliveira *et al.*, 2016). It is important to acknowledge fire modeling faces limitations from static inputs that make firing operations unrealistic (Finney, 2006). In reality, myriad factors including heterogeneity of fuels, operational timing, environmental conditions, and direction and speed of wildfire spread influence firing operation depth and fuel consumption (Holsinger *et al.*, 2016). Additionally, fire interactions between intentional ignitions and wildfire, and spotting from firing operations are not captured in simulations (Finney, 2006). Our improved approach to modeling firing operations adds some realism by removing adjacent fuels, but does not account for whole fire containment with firing operations, turnover probabilities, or the environmental factors and interactions listed above (Aparício *et al.*, 2022). Future iterations may pair our approach with wildfire perimeter trimming functions, assess effectiveness using spread direction calculated from fire perimeter datasets, and include intersecting roads as containment line to simulate firing operations at scale (Petrovic and Carlson, 2012; Thompson *et al.*, 2021; Gannon *et al.*, 2023). Aside from a robust solidification of the concept that fuel breaks should be utilized in conjunction with firing operations, implications include the construction of fuel breaks adjacent to features with fewer sources of spot fire causing embers. In practice, this would include building fuel breaks along linear features with already reduced fuels or areas where fuels are already completely removed, such as roads, the latter of which is already common practice (Green 1977). These areas require less pre-treatment on the “green” or “black” sides in the event of a wildfire, enhance firefighter safety, and increase the likelihood of limiting fire spread, however, targeting areas with reduced fuels for adjacent treatment construction may be viewed as essentially building one fuel break alongside another. Ultimately, managers may deem other areas without pre-existing buffers as higher priority targets for linear fuel reduction, while locating these treatments where first responders can quickly deploy to initiate indirect attack tactics.

4.4.4 Fuel Break Arrangement and Geometry

The findings in our fuel break configuration case studies provide intriguing hypotheses for future research. Generally, closer proximity, lower sinuosity, and longer fuel breaks were associated with lower risk when treatments were leveraged with firebreaks or firing operations. Treatment proximity mitigates fire spread, behavior, and subsequent risk at multiple scales of analysis (Ott *et al.* 2023). Individual fires may encounter multiple treatments at different angles, limiting or forcing flanking or backing behavior contingent upon spread direction and fuel types inside treated areas. In probabilistic fire modeling environments, areas nearby treatments are sheltered from fires spreading from multiple directions, limiting total burned area and reducing risk dependent upon treatment configuration (Finney, 2001; Finney, 2007). A previous investigation of fuel break sinuosity and length found that straighter and longer treatments intercepted more fires, but interception lengths were generally longer for non-sinuuous treatments (Ager *et al.*, 2023). Fires intersecting with less sinuous treatments may be less likely to flank towards fuel break portions that are either more susceptible to spotting due to smaller widths, or that change angles or terminate, allowing fires to spread beyond treatments (Finney, 2007).

The relationship between UWR, leverage intensity, distance from treatment, and wind-treatment alignment were generally positive and effect sizes varied between case study configurations. Increasing leverage intensity was associated with decreasing risk values further from treatments, especially on leeward fuel break sides (Figure 7; Supplementary Materials Table 7). Fuel breaks that are unstaffed or leveraged with a firebreak exert minimal, but visually detectable influence on risk over distance compared to controls (Figure 8; Figure 9). Firing operation leverage on the Branching FBN decreased risk up to 3km from treatment boundaries, while the Single Segment fuel break and Enclosed Networked exhibited more minimal impacts on UWR (Figure 9). The influence of wind and treatment alignment also reduced risk, albeit to a lesser degree than distance. While we did not include an interaction between distance and wind alignment due to the number of parameters already included in our models, visibly larger reductions on leeward treatment sides are apparent (Figure 7; Supplementary Materials Table 7).

Previous research using burn probability modeling shows that treatments reduced burn probability until about 10km downwind of treatments and 5km on the upwind side in Boreal forests (Stockdale *et al.*, 2019). Managers commonly place treatments orthogonal to wind directions occurring during times of fire danger (Collins *et al.* 2013), especially those intended for firefighter leverage, so that they are well positioned to intersect with head fire spread (Finney, 2007). Alternatively, if treatments are placed to control backing fire spread locations upwind of high risk areas may be favored (Gannon *et al.*, 2023; Young *et al.*, 2024). Positioning strategic treatments like fuel breaks near HVRAs or along fire excluded area boundaries further from protection objectives can mitigate negative impacts and provide fire management options when probable directions of incoming fire spread are considered (Aparício *et al.*, 2022; Ortega *et al.*, 2024; Nguyen *et al.*, 2024).

4.4.5 Limitations and Future Research

Burn probability modeling is widely used by managers and researchers assessing planned and existing fuel treatments. However, there are many limitations of this approach that should be disclosed to provide appropriate caution in interpreting findings from such studies (including the

present one). Rothermel-based surface fire spread and linked crown fire models exhibit unrealistic overestimations of burned area while underestimating wind driven runs (Finney *et al.*, 2011). Future research may assess individual fires-fuel break intersections using Rothermel based models, however, the coarse resolution of inputs and consequent lack of detail describing fine-scale interactions on treatment boundaries creates opportunities for computational fluid dynamics modeling and fine scale fuel models derived from LiDAR scanning (Marcozzi *et al.*, 2023; Atchley *et al.*, 2024).

While ignitions were placed in identical locations across each simulation of the same landscape, stochastic differences from the program's spotting algorithm, which assigns a random likelihood for spot fire ignitions from fire brands, cause minor differences between simulations (Finney, 2006). Additionally, random ignition placement is a limitation of this study and future research using our framework may consider ignition probability datasets to place fire origins, increasing realism by simulating the influence of human and natural wildfire sources (Oliveira *et al.*, 2016; Moran and Thompson 2024).

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

The use of linear mixed modeling provides interpretable results and statistical significance thresholds to determine relevant relationships, while limiting data quantity and the number of parameters (Zurr *et al.*, 2009). Spatial subsampling and random effects for plot locations controlled for some spatial autocorrelation (Ver Hoef *et al.*, 2001). Future iterations may include spatial lag terms and machine learning algorithms to maximize data, but interpretation of results may be challenging relative to linear models (Ver Hoef *et al.*, 2018). While additional parameters including interaction terms may be desirable, linear models risk over-fitting or non-convergence errors as parameters increase (Zurr *et al.*, 2009). Additional interaction terms, such as between distance and wind-treatment alignment, may provide additional information useful for managers constructing fuel breaks. Despite existing flaws, assessing the intersections of wildfire hazard and fuel break characteristics and leverages provides relevant management findings on landscape level fuel break effects on risk and treatment parameters for fuel breaks.

4.5 CONCLUSION

Lengthening dry seasons and increasing human ignitions during adverse weather events are regularly increasing wildfire related losses in Southern California (Keeley and Syphard 2025). As hazardous conditions intensify, fire managers require improved risk mitigation strategies for planning and emergency response. Our research demonstrates that even during

adverse conditions, fuel breaks can reduce hazardous risk to first responders while creating opportunities for fire control within and adjacent to linear treatments. However, these benefits depend on adequate construction planning. Fuel managers should ensure linear treatments are placed in areas easily accessible to firefighters and include pre-established containment line or roads to minimize ignition spread from invasive annual grasses. Managers should consider how any mitigation action affects the level of risk to first responders and the metric and methods presented in this study contribute to this critical goal.

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

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

4.6 TABLES

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

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

Table 4: Thresholds of firefighting effectiveness using different resources and resource combinations with inferred difficulty weightings and associated citations. The literature and data in this table were used to compute weights for Uncontrollable Wildfire Risk.

	Treatment Size (ha)	Proportion of Landscape Treated	Median Fire Size (ha)	Mean UWR	Area Burn Change Per Treatment Area (ha)	UWR Percent Change	Differenced Hazard Normalized
Single Segment - Limestone Ridge – Southern California Coastal Scrub							
Untreated	0	0%	456.21 ± 1239.60	7.60 ± 1.76	-	0	0
Unstaffed	17.92	0.33%	457.29 ± 1238.73	7.60 ± 1.77	+123.71	-0.04%	-0.99
Firebreak	17.92	0.33%	445.86 ± 1242.53	7.59 ± 1.76	-1043.22	-0.23%	-5.46
Firing	94.11	1.74%	423.63 ± 1256.35	7.50 ± 1.81	-761.33	-1.43%	-6.24
Branching Network - Boundary Ridge – Southern California Dry-Mesic Chaparral							
Untreated	0	0%	578.25 ± 346.95	7.72 ± 1.87	-	0	0
Unstaffed	282.35	1.04%	572.22 ± 342.80	7.68 ± 1.88	-72.08	-0.45%	-3.37
Firebreak	282.35	1.04%	566.19 ± 339.48	7.68 ± 1.88	-164.80	-0.48%	-3.55
Firing	689.71	2.56%	486.00 ± 336.58	7.56 ± 1.92	-338.51	-2.06%	-6.21
Enclosed Network - Mount Lowe – Northern and Central California Dry-Mesic Chaparral							
Untreated	0	0%	82.08 ± 278.67	4.17 ± 2.62	-	0	0
Unstaffed	203.75	0.58%	81.99 ± 280.63	4.16 ± 2.62	+15.31	-0.18%	-1.32
Firebreak	203.75	0.58%	81.18 ± 267.18	4.15 ± 2.60	-93.25	-0.47%	-3.36
Firing	872.47	2.49%	78.93 ± 207.36	4.08 ± 2.53	-135.93	-2.09%	-3.51
Multiple Segment Network - North Mountain – Southern California Dry-Mesic Chaparral							
Untreated	0	0%	1050.57 ± 951.47	8.64 ± 2.38	-	0	0

Unstaffed	135.63	0.60%	1052.19 ± 963.43	8.63 ± 2.39	+98.60	-0.12%	-1.76
Firebreak	135.63	0.60%	1018.98 ± 889.73	8.59 ± 2.36	-1863.03	-0.59%	-8.41
Firing	632.63	2.81%	822.06 ± 788.54	8.43 ± 2.33	-1417.39	-2.41%	-7.41

Table 5: Descriptive statistics for treated proportions of landscapes, change of uncontrollable wildfire risk, fire size, and burned area organized by landscape and fuel break leverage scenarios. Area burned reductions, UWR percent change, and Normalized UWR difference were calculated in reference to untreated landscapes. The most commonly occurring vegetation type inside of and within a 50m buffer of FBN polygons (LANDFIRE, 2020) is described in the top row of each section.

4.7 FIGURES

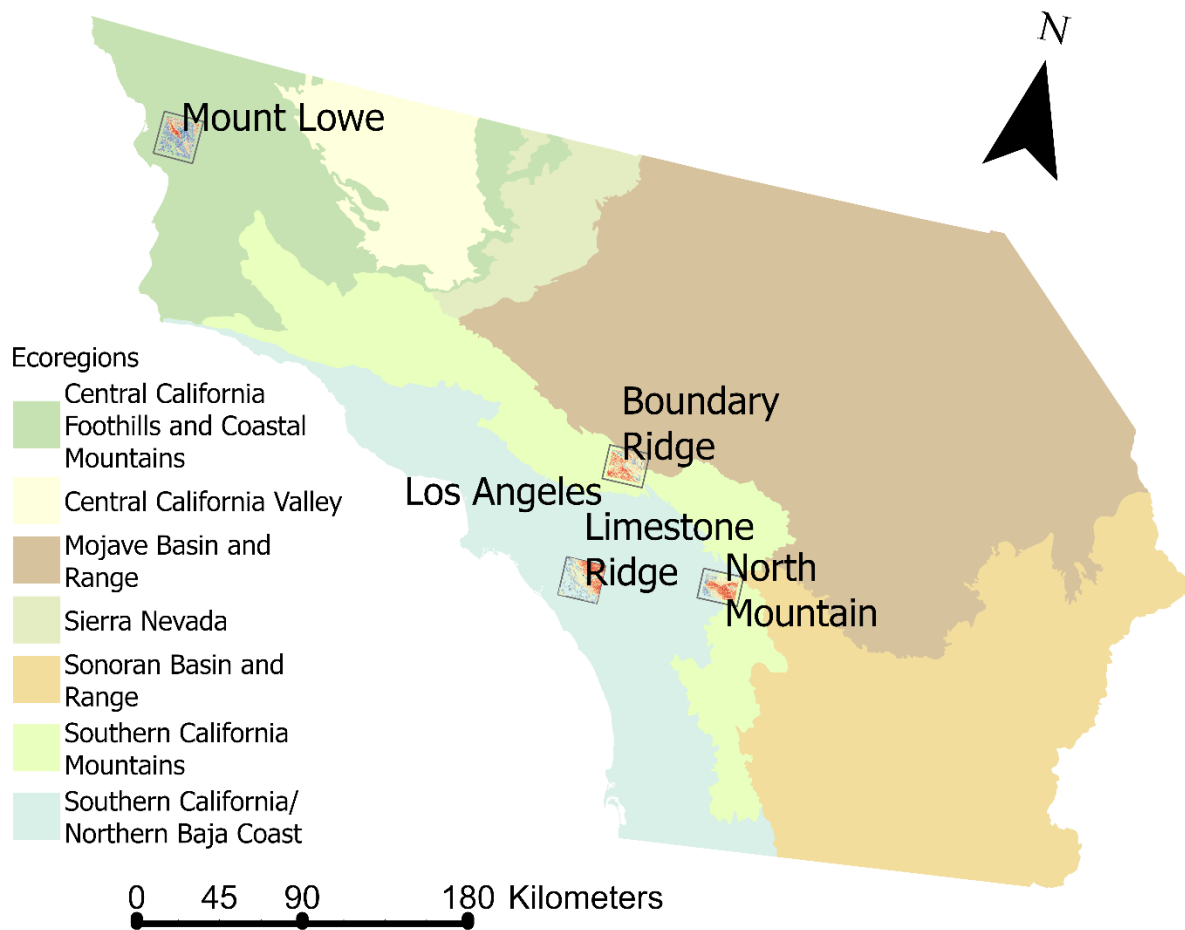


Figure 4: Map of Southern California with EPA level III ecoregions (Griffith et al., 2016). Fuel break case study locations are labeled and UWR rasters extents are used to highlight the location and size of fire modeling landscapes.

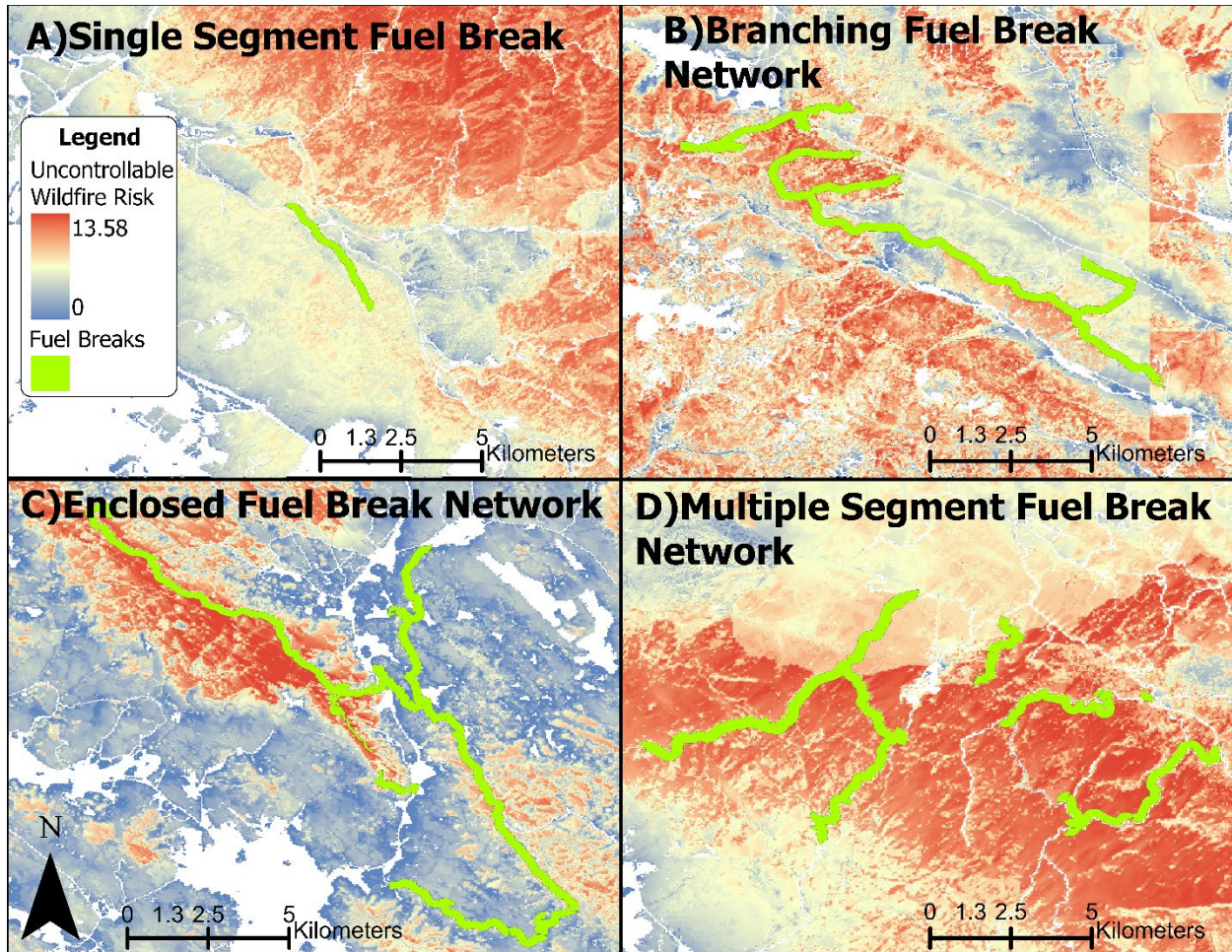


Figure 5: Case study fuel break configurations overlaid onto rasterized Uncontrollable Wildfire Risk, with communities and roads masked to NA values. Firing operation polygons are included due to the small size of some treatments. A) The Limestone Ridge Single Segment fuel break, located in Limestone Canyon Regional Park. B) The Boundary Ridge Branching Network, located southeast of Wrightwood, CA. C) The Mount Lowe Enclosed Network, located northeast of San Luis Obispo, CA. D) The North Mountain Multiple Segment Network, located east of Hemet, CA. D).

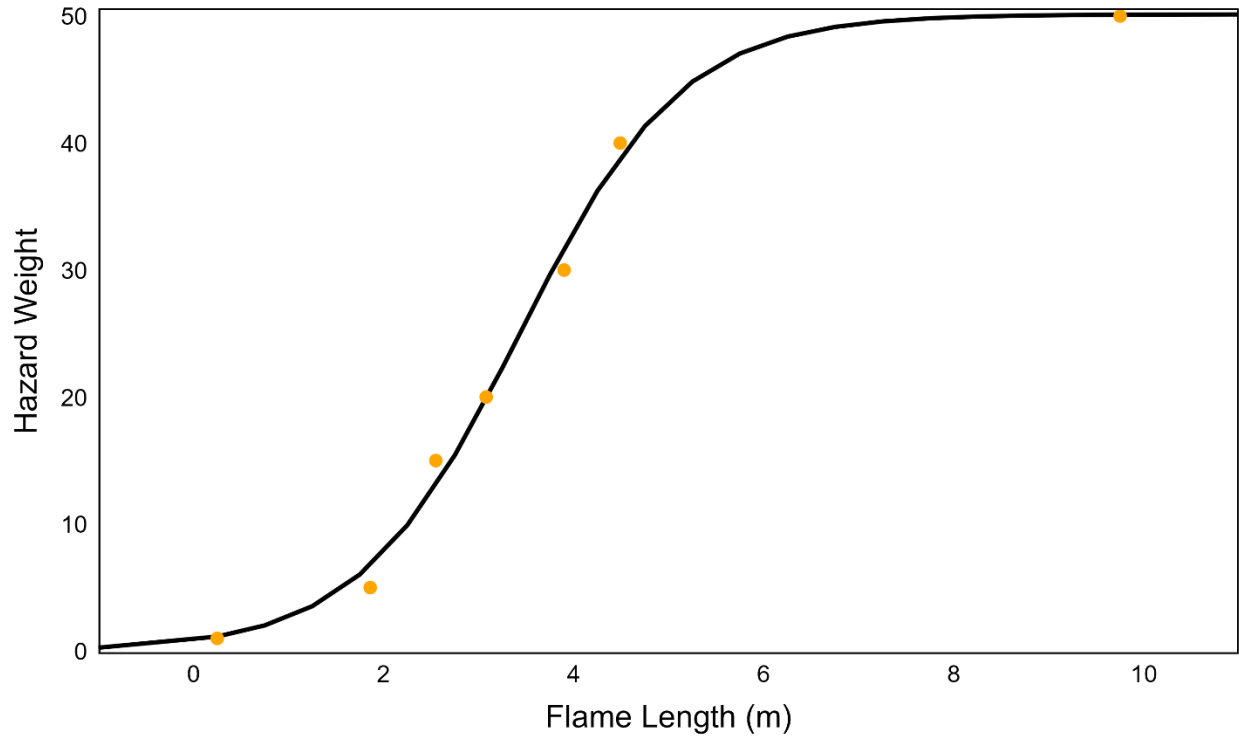


Figure 6. Logistic growth model of control hazard over increasing flame length, which reflects the initial ease and progressive difficulty of fire suppression (Equation 3). Conditional Flame Length Categories were input into this model and outputs were used as hazard weights to compute Uncontrollable Wildfire Risk (Equation 4). Orange dots represent thresholds of suppression effectiveness of differing resource types and combinations at varying flame lengths, which were derived from previous empirical literature. The first and final thresholds were added by researchers to ensure weights remained above 0 and below 50.

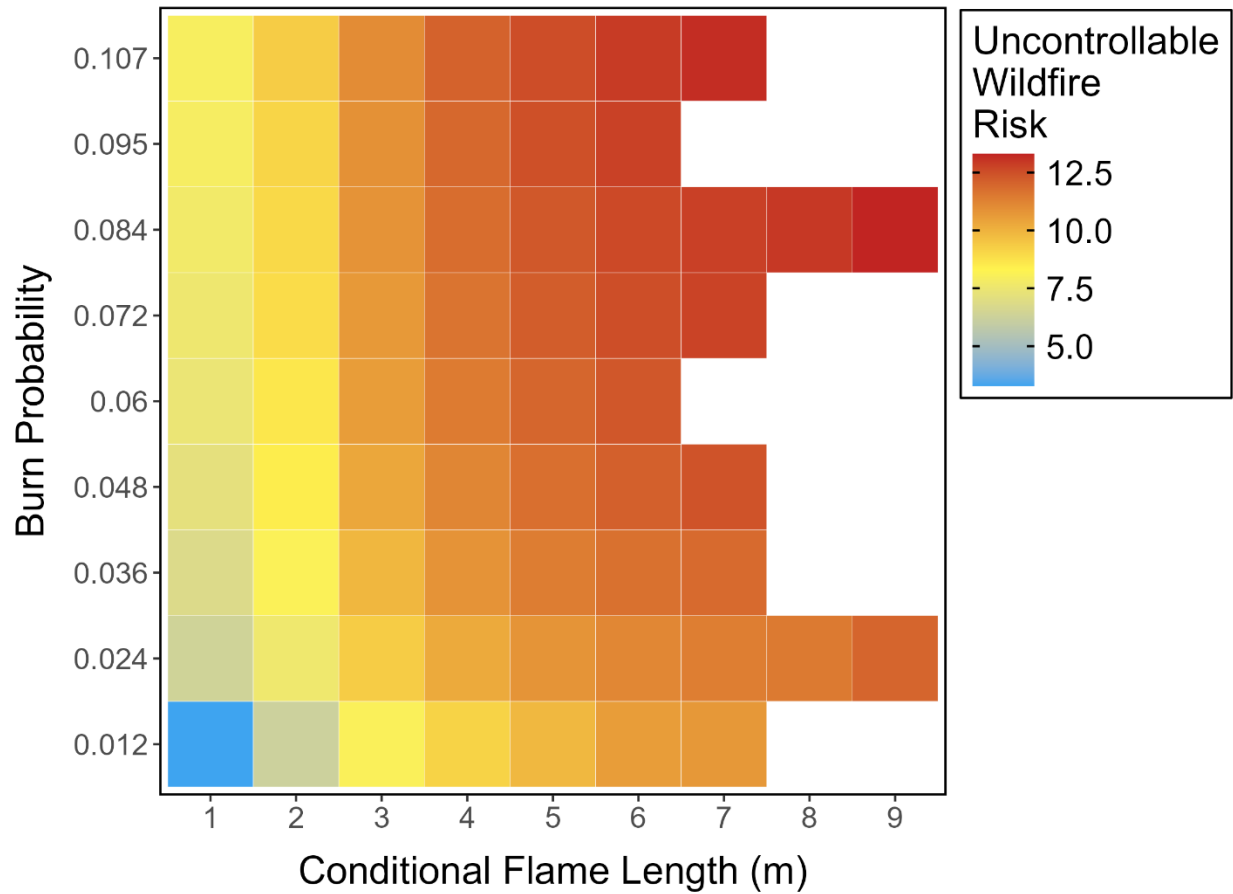


Figure 7. Heat map of average Uncontrollable Wildfire Risk (UWR) (Equation 4) at intersecting categories of Burn Probability (BP) and Conditional Flame Length (CFL) using a 120-meter subsample of UWR, BP, and CFL values at identical locations on untreated case study landscapes. Relative to BP, UWR maps closely onto CFL, therefore lower levels of risk are possible when CFL is low, and BP is high.

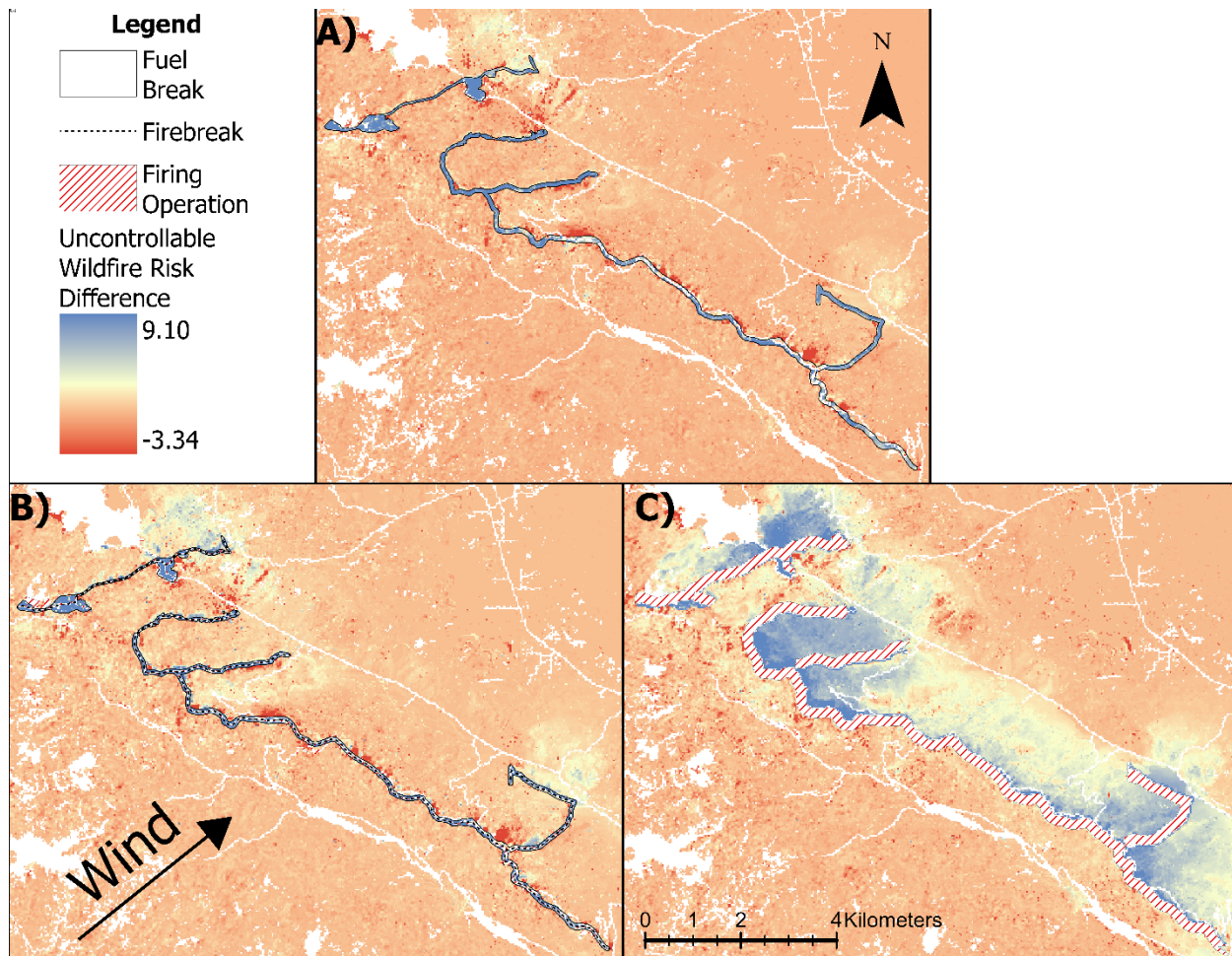


Figure 8. Uncontrollable Wildfire Risk on the Boundary Ridge Branching Fuel Break Network's leverage scenarios subtracted from risk values on the untreated landscape. Southwest winds and identical ignition locations were used on all modeling runs. Values above 0 are associated with decreased risk compared to control conditions, while negative values indicate increased risk. A) Unstaffed fuel break. B) Fuel break leveraged with a firebreak. C) Fuel break leveraged with a firing operation.

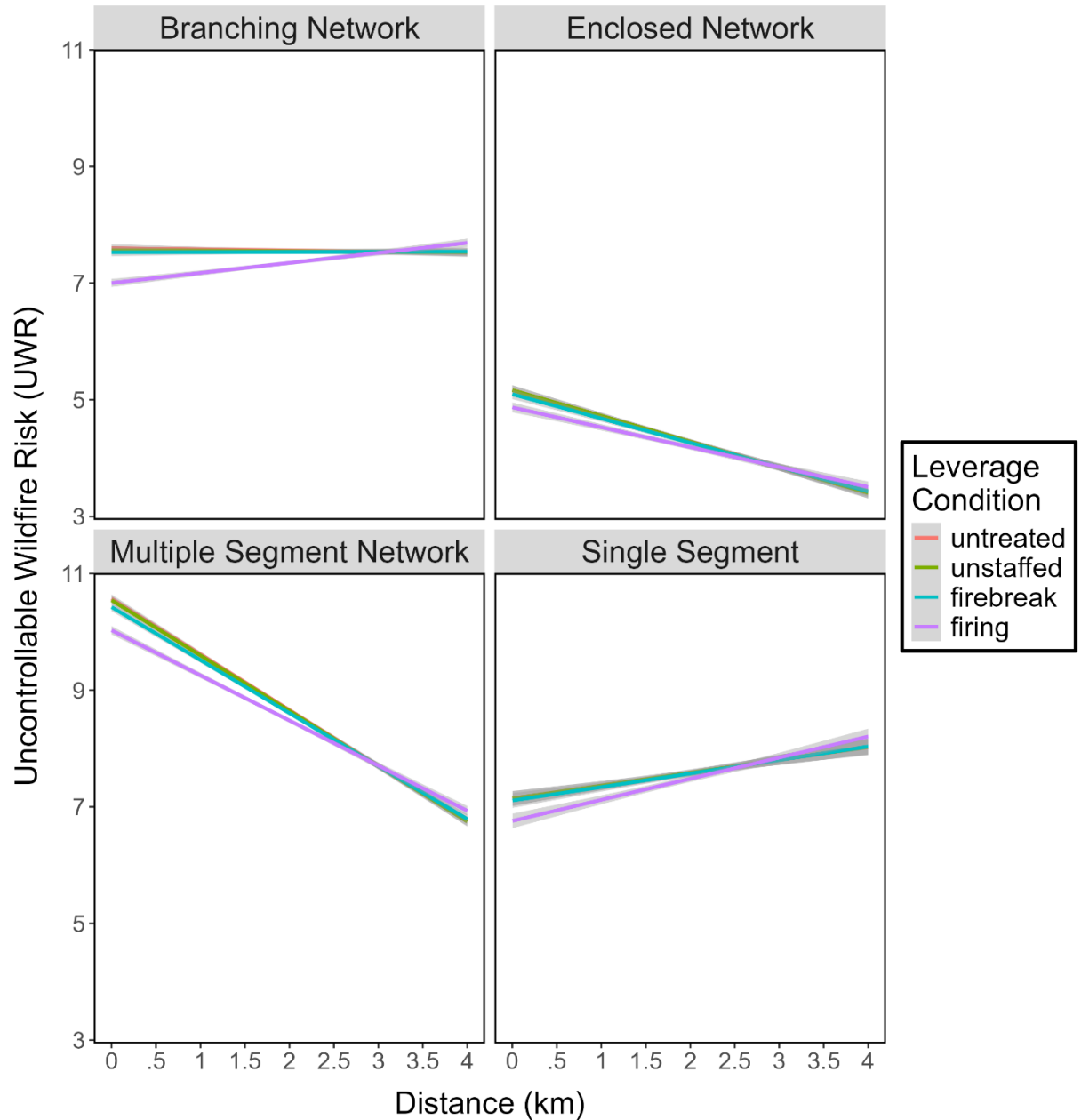


Figure 9. Linear models of predicted Uncontrollable Wildfire Risk (UWR) over actual distance with 95% confidence intervals in shaded gray. Each panel is for a fuel break configuration and each line is a leverage condition. Predicted values were calculated across the range of fuel model inputs. Confidence intervals for fuel break and indirect leverage overlap with untreated for all configurations, while firing leverage shows a significant local decrease in risk near treatments, which converges with untreated risk levels as the distance from fuel breaks increase. The largest local decrease in risk is apparent for firing operation leverage on the Branching and Multiple Segment Networks, while the smallest difference is visible in the Single Segment and Enclosed Network graphs.

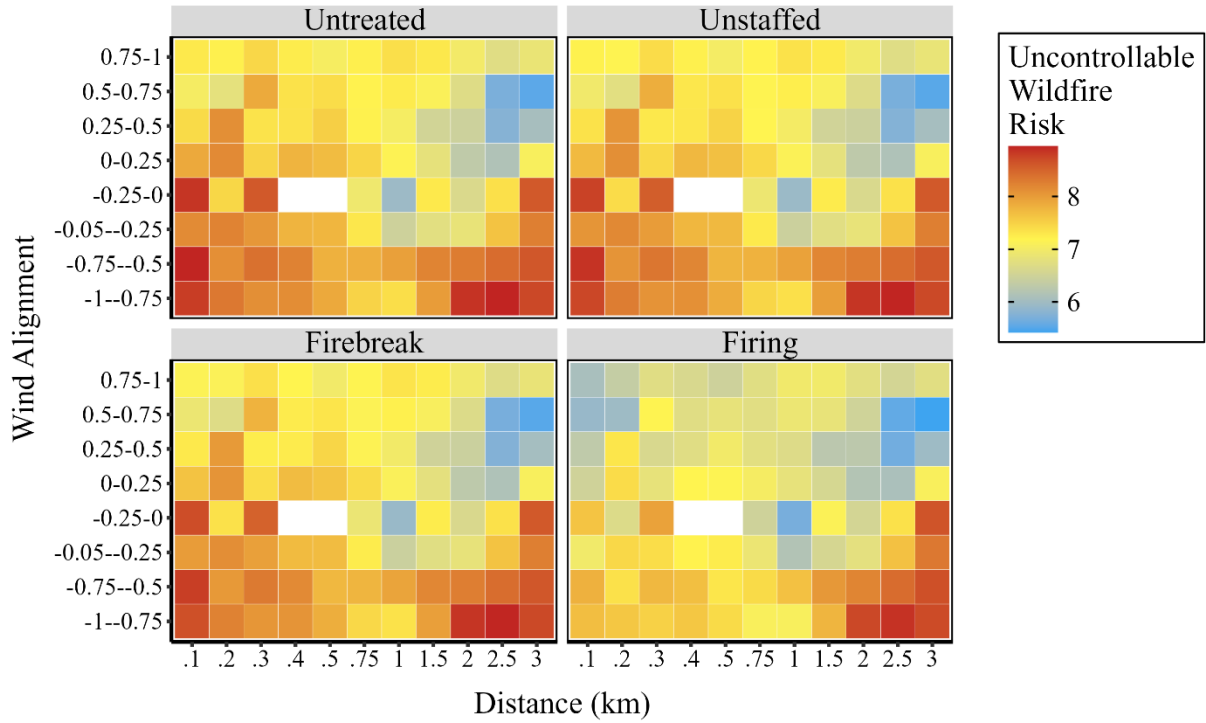


Figure 10. Average predicted Uncontrollable Wildfire Risk at intersecting values of distance from sample point alignment with wind and treatment direction (1 = downwind of treatments/-1 = upwind of treatments), on the Boundary Ridge Branching Fuel Break Network. The influence of fuel break leverage is apparent on the leeward side of treatments as leverage intensity increases. Predicted values were calculated across the range of fuel model inputs, reflecting realistic predictions for actual landscape conditions.

5 TRANSITION

The last two chapters have focused on linear fuel treatments, both the decisions that prompt their construction and uses, but also evaluations of different configurations using fire spread modeling. However, there is much to learn about the use of fuel treatments generally during active fire management. Specifically of interest is how treatments influence tactical decisions made on large wildfires, since these extreme events represent much of the annual area burned in the United States, on average. In the next two chapters, we use the 2021 Caldor Fire as a case study example because qualitative examination of the impacted area and anecdotal evidence from fire managers indicated that fuel treatments influenced the course of events. Using a semi-structured interviewing protocol, 13 on-the-ground fireline supervisors were interviewed about tactical decisions, and the themes from this data were used to develop a tactical decision framework to describe decision factors, processes, and outcomes.

6 TACTICAL DECISION FACTORS, TYPES, AND OUTCOMES ON THE 2021 CALDOR FIRE IN THE CONTEXT OF FUEL TREATMENTS

6.1 INTRODUCTION

The tools and tactics of wildfire management and control have remained resistant to change since the mid-20th century despite increasing fire behavior and worsening impacts on Wildland Urban Interface/Intermix (WUI) areas (Pyne, 2015). To stop spreading flames, responders will construct containment line by hand or machinery (lines dug to bare mineral soil to interrupt fire spread), use hoses and water, use aircraft to slow fire growth with water or retardant, or burn vegetation between planned containment lines and the actual fire (Plucinski, 2019). The effectiveness of these tactics is dictated by the fire's behavior and the speed at which resources can construct strategically placed containment lines (Burgan, 1979; Hirsch and Martell, 1996). Given the interplay between weather conditions, fire behavior, and human actions, the apparent simplicity of these tactics masks the complex nature of wildland firefighting tactical decision making (Thompson, 2014).

Decision makers on wildland fires must navigate intersecting sources of uncertainty and risk from rapidly changing fire behavior, coordination with adjoining resources, and shifting incident management objectives (Thompson and Calkin, 2011; Dunn *et al.*, 2017). Management of these factors requires abundant information that accurately describes both risks and hazards (Thompson and Calkin, 2011; Dunn *et al.*, 2017; Rapp *et al.*, 2021). While firefighting tactics have remained relatively unchanged, sources of information have increased in recent years, including mapped spatial models that display suppression difficulty and hazards from dead trees, as well as the location of uncontained fire perimeter using drones and aircraft (Dunn *et al.*, 2019; Johnson *et al.*, 2026). These tools influence the decision space, or number of options available to managers, by increasing the situational awareness of current and future fire behavior, and potential control locations (Bossert, 1998; Calkin *et al.*, 2021; Young *et al.*, 2025). Advances in these tools have occurred rapidly and programs to increase their influence and adoption by fire managers have been successful (Calkin *et al.*, 2021). While the prevalence of digital decision support systems is increasing, on-the-ground fire managers still rely upon their personal experience and communication to develop, select, and execute tactical decision options (Rapp *et al.*, 2020).

Decision space may be increased, and uncertainty of fire behavior decreased, through the presence of previously completed wildland fuels management projects positioned strategically for use during firefighting operations (Stephens *et al.*, 2023; Greiner *et al.*, 2025). Fuel management involves the removal or rearrangement of wildland fuels for multiple objectives including the reduction of negative ecological fire effects, increasing firefighter safety and effectiveness, and reducing fire risk to built infrastructure (Hood *et al.*, 2022; Vorster *et al.*, 2024). When mechanical and prescribed fire treatments are large enough and placed strategically, potential benefits include decreased suppression costs, burned area, and structure loss if firefighters incorporate treatments into tactical decisions (Thompson and Anderson, 2015; Sanchez *et al.*, 2019; Gibbons *et al.*, 2025; Johnson *et al.*, 2026). Fuel treatments may be incorporated into incident response via long term strategic planning, helping decision makers

place primary or contingency containment line in locations where firefighters will have to complete less preparatory work in advance of the fire's arrival (Moghaddas and Craggs, 2007; Greiner *et al.*, 2025). While much is known about the general use of fuel treatments during fire management operations, detailed case studies of fuel treatment use during large and complex wildfires are lacking.

The Incident Command System (ICS) was developed for the management of large and complex wildfires in Southern California, USA (Auf der Heide, 1989). ICS provides the scaffolding for Incident Management Team (IMT) positions with a hierarchical organization chart that designate incident management responsibilities (Figure 11) (FEMA, 2017). IMTs are ranked in accordance with the wildfire complexity they are qualified to manage. Incident complexity is determined by growth potential and exposure of valuable resources. Type 3 IMTs are typically responsible for less complex wildfires managed locally. Prior to 2024, Types 1 and 2 IMTs were nationally available to manage the most complex wildfires (now merged with Type 2 IMTs into Complex IMTs) (NWCG, 2024).

Strategic decisions on federally managed wildfires, whether to fully suppress a wildfire or manage for other objectives, are determined and communicated by the Agency Administrator (AA) and overseen by the Incident Commander (Steelman and McCaffrey, 2011; Fillmore and Paveglio, 2023; Buettner *et al.*, 2025). Division Supervisors (DIVS), who are responsible for operations on sections of wildfire perimeter, coordinate with Operations Section Chiefs to develop tactical plans to achieve strategic goals established by IMT Command and General Staff (Bigley and Roberts, 2001). DIVS may be granted decision making latitude at the discretion of the Incident Commander and Operations Section Chief (Bigley and Roberts, 2001). This decentralized decision making structure prevents overwhelming individuals in command staff positions who carry additional responsibilities, such as planning, logistics, and stakeholder management, and media interactions (Bossert, 1998; McLennan *et al.*, 2006). Therefore, understanding DIVS decision making is of utmost importance for researchers seeking to improve wildland fire outcomes and a gap exists in current literature, which has primarily focused on fire management strategy (Calkin *et al.*, 2013, Wibbenmeyer *et al.*, 2013; Fillmore *et al.*, 2024).

Multiple decision models and frameworks have provided insights into incident management decision making (MacGregor and González-Cabán, 2011; Rapp *et al.*, 2021; Fillmore *et al.*, 2024). When facing uncertainty and time-pressure, decisions may be captured using the Recognition-Primed Decision-making, where decisions are made using previous experience and mental simulation of outcomes. (Taynor *et al.*, 1990; MacGregor and González-Cabán, 2011; Klein, 2017; Zimmerman, 2012) When time and information are abundant, decisions may resemble the Rationale Choice model, where managers make the utility maximizing choice after comparing other options (Taynor *et al.*, 1990; Klein, 2017; Zimmerman, 2012). Other applications of utility-theory have shown that fire managers are prone to framing effects and prefer to protect structures rather than ecological resources regardless of economic value (Calkin *et al.*, 2013, Wibbenmeyer *et al.*, 2013). Humanistic approaches have demonstrated how strategic decisions, specifically whether to manage a fire for ecological benefit are the product of sociopolitical, risk, and environmental factors considered through a process distributed across multiple individuals (Taynor *et al.*, 1990; Fillmore *et al.*, 2024). Thompson *et al.*, (2014) proposed that human factors affecting tactical decisions made during wildland fires could be categorized as social, institutional, and psychological and that managers are generally at

risk of adhering to simplifying rules that bias decision making. Finally, risk may emerge from poor communication on wildfires, which may be attributable to unfamiliarity with coworkers and overwhelming amounts of information during incident response (McLennan *et al.*, 2006; Nowell and Steelman, 2015). Lacking in the current literature is a framework for tactical decision making at the fireline supervisor (DIVS) level, which is the focus of this research.

California, USA experiences the largest wildfires and most costly wildfires in the country (Thompson, 2013; Hand *et al.*, 2017). In California, federal and state organizations are responsible for managing the risk associated with wildfire prevention and response, including the US Forest Service (USFS) and the California Department of Forestry and Fire Protection (CAL FIRE) (Starrs *et al.*, 2018). Starrs *et al.*, (2018) suggests that CAL FIRE, which is primarily responsible for state and private lands, tends to employ aggressive tactics relative to the USFS. Both agencies implement preventive measures, such as fuel treatments to mitigate the ecological, social, and economic impacts of wildfires (Starrs *et al.*, 2018). Additionally, these agencies must collaborate through formalized mutual aid agreements to coordinate firefighting resource allocation, evacuations, and incident management strategy (Nowell and Steelman, 2015; Carney *et al.*, 2023).

The 2020 and 2021 fire seasons in California produced large and destructive wildfires fueled by extreme drought, weather, and fuel conditions, straining the capacity of firefighting resources (Thompson *et al.*, 2023). Building on the work of Thompson, (2014) and Fillmore *et al.*, (2024), we investigate tactical decisions and their rationale on the 2021 Caldor Fire. Targeting DIVS as our sampling frame, we conducted GIS-map guided interviews during the Spring of 2022 to assess firefighting operations on the Caldor Fire to deepen our understanding of A) What were the tactical decision-making processes and their contributing factors, and B) How fuel treatments influenced decision making. This is part of a paired study, the second of which takes the tactical decision framework developed here and examines how decisions changed over time (Johnson *et al.* *In Review*). This research elucidates how mid-level incident management staff, who are largely responsible for tactical decisions, make those decisions and how fuel treatments can change suppression actions.

6.2 METHODS

6.2.1 Study Incident

Fire behavior, values at risk, and Incident Management organization varied during the Caldor Fire. While the fire was actively spreading (Aug 14-app. Sep 17) multiple IMTs assumed responsibility for operations on the fire due to maximum assignment lengths and changing operational complexity over time. Presiding management included a local Unified Command Team consisting of CAL FIRE and USFS personnel (Aug 14-18), 3 Type 1 IMTs (Aug 18-Sep 17) and multiple Type 2 IMTs (Sep 17-Oct 21). To assist with resource and operational fire management, a National Incident Management Organization (NIMO) assumed control of some operations on Aug 22, and on Sep 2 the fire was split into east and west “zones” managed by separate USFS and CAL FIRE IMTs. Threatened resources included sources of municipal drinking water, homes and communities, as well as energy and recreation infrastructure. Based on CAL FIRE damage inspection criteria (Henning *et al.*, 2016), 1,003 structures were destroyed, including approximately 450 out of the 600 homes in the community of Grizzly Flats

and an additional 330 structures located along Highway 50. Fuel treatment data shows that 16% of the Caldor Fire's footprint was treated by federal, state, or local agencies within the last 20 years (USFS, 2026; TRCD, 2026). Fire suppression forces constructed approximately 800 km of containment line of which 136 km or 17% overlapped with recorded fuel treatments (Arkowitz *et al.*, 2025).

6.2.2 Conducting Interviews

The Caldor Fire (Figure 12) was selected as a case study due to the incident's human impact, the density of fuel treatments within the fire's perimeter, and post-event reporting by federal agencies and media outlets emphasizing the inclusion of fuel treatments in incident response decision making (Safford and Saberi, 2026). Potential interviewees assigned to the Caldor Fire as DIVS were initially identified through Incident Action Plans, which are produced daily by IMTs and record resource assignments and high-level objectives. DIVS were selected due to their responsibility for implementing tactical actions to achieve strategic goals on sections of the fire's perimeter (Bigley and Roberts, 2001). We employed purposive typical case sampling, such that, we ensured a robust record of tactical decisions across the fire by not intentionally sampling individuals who were on operationally intensive divisions (Nyimbili and Nyimbili, 2024).

We interviewed USFS and CAL FIRE employees because these agencies were responsible for incident management, and our access to interviewees was limited by author-agency contacts. The experiences of interviewees who fulfilled additional roles, such as Engine Captain, Task Force Leader, or command staff positions were included in this analysis if interviewees demonstrated familiarity with operations when they were not assigned as a DIVS. To ensure saturation of tactical decision making on the Caldor Fire, we incorporated one participant who only fulfilled a position higher in the ICS organization chart than DIVS, but who was familiar with tactical operations across the duration of the fire (Bryman, 2016). Their exact position is omitted from this writing to preserve anonymity.

We conducted our interviews between February and April of 2022. Our interview protocol included a GIS-based visual elicitation tool (hereafter, map-elicitation) and closed and open-ended questions in three sections (Supplementary Materials) (Moore-Cherry *et al.*, 2015; Jackman *et al.*, 2022). Interviewees were encouraged to narrate their experiences, and probing questions elucidated additional details. The questions focused on decisions, decision rationale, decision outcomes, and risk tolerance with an emphasis on actions that incorporated fuel treatments. The risk tolerance questions were omitted from this analysis. The first section gathered demographic information and the first and third sections measured general perspectives on the tactical benefits and outcomes from fuel treatments. The second section utilized the map-elicitation tool to promote memory recall and facilitate narration of events. This portion of the protocol was iterative and completed for each shift an interviewee worked. In total, we conducted 13 interviews, gathering information over approximately 107 individual shifts.

6.2.3 Interview Analysis

Interview data were analyzed using a three-stage thematic coding process that incorporated inductive and deductive principles (Glaser and Strauss, 1998; Bryman, 2016). Interview transcription and editing was conducted with OtterAI transcription services ([Otter.ai](https://otter.ai)).

2025). Interview data were then analyzed using Nvivo 15.2 software to reveal distinct patterns and unique findings between interviews (Lumivero, 2025).

The following analysis is described in terms of codes/themes (groups of text sharing similar meanings), stages of analysis (topic, thematic, and analytic), and references (individual text section assigned to a code/theme) (Boyatzis, 1998). In the first stage of the coding process, topic coding, interview data were divided into broad reference groups and similar topics and associated data were aggregated. The second stage of the coding process, thematic coding, involved the creation of detailed themes. Transcript sections in this phase were shorter, allowing refined details to emerge from broader topics. Similar to topic coding, thematic coding involved the identification of nearly identical themes and aggregation. The final stage of the process, analytic coding, involved the regrouping of topics and themes by identifying relationships between codes. The final step produced a time-agnostic tactical decision making framework, and themes relevant to how fuel treatments were incorporated into decisions. Constructing a framework from qualitative data provides a managerially relevant synthesis of the analysis and enhances the communication of the long-form results (Tumiran, 2025).

The following results describe a time-agnostic tactical decision framework and its constituent themes and sub-themes. For an investigation of these themes over time in the context of incident management and fire growth, please see (Johnson *et al.*, *In Review*)

6.3 RESULTS

6.3.1 Tactical Decision Process Framework

Interview data revealed that tactical decisions on the Caldor Fire could be described using a process framework showing the pathways by which decision factors influenced decision types in pursuit of strategic objectives (Figure 13). Below, we elaborate on the descriptive criteria of analytic codes and constituent themes comprising the framework (Tables 1).

6.3.1.1 Decision Types

Emergent from interviews are distinct tactical decision processes we describe as Reactive and Anticipatory decision making, and Sequencing of Action (Figure 13). Anticipatory decisions reflect an increased decision space and were almost exclusively made following extensive discussion between interviewees, DIVS in command of adjoining sectors of the fire, and IMT personnel. These decisions considered potential fire behavior, impacts on values at risk, firefighting resource availability, and long term incident objectives. When conducting Anticipatory decisions, interviewees assigned resources to control the fire's perimeter with direct fireline or indirect firing operations in light of advantageous fuel and weather conditions. Conversely, when fire behavior was perceived as uncontrollable and structures were threatened, interviewees often deployed resources around homes well in advance of the fire front's arrival (e.g. *As we started to get a hold of the spot fire, that area there... started to be an area of concern just because of the potential impacts [on structures]... so we had to bolster that area with additional resources*"). This interview text provides an example of an Anticipatory decision, while acknowledging a Sequence of Action required to achieve their objectives.

Sequences of Action were descriptions of hierarchies of tasks (e.g. I need to accomplish x before y) established from incident management directives set forth by IMT members. Each task typically involved multiple Anticipatory decisions. Broadly, this process was categorized as either linear prioritization, risk-based prioritization, or shifting priorities. Linear prioritization occurred when a series of goals were established to accomplish a final objective (e.g. conducting mop-up after fireline has been constructed). Risk-based prioritization occurred when interviewees planned tactics in consideration of potential fire impacts (e.g. planning to address threats to structures before conducting perimeter control). Sequencing of Action could be both linear and risk based. An example of this would be conducting a firing operation in advance of a predicted fire spread event and assigning resources to ensure it remains contained after completion. Shifting priorities occurred when management plans changed because of current or predicted fire behavior. While Sequencing of Action typically preceded Anticipatory decisions, the nature of the fire behavior that frequently triggered priority realignment and subsequent reallocations of resources could force interviewees to react quickly.

The unexpected consequences of rapidly changing conditions reduced interviewees' decision space and challenged adherence to previously Sequenced Actions. At times, these circumstances forced interviewees to pivot into Reactive decision making, which was in response to existing rather than future conditions. While tactics were often developed in collaboration with adjoining DIVS, interviewees described fewer interactions with adjoining supervisors relative to other decision types when operating Reactively. These decisions included defensive firing operations around structures and perimeter control operations lacking extensive consideration of whether an action would be successful. Reactive decisions occurred most frequently during episodes of active and extreme fire behavior, occasionally resulting in close-calls of firefighter injury. One example is illustrated by this quote from an interviewee who initially describes a lagging decision followed by a rapidly Reactive decision resulting in risk to personnel (*"I kept pushing for you know let's get the torches out let's get ready to burn this and they were kind of like yeah I don't think that's going to happen... and then we pulled back... and then he took the folks back down in there... and they barely made it back out."*). Inevitably, even well planned tactics could result in Reactive decision making, such as unexpectedly changing weather conditions causing extensively planned containment line construction to fail. While these episodes did occur, the subsequent decisions to mitigate their outcomes were often determined by the environmental, risk, operational, resource, and institutional decision factors described below.

6.3.1.2 Decision Factors

Here, we describe decision factors' constituent themes and descriptive criteria relative to their influence on subsequent decision types (Figure 13 and Table 6). These factors are combinations of themes derived from interviewee explanations of the outcomes from and rationale for tactical decisions. Environmental themes included current fire behavior, fuels, topography, and weather conditions, time of day, and interactions between the environment and other factors. During the fire, aligned fuel, topography, and weather conditions (e.g. red flag conditions, fire moving upslope through dense vegetation) caused extreme fire behavior *"Some of the most impressive... in my entire career"*, inhibiting Anticipatory decisions and inducing Reactive decision making. Conversely, when perimeter control operations were successful, *"nonexistent"* fire behavior was often described when fire weather abated, or combustible fuels

were consumed (e.g. granitic features halted fire spread). These environmental conditions facilitated Anticipatory decisions by providing increased decision space, often in the form of options for fireline placement, and time. Time of day influenced diurnal weather patterns and interacted with other decision factors when resource availability and visibility changed. Decreased visibility made overhead hazard assessments of fire-damaged trees challenging (environment interacts with risk) and decreased the number of available firefighting aircraft and heavy equipment operation supervisors (environment interacts with resources). Conversely, interviewees reported improved outcome achievement as temperatures lowered and humidities increased at night. Additionally, the environment interacted with resource availability when heavy equipment operations ceased due to rocky and steep terrain, which slowed subsequent actions in pursuit of perimeter control.

Situations where firefighting resources were abundant, competent, well-rested, and supported logistically were generally conducive to Anticipatory decisions. Interviewees described how firefighting resource limitations reduced tactical options, “*Some of the normal tactics we did in the past... we just didn’t have the resources*”, creating conditions that could induce Reactive decision making and challenge the pursuit of strategic objectives. Resource competency and characteristic themes occurred when interviewees matched resources with appropriate assignments. This could include selecting a specific resource type to complete certain tasks (e.g. using skilled hand crews for complex firing operations) or providing additional supervision to resources unfamiliar with hazardous conditions such as extreme fire behavior adjacent to structures. Firefighting shift lengths on the Caldor Fire were often in excess of 24 hours. Interviewees indicated that firefighter fatigue impacted resource performance and was typically referenced in situations conducive to Reactive decision types. Reported fatigue influenced resource availability and competency when firefighting resources were actively engaged in operations for extended periods, leading to fatigue and reduced performance. Logistical support, such as food and water, was most frequently mentioned in reference to remote firefighting operations, and was noted to absorb considerable supervisor attention when it emerged. While we found these factors could contribute to Reactive decisions, interviewees generally incorporated resource limitations into Anticipatory decisions throughout the fire.

While coordinating operations, interviewees communicated with their supervisors, peers, and subordinates to reallocate resources toward high priority tasks, to plan and discuss tactics, and to execute plans. Communication failure (e.g. “*We tell them our problem areas... and we come back... and they were not in those areas*”) could induce hazardous situations and Reactive decisions, challenging progress toward pursued objectives. Conversely, disagreements during planning and discussion (e.g. denying the implementation of a firing operation) frequently occurred during sequencing of action and Anticipatory decision types. Although not all interviewees demonstrated negative affect towards disagreements, others indicated that they enhanced the exchange of information and ideas.

Other operational considerations include time to action, span of control, and situational awareness. The time to begin or finish an operational task was influenced by distance to assignment location, resource type and quantity, and the emergence of unexpected fire events. Span of control is the number of resources and individual operations an individual can manage without becoming overwhelmed. Themes relating to span of control include the fulfillment of multiple simultaneous roles (e.g. Division Supervisor and Engine Captain), delineating spatial zones of responsibility (e.g. division breaks), and resource management across large areas. To

avoid becoming overwhelmed, interviewees described additional coordination between peers and supervisors. One example mentioned multiple times was communicating to ensure incoming resources, such as firefighting aircraft, communicated with the correct supervisor when transitioning between assignments. Situational awareness facilitated Anticipatory decisions with interviewees describing taking time in the beginning of new assignments to gather information by conducting reconnaissance of their division, examining daily fire progression maps, or communicating with colleagues.

Risk factored into decision making through pre-emptive assessments and immediate concerns of fireline impacts, threats to infrastructure, firefighter and public safety, and emerging complexity from intersecting sources (complex risk). Pre-emptive assessments were noted frequently when firelines were established, threats to control known (e.g. fire damaged trees falling across firelines), and planned sequences of action were well established. Some interviewees described extreme challenges to control that nullified historically viable tactics, which were perceived to require nonstandard solutions to mitigate the continuation of atypical events (e.g. *“They had these little cracks in the granite that the fire kept going through and I wanted the retardant in there. So I'm probably wasting 95% of the retardant but that 5% in those little cracks. I wanted it in there to buy us time because [hot]shots would have to get down in there and there's a lot of country”*).

Immediate concerns emerged when fire spread threatened established or planned perimeter control efforts unexpectedly, often inducing Reactive decisions. Similarly, threats to infrastructure absorbed attention and resources and was frequently the primary impetus of decisions when structures were nearby and threatened. When non-firefighting personnel were present and in potential danger, risks to public safety prompted interviewees to divert from planned operations and evacuate members of the public. When repopulation of evacuated areas was ongoing, interviewees managed risks perceived by the public with actual risks to containment (e.g. extinguishing smoldering vegetation miles inside of the fire perimeter). Firefighter safety, while infrequently mentioned, was implicitly considered in many decisions such as conducting indirect tactics in lieu of direct attack during instances of extreme fire behavior. Some interviewees noted local resources and new supervisors could have higher safety risk tolerances, leading them to assign or accept high-risk assignments. One interviewee explicitly mentioned that firefighter safety only became the primary concern once perimeter control operations were nearing completion. Complex risk was typically the result of multiple ongoing operations during periods of active fire growth (e.g. *“So structure protection, structure group, active firefighting and a burn patient(s) all at once”*), almost exclusively inducing Reactive decision making as interviewees were forced to manage emergent risks.

Institutional factors mentioned during interviews included interagency culture and policy differences, shift lengths, organizational lag time, organizational change, and incorporating local knowledge. CAL FIRE interviewees frequently mentioned that the shift pattern differences between CAL FIRE and federal resources (24 vs. 16 hour shifts) challenged night-time staffing levels. Conversely, some USFS interviewees mentioned that CAL FIRE IMTs frequently moved federal DIVS between locations during assignments which challenged attempts to gain familiarity with assignment locations and conduct long term planning. Other differences included observations that federal resources did not engage in structure protection, were favored for fireline construction in locations distant from roads, and were more likely to favor indirect firing operations in lieu of direct attack. Organizational change occurred when incident management

transitioned, which facilitated innovative resource management while at times triggering organizational lag times for planning. Two prominent examples of innovative resource management were the creation of operational groups for specific tasks (e.g. creating specialized firing groups) and using local knowledge to support long-term planning. These two innovations converged when personnel assigned to specialized firing groups planned a complex firing operation that leveraged local knowledge of fuel treatments and common weather patterns. Additionally, these groups were able to use swing-shifts (shifts non-aligned with the typical 24 or 16 hours to leverage advantageous firefighting conditions) once the institutional support was in place to plan future operations. Lag times occurred when managing organizations were unable to produce planning documents at typical periods or left areas of the fire unstaffed because organizing features (division or zone breaks) had not been clearly defined.

6.3.1.3 Pursued Outcomes

Tactical decisions on the Caldor Fire were in pursuit of three primary outcomes: perimeter control, protection of property and life, and holding established fireline (Figure 13). Interviewees pursuing perimeter control described the construction of direct and indirect containment lines to arrest fire spread with the goal of constraining the fire's size. This outcome was primarily pursued with Anticipatory decisions, although some interviewees described Reactively attempting containment. The protection of property and life was indicated by interviewees making decisions to protect structures, evacuate the public, or to explicitly safeguard firefighter safety, such as by withdrawing resources to safety zones during episodes of unmanageable fire behavior. This outcome was pursued both in Anticipation of future fire effects and Reactively, when fire behavior became unmanageable. Holding established fireline occurred after perimeter control operations ceased and included mop up and patrol decisions to ensure that the fire remained inside of established boundaries. Holding established fireline was rarely the result of a Reactive decision, since those decisions typically occurred after the more challenging conditions experienced on the Caldor Fire.

6.3.2 Fuel Treatment Leverage

Interviewees used (leveraged) fuel treatments to increase their decision space, leading to improved firefighting effectiveness, time for operations, firefighter safety, to reduce risk to infrastructure, and management of operational and fire behavior uncertainty. The specific tactics used in conjunction with fuel treatments were indirect and direct fireline placement, safely accessing the fire perimeter, contingency line construction and increasing aerial firefighting effectiveness due to decreased fuel loads and increased penetration of water in thinned forest canopies (Table 7). Whether treatments were leveraged depended upon a suite of factors described in detail below.

6.3.2.1 Fuel Treatment Leverage Decision Factors

Interviewees favored large and connected fuels reduction projects, where multiple fuel strata were reduced, that were placed advantageously for fire management (along roads and/or ridgetops), that were recently maintained, and that considered local ecology. Small treatments did not improve suppression outcomes while the fire was actively spreading because they did not reduce fire behavior beyond treatment boundaries. After constructing containment lines through treatments, one interviewee described “[*Then the fire*] made its run through timber that wasn’t

treated and button hooked our control lines and our efforts in that area.” Interviewees discussing treatment type mentioned that mastication decreased flame lengths. However, the heat emitted from masticated fuel beds limited suppression in these treatments especially when masticated fuel beds were old and dry. Others emphasized the need for canopy fuel reduction done to reduce the likelihood of crown fire initiation as crucial to operations. Some interviewees described the challenges of managing fire behavior in fuel treatments with closed canopies, particularly when on federal lands. Incomplete and unmaintained pile burning units hindered control efforts due to their receptivity to ember cast. Once ignited, unburned piles resulted in large numbers of additional spot fires and significant localized heat that could overwhelm firefighters.

Other interviewees noted that local ecology was important, specifically in areas receptive to invasive annual grasses, such as roadside or masticated and burned fuel breaks. Areas where invasive grasses were introduced could act as a receptive area for firebrands, leading to rapid spot fire expansion in flashy fuels. However, these treatments could still increase suppression effectiveness due to decreased flame lengths relative to untreated fuel conditions. Due to the extreme conditions experienced during the 2020 and 2021 fire season, one interviewee indicated that fire management agencies should expand the construction of “Fuel Exclusion zones”, where all vegetation is completely removed.

All interviewees reported that some fuel treatments diminished fire behavior on the Caldor Fire, even during extreme conditions. However, during extreme conditions localized reductions in fire behavior were compromised by long distance spotting over treated areas (e.g. *“The fuel treatment may be okay for a normal fire. But some of the days... there was no way a fuel treatment’s going to work because it’s going to spot right over it.”*). During periods of rapid fire growth, some interviewees noted that treatments still increased the amount of time to make decisions to move resources or protect structures. This phenomenon was rarely mentioned and multiple instances of fuel treatments exhibiting ineffective influence on reducing fire behavior during extreme conditions were described in interviews.

Knowledge of treatment location was essential for treatments to be effectively incorporated into tactical decisions. All interviewees were aware of treatment locations at various points during the fire, although only one interviewee was informed of treatment locations through official channels. Others were local resources who had participated in treatment planning, were informed by local resources knowledgeable of treatment locations, or observed treatments when conducting reconnaissance to develop situational awareness. Knowledge of treatment location was often facilitated by long-term tactical planning facilitated by the IMT. Knowledge of treatment location helped conduct on-the-ground tactics irrespective of treatment type, intensity, or maintenance, because treatments are typically placed in locations with access and gentle topography.

Interviewees described preferences for specific types of resources to conduct operations in fuel treatments and the influence of treatments on the willingness to accept assignments. The resource type most frequently employed in combination with treatments were bulldozers, which could operate at increased speed as the amount of necessary work in treated areas was reduced. Interviewees were directly asked whether treatments increased resources’ willingness to accept assignments stated that this was the case. However, experience and additional circumstances

such as fire behavior and distances to safety zones exhibited a greater impact than fuel treatments on firefighting resources' willingness to accept assignments.

6.3.2.2 Fuel Treatment Leverage Outcomes

During the Caldor Fire, interviewees experienced highly uncertain conditions and limited tactical options due to rapidly progressing fire behavior and large areas of responsibility (i.e. large divisions) that challenged attempts to assess the feasibility of tactics. Fuel treatments were used to decrease firefighting uncertainty and decision space by providing known locations with decreased fuel hazard. For this reason, fuel treatments were incorporated into planning to increase the likelihood of firefighting success, expanding available options, and acting as landmarks for physical orientation. When hazards from unpredictable fire behavior or challenging terrain limited opportunities for control, interviewees viewed fuel treatments as some of the only places where firefighters could safely and effectively engage the fire. While considering adjacent operations that he considered unnecessarily risky, one interviewee described fuel treatments this way *“When you have fuel treatments a mile away, and it's a backing fire and a road to get people out safely. I'd be more willing to do that. At the end of the day, well, where are you going to tie it in? Because the whole mountain range is not forgiving ground.”*.

In addition to acting as zones of increased certainty, fuel treatments were used to increase available time for decision making. While some interviewees described decreased fire behavior as contributing to increased time for decision making, interviewees described the decreased workload required in fuel treatments as the primary influence on increased decision making time *“It's easier to see through the forest, to see your landmarks, to see where you're heading. You know crew captains are going to be able to hang flags farther. Your hand crews are going to push line faster. Your dozers are going to be able to push line faster.”* Firefighters were able to move more quickly through fuel treatments because less fuel required removal to complete and prepare containment lines. Once firefighters completed activities inside of fuel treatments they were available for assignments elsewhere on the fire, increasing efficiency.

Interviewees described how fuel treatments provided firefighter safety and increased opportunities to achieve infrastructure protection objectives. Treatments provided access to the fire's edge, serving as areas where safety zones could be quickly constructed or, when constructed along roadways, to shelter from intense fire behavior. Fuel treatments around structures allowed firefighters to protect infrastructure during periods of rapid fire growth. For example, one interviewee described how treatments allowed firefighters to remain on scene and defend structures for longer periods of time than would have otherwise been possible had the area not been treated *“Even though it didn't meet with a lot of success. We were very, very aggressive all night and eventually started making progress. We probably would have completely pulled out of Grizzly Flat altogether had they not had the extensive fuels work in there they'd done.”*

Interviewees reported that the outcomes provided by fuel treatments allowed firefighters to more effectively plan and enact operations due to reduced fire hazard and increased probabilities of success. Interviewees described multiple examples of complex direct and indirect containment operations that were planned to connect areas with decreased fuel loading. Many of these areas were completed fuel treatments placed near communities, along roads, and on ridge tops. Some interviewees who participated in these operations described the presence of fuel

treatments as critical to the operations' success. For example, one interviewee noted *"the fuels projects definitely dictated where we started and where we went. And it ended up being one of the few successful plans on the whole fire for the first week or two."* In reference to a complex firing operation that contained a substantial portion of the fire's perimeter.

While fuel treatments increased firefighting effectiveness and safety, interviewees stated that they were not a panacea to the challenges posed during the Caldor Fire's management. Already planned tactics were unlikely to be altered specifically to take advantage of fuel treatments if objectives could be achieved in a different location that kept the fire smaller or further away from structures. One interviewee noted that timing is a key factor *"It's all a timing thing. If you don't have time to get ready for it and if it doesn't hit your fuel project at the right time, then it's going to be useless."* Another described how many areas on the Caldor Fire feature natural barriers to fire spread, like rock outcroppings, or naturally occurring reduced fuel profiles, and that decision makers are not necessarily looking for areas that have undergone fuels reduction *"I mean it was pretty open and it was a perfect opportunity for us to try and pick it up and... it hadn't been treated."*

6.4 DISCUSSION

Our decision process framework for the 2021 Caldor Fire provides insight into the influence of incident management on fireline-level tactical decisions. Tactical decisions were bifurcated, being either rapid and Reactive or deliberate and Anticipatory of future fire impacts, which typically occurred as part of a planned Sequence of Actions. These decisions were motivated by operational, environmental, resource, risk, and institutional factors in pursuit of three distinct outcomes: protection of property and life, perimeter control, and holding pre-established containment line (Figure 13). Tactical decision space and the uncertainty of future fire behavior was influenced by the presence of areas where wildland fuels had been intentionally modified. These fuel treatments were incorporated into tactical decisions to increase containment effectiveness, resource efficiency, and firefighter safety.

6.4.1 Tactical Decision Processes on the Caldor Fire

Our work advances concepts established in prior analyses of incident management strategy (Canton-Thompson *et al.*, 2008; Thompson, 2014; Fillmore *et al.*, 2024). These studies established qualitative categorizations describing the drivers of high-level incident management decisions. In our descriptive framework we narrow our focus to tactical decisions. These decisions are influenced by incident strategy, but typically occur at lower levels of the ICS organization chart relative to previously sampled populations (Figure 11). Additionally, we describe different decision processes and outcomes as they emerged from the themes of fireline supervisor interviews. In many regions across the globe incidents similar to the Caldor Fire are predicted to increase, lending additional relevance to our findings (Pausas and Keeley, 2021).

We found that fireline-level decisions were driven by operational, resource, institutional, environmental, and risk considerations. The descriptive criteria of these factors influenced the types of decisions interviewees conducted. We posit that the differences between our findings and similar research are primarily a product of our sampling frame, the use of an individual case study fire, and the narrowed emphasis on tactical decisions (Canton-Thompson *et al.*, 2008; Thompson, 2014; Fillmore *et al.*, 2024). Tactical decisions are implicitly different from strategic

decisions in temporal and spatial scope (Castellnou *et al.*, 2019; Pietruszka *et al.*, 2023; Pietruszka *et al.*, 2024). For example, the strategic decision to manage a wildfire for resource benefit impacts all tactical decisions for the duration of a wildfire. Conversely, the decision to construct direct fireline or conduct a defensive firing operation during structure protection on a large wildfire may not dictate subsequent actions. While exceptions exist (Rapp *et al.*, 2021), this minutiae reflects a crucial difference in units of analysis not previously investigated in empirical fire management decision studies.

Our findings for decision types echo foundational decision making research on expert decision making in the face of uncertainty and time pressure on wildfires (Taynor *et al.*, 1990; Zimmerman, 2012; Klein, 2017). Decisions coded as reactive were typically driven by constraints in time, resources, and information in the face of uncertain fire behavior and impacts. These conditions mirror the impetus for the design of the Recognition-Primed Decision model, where experts in time pressured environments select the first best solution to a problem based on previous experiences, mentally simulate the decision, and reevaluate and select the next option if the original choice does not lead to the desired outcome (Klein, 2017). This model limits the requirement for deliberations and provides satisfactory solutions when experts have previously experienced similar situations. However, Reactive decisions may be ill-suited during extremely large fire spread events driven by climate change and fuel accumulation and when resources are scarce (Pausas and Keeley, 2021; Thompson *et al.*, 2023). Indeed, interviewees indicated that the aforementioned factors did limit their tactical space and effectiveness. Important to note is that the Caldor Fire burned simultaneously to the Dixie Fire, which at its peak was assigned one quarter of firefighting personnel in the United States (Thompson *et al.*, 2022), which likely strained the ability of local incident managers to deploy resources on the Caldor Fire. As instances of multiple simultaneous large wildfires increase, fireline level decision makers will continue to be challenged, especially during emerging incidents (Thompson *et al.*, 2023).

When time for deliberation, abundant resources, institutional support, and information were abundant, interviewees Sequenced Actions and made Anticipatory decisions, which collectively resemble the rational choice model described in Klein *et al.*, (2017). The rational choice model describes when experts actively compare the strengths and weaknesses of solutions to a problem and select the choice that will achieve the best solution (Zimmerman, 2012; Klein, 2017). In a discussion of the utility of decision support systems, the rational choice model was suggested to only be employed on wildfires when there is ample time and information for decisions (Zimmerman 2012). Our results show that these decisions were typically the product of deliberation between multiple personnel (Taynor *et al.*, 1990), often dictated by IMT members established directives.

It is important to note that personnel in DIVS positions are typically working with different information relative to IMTs. IMT members may have a suite of tools to support decision making, including dynamic spatial mapping and fire modeling products (Zimmerman, 2012; Dunn *et al.*, 2017; Calkin *et al.*, 2021). While DIVS may periodically have access to this information, Anticipatory decisions were initially informed by IMT member objectives, and often shifted according to localized information and fire behavior. Under ideal circumstances, IMTs use the information available to them to inform and support division supervisor decision making, however, there is risk that the siloing of information amongst the different levels of the ICS organization chart may perpetuate sub-optimal outcomes during rapidly changing incidents. Current solutions to this problem exist in the Incident Strategic Alignment Process (ISAP), which

seeks to connect and inform various stakeholders of incident management so that risk definitions are shared and sources of uncertainty are mutually understood (Buettner *et al.*, 2025).

6.4.2 Fuel Treatments Affect Decision Making

In comparison to the Caldor Fire tactical decision framework, fuel treatments changed environmental (e.g. fuel conditions) and risk factors (e.g. potential fire behavior), and their use was frequently dictated by operational (e.g. reconnaissance and coworker communications) and institutional concerns (IMT facilitated planning). Importantly, their incorporation into larger plans was dependent upon collaboration with local agency staff familiar with fuel treatment planning and construction (Greiner *et al.*, 2025). Existing frameworks leverage local treatment knowledge for pre-fire planning (Thompson *et al.*, 2022). To achieve successful use in the future during incidents like the Caldor Fire, frameworks designed for wildfire response communication, like ISAP (Buettner *et al.*, 2025), may seek to connect local fuels staff to IMT and DIVS responsible for tactical planning.

When in known locations and over large enough areas, fuel treatments increased interviewee decision space by providing options for containment line placement with improved safety and access (Greiner *et al.*, 2025). However, interviewees placed containment lines where they believed it was most likely to be successful, regardless of whether or not fuel treatments were present. This reflects previously established findings on large fire containment, which is generally a function of advantageous weather rather than firefighting effort (Finney *et al.*, 2009; Young *et al.*, 2024). With unpredictable fire weather increasing, recent investments in fuels management will need to increase substantially to ensure fuel treatments are available for firefighting leverage under conditions when operations can be effective (North *et al.*, 2015).

The construction of containment line is typically accompanied by “preparation”, or the removal of surface fuels within a set distance of down-to-mineral-soil fireline (Hirsch and Martell, 1996; Plucinski, 2019). During indirect line construction, surface and ladder fuels may be removed a considerable distance, while removal adjacent to firelines during direct line construction may be less intensive as the fuel may already be involved in combustion (Plucinski, 2019). Interviewees described how fuel treatments reduced the workload required for direct and indirect fireline construction, slowed rates of spread, and provided good locations to stop fire progression during favorable conditions. However, researchers should take note that the decision making component of fireline placement (firefighters place firelines in areas with lower fuel loadings relative to adjacent areas regardless of whether they were intentionally treated), may confound future quantitative assessments of firelines constructed inside of fuel treatments if these firelines are compared to untreated lines (Young *et al.*, 2025). Accurate assessment of the benefits of fuel treatments for wildfire operations will benefit from additional data on the work capacity and locations of different resources working on complex wildfires (Thompson *et al.*, 2017).

6.5 CONCLUSION

Wildland fire managers face heightened uncertainty and time pressure as increasingly unpredictable fire behavior occurs on incidents burning near values at risk. The Caldor Fire is one example of such a wildfire, and since the time of burning, other rapidly growing fires have

entered the growing list of highly destructive wildfires in California state history, such as the Palisades and Eaton Fires in January, 2025. This paradigm lends relevance to our analysis of decision making on the Caldor Fire, which reflects conditions decision makers will face in increasing abundance in the near future.

6.6 TABLES

<u>Operational</u>	<u>Environmental</u>	<u>Resource</u>	<u>Risk</u>	<u>Institutional</u>
Communication	Fire behavior	Resource availability	Pre-emptive mitigation	Interagency differences
Time to action	Time of day	Competencies and characteristics	Threats to infrastructure	Shift lengths
Span of control	Fuels, topography, and weather	Resource fatigue	Immediate concerns	Organizational change and lag time
Situational awareness	Interactions with other primary themes	Logistical support	Firefighter and public safety	Incorporating local knowledge
-	-	-	Intersecting sources of risk increase complexity	Organizational change

Table 6: General themes associated with Decision Factors from interviews of Caldor Fire operational decision makers.

<u>Leveraging Treatments</u>		
<u>Decision Factors</u>	<u>Uses</u>	<u>Outcomes</u>
Treatment characteristics (size, location, type, and intensity)	Containment line	Increased firefighting effectiveness and efficiency
Treatment location knowledge	Anchoring line placement	Reduce uncertainty from fire behavior
Fire behavior approaching and inside of treatments	Fire perimeter access	Increased time for operations
Firefighting resource characteristics	Contingency line construction	Reduced risk to infrastructure
Alignment with decisions in time and space	Aerial suppression	Increased safety

Table 7: Themes associated with the decision factors for, uses of, and outcomes of treatment leverage on the Caldor Fire.

6.7 FIGURES

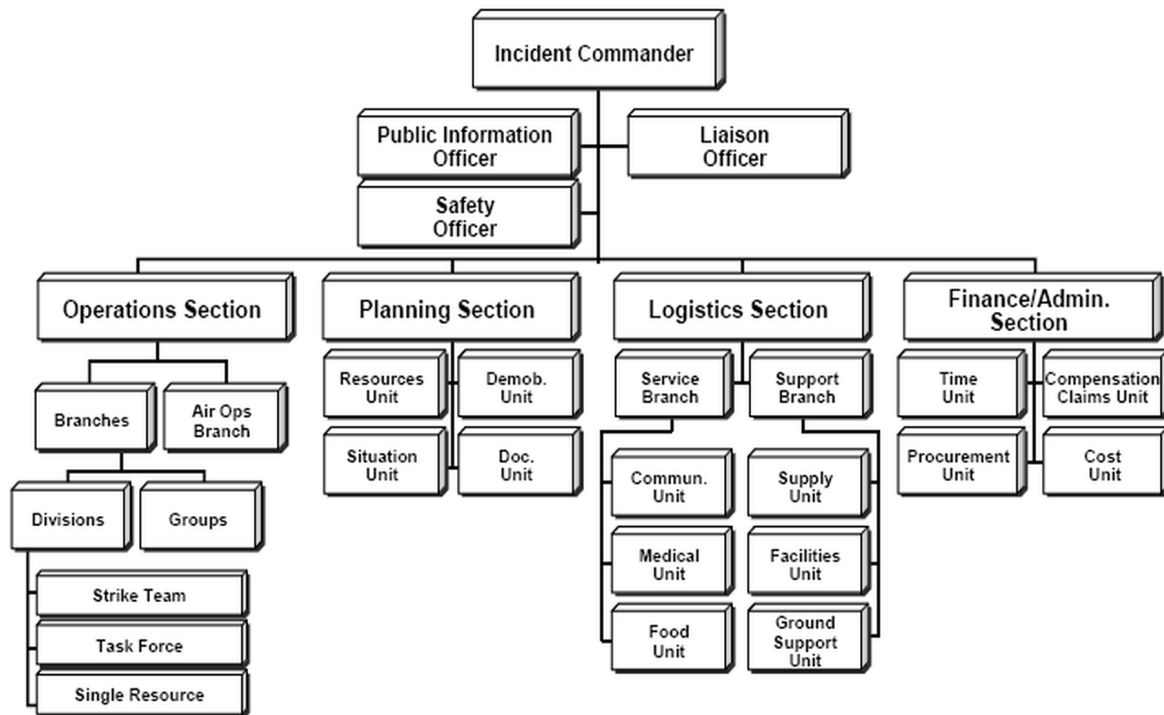


Figure 11: The Incident Command System Organization Chart (FEMA, 2017). This structure, originally developed for wildfire management in Southern California, USA, has been widely adopted for emergency response in the United States and other countries. Interviews in this study targeted primarily Division Supervisors, and included individuals in Branch and Command and General Staff positions.

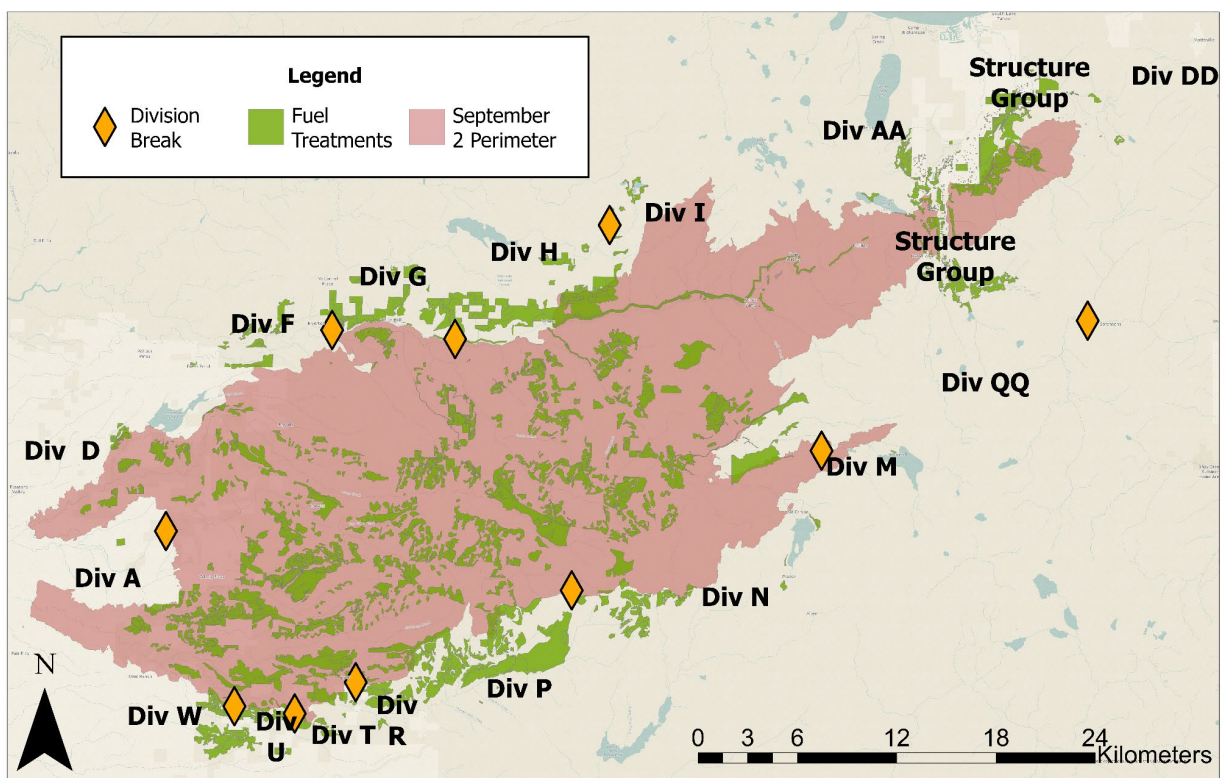


Figure 12: Map of the Caldor Fire perimeter on September 2, 2021 with Division names, division breaks, and fuel treatments. Division breaks are labeled by orange diamonds. If a division break does not appear between two division labels, it was not available in the incident GIS data published for September 2.

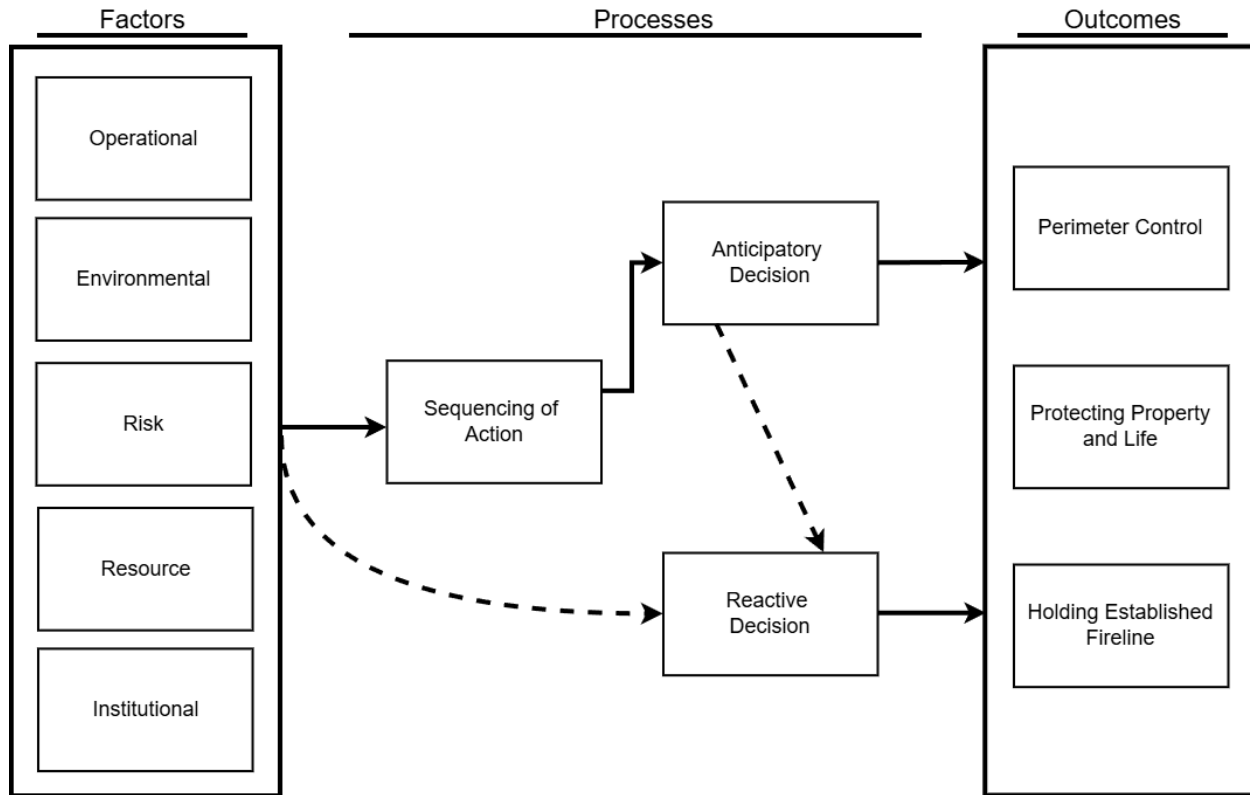


Figure 13: The Conceptual Decision-Making Framework illustrates the Decision Factors (left) that determine subsequent Decision Processes (center) and Pursued Outcomes (right) created from Caldor Fire interviews of operational personnel. The dashed lines between decision factors and Anticipatory Decisions with Reactive Decisions indicates that some situations contain combinations and levels of decision factors that result in A) bypassing Sequencing of Action into immediate Reactive Decision Making or B) nullify previous planning and objective-setting due to rapidly changing conditions, resulting in Reactive Decision Making. All decision processes may be in pursuit of the same Outcomes, although the frequency of pursuit may vary.

7 **TRANSITION**

The time agnostic tactical decision framework presented in the previous chapters provides unique insights into fire management decision making at a level not previously explored with humanist methods. While it provides a detailed generalizable set of conditions and decisions for fire management tactical decisions, it leaves unexplored the influence of time relevant factors and how they influence decisions on a large wildfire. To shed light on the influence of incident management organization, fire behavior, and their interactions on tactical decisions, in the following chapter the themes that compose the framework, are categorized by the day on which they occurred. Then, the Caldor Fire’s timeline is split into four “Operational Phases” using fire behavior and incident management team transition, revealing the stabilizing influence of organized incident management on uncertainty.

8 THE INTERWOVEN INFLUENCE OF FIRE BEHAVIOR AND INCIDENT MANAGEMENT CHANGED DECISIONS OVER TIME ON THE 2021 CALDOR FIRE

8.1 INTRODUCTION

Multiple state and federal organizations are responsible for enforcing the rules and norms of wildfire management in the United States (Nowell and Steelman, 2019). To rapidly plan and execute strategy and tactics during large wildfires, these institutions mobilize Incident Management Teams (IMTs) (Bigley and Roberts, 2001; Thompson, 2013; Buettner *et al.*, 2025). IMTs are temporary organizations, hierarchically structured under the Incident Command System (ICS) to streamline decision making (Bigley and Roberts, 2001; Thompson, 2013). Top-down decision making can prevent decision paralysis and facilitate objective-setting during hazardous fire management operations (Nowell and Steelman, 2019). However, the proliferation of large wildfires, which increase in complexity as they spread across jurisdictional boundaries and threaten Wildland Urban Interface or Intermix areas (WUI), challenges the current paradigm (Thompson, 2013; Thompson *et al.*, 2023).

Incident complexity emerges from intersecting sources of uncertainty, including from fire behavior, firefighter and public safety, exposure to values at risk, and increasing numbers of involved actors (Thompson and Calkin, 2011). Ideally, IMTs manage uncertainty by improving information flow, firefighting resource allocation, setting strategic objectives, facilitating planning, and decentralizing decisions to on-the-ground decision makers, such as Division Supervisors (DIVS) (Bigley and Roberts, 2001; Thompson and Calkin, 2011). However, as operations become increasingly heterogeneous over large areas, uncertainty and time-pressure may cause vertically structured decision making to break down, potentially leading to longer and more hazardous incidents. (McLennan *et al.*, 2006; Bearman *et al.*, 2014; MacGregor and González-Cabán, 2011; Thompson, 2013). These dynamics are well explained by complexity theory, which ascribes uncertainty to the intersections of multiple, rather than individual systems (Thompson, 2013; Walton, 2014; Young *et al.*, 2024). Complex systems move away from and towards “attractor states”, phases of stabilization during which uncertainty decreases and decision making improves, which should reflect in instances of well planned tactical decisions (Walton, 2014; Young *et al.*, 2024).

Ample evidence exists that variation in management decisions between incidents are attributable to IMTs and regional influence (Thompson, 2013; Hand *et al.*, 2017; Katuwal *et al.*, 2017). Resource ordering and strategic decisions are explained by numerous factors, including proximity to structures and growth potential, however, much of this variation can be explained by individual decision makers and their risk preferences (Wibbenmeyer *et al.*, 2013; Calkin *et al.*, 2013; Hand *et al.*, 2017; Fillmore *et al.*, 2024). More resources are often assigned to fires than is necessary to completely contain active spread, which may be attributable to resource hoarding behavior in the event of containment failure or new ignitions nearby (Holmes and Calkin, 2013; Hand *et al.*, 2017; Katuwal *et al.*, 2017). Investigations of regional differences have demonstrated wildfires in California are typically assigned more resources to fires that are contained quickly relative to other regions (Thompson, 2013; Hand *et al.*, 2017). Potential

explanations to these trends include aggressive suppression policies and a large preponderance of WUI communities (Thompson, 2013; Hand *et al.*, 2017).

On a single wildfire, temporally simultaneous operations can be highly variable, although activities may become homogeneous as containment is achieved (Katuwal *et al.*, 2017; Dunn *et al.*, 2017; Simpson *et al.*, 2019; Plucinski, 2019). Research investigating the heterogeneity of wildfire operations and decision making have temporally segmented events using fire behavior changes and incident management transitions (McCool *et al.*, 2006; MacGregor and González-Cabán, 2011; Katuwal *et al.*, 2017; Plucinski, 2019; Simpson *et al.*, 2019). Investigations of decision making have segmented decision making into pre-fire, during fire, and post-fire by different decision making groups (communities, agencies, and individuals), whose decisions in one phase will affect themselves and others in subsequent phases (McCool *et al.*, 2006). MacGregor and González-Cabán, (2011) developed “event-frame” models of incident management decision making by dividing fires by incident management transitions and fire behavior and examining decisions collated from official documentation and interviews and categorizing these decisions using different models for decision making. They found distinct differences between Initial and Extended Attack decisions, and emphasized the importance of incorporating local knowledge, and pre-fire planning (MacGregor and González-Cabán, 2011). Temporal segmentation of fires is vital to understand decisions, and previous studies have primarily focused on coarse model development in lieu of emphasizing the multiplicity of individual tactical decisions made on wildfires to achieve objectives. This leaves a gap for a study focusing on the tactical decisions and factors made by on-the-ground decision makers for a large and complex wildfire.

An opportunity exists to examine the nature of the decentralized decisions made on large wildfires. Specifically, how they occur, and how these decisions are influenced by changes in incident management structures over time. Using the 2021 Caldor Fire as a case study example, we established four operational phases after constructing an incident timeline with fire growth and incident management data (MacGregor and González-Cabán, 2011). To better understand how tactical decisions change over time, we used themes derived from DIVS interviews from Johnson *et al.*, (*In Review*) to examine the influence of pre-fire mitigation, changing incident management, and the fire environment on decisions over time. Additionally, we provide insight on interviewee perceptions of key events on the fire which were highly publicized in the media, such as the “Miracle at Christmas Valley”, where very few structures were lost during a large spread event (Safford and Saberi, 2026).

8.2 METHODS

8.2.1 Study Incident

The Caldor Fire was reported east of Omo Ranch, California, in the Eldorado National Forest at 1854 PST on August 14, 2021 at approximately 900m ASL (ONCC 2021). The fire was managed under a full-suppression strategy, and was declared 100% contained on October 21st after burning 89,773 ha (Safford and Saberi, 2026). The Caldor Fire’s rapid spread was influenced by the variable biophysical and climatic conditions across its footprint (Figure 14). Vegetation in the fire’s footprint was typical of 900-2700m ASL elevations in the Northern Sierra Nevada. At lower elevations crown-fire adapted chaparral, dominated by *Arctostaphylos*

(manzanitas) and ceanothus, persists accompanied by frequent-fire pinus ponderosa (ponderosa pine) and jeffreyi (Jeffrey pine) dominated pine-mixed conifer forest. As elevations increase, the natural range of species adapted to higher severity fire, such as abies magnifica (red fir) and pinus contorta (lodgepole pine) is reached, and patches of bare granite and soils become common (LANDFIRE, 2016). Precipitation ranges from annual averages of 1006 mm on the western fire perimeter to 867 mm toward the east, with the majority of rainfall occurring between October and April (WRCC, 2026; Safford and Saberi, 2026). Fuel availability was influenced by long-term drought (Wang *et al.*, 2022), and Red Flag Warnings and Fire Weather Watches were present 11 out of the 60 days the fire was reported as uncontained (Figure 15).

8.2.2 Interviews

Between February and April of 2022 we conducted event-centered calendar based interviews of USFS and CAL FIRE DIVS who worked on the 2021 Caldor Fire. Centering our analysis on a single event facilitates elicitation of chronological descriptions of a wildfire incident (Jackman *et al.*, 2022). Our interview protocol consisted of closed and open ended questions that were repeated for each day the interviewee was assigned to the fire. If an interviewee fulfilled additional roles, we asked about tactical decisions on these days as well. Additionally, we supplemented our interviews with an individual who only fulfilled a position above DIVS in the organization chart, to ensure saturation (Bryman, 2016). We interviewed 13 personnel in total, collecting individual daily accounts of approximately 107 shifts (Figure 16).

During interviews, we used a GIS based calendarized map-elicitation tool to enhance participant memory recall and encourage interactivity and narration of daily events on the Caldor Fire (Figure 17) (Moore-Cherry *et al.*, 2015; Jackman *et al.*, 2022). The map in question was created from a collection of fire perimeter, operational (division breaks, drop points), and fuel treatment data and presented using an online map (Arkowitz *et al.*, 2025; USFS, 2026; TRCD, 2026). Visual elicitation methods encourage interviewees to provide additional details on characteristics of the visualized material and reveal more nuanced experiences relative to standalone interviewing (Orr *et al.*, 2020). For additional information regarding our methods, see Johnson *et al* (*In Review*).

8.2.3 Defining Incident Management Phases

We examined the influence that fire growth events and IMT transitions (MacGregor and González-Cabán, 2011) had on reducing uncertainty in the context of four “Operational Phases.” These phases should represent shifting attractor states where the stability of the decisions in terms of uncertainty management is apparent (Walton, 2014).

The first phase (Phase 1: Reactive-Initial) began on August 14th when the Caldor Fire was reported and ended when a Type 1 Incident Management Team established command on August 18th. The second phase (Phase 2: Stabilizing Organization) then begins and ends when the stability offered by the IMT is tested as the fire approached Echo Summit, impacting numerous structures along Highway 50 and threatening communities south of Lake Tahoe (Table 8). The third phase (Phase 3: Challenging Stabilization) lasted from August 29th until September 2nd, when the fire was split into two zones, each of which having a Type 1 IMT in control of operations. The fourth phase (Phase 4: Stabilized Recovery) lasted until the fire was declared fully contained on October 20th (Table 9). Information to establish these phases was extracted from Incident News and Notes on the Northern California Geographic Coordination Center’s

website (ONCC, 2021) and from the triangulation of fire spread events using interview data and changes in infrared detected fire perimeters.

Although we suggest that the 4th phase ends on October 20th, interviewees were asked to comment on actions taken through September 16th, when the fire exceeded 70% containment. Katuwal *et al.*, (2017) found that, on average, perimeter control operations were complete when fires reached 70% containment. Inaccurate self-reporting of containment may be attributable to incomplete mop-up, where smoldering material is fully extinguished a set distance away from the containment line, lack of confidence in completed mop-up, or so that IMTs can reach the ends of their official assignments (typically 14 days) (Katuwal *et al.*, 2017). On the Caldor Fire, a firing operation on the southwest was completed that added an additional 1,200ha after interviews ceased, although the fire had not grown in the 7 prior days (Figure 15).

8.2.4 Analysis

We analyzed interview data using a three-stage thematic analysis incorporating inductive and deductive principles. The themes were used to construct a tactical decision making framework for decisions made on the Caldor Fire. For an in depth explanation of the tactical decision making themes agnostic of time, see Johnson *et al.*, (*In Review*).

Temporal analysis was completed by creating a matrix of post analytic stage themes with the phase case values described above (Simpson *et al.*, 2019). Separate case values were created for each day between August 14th and September 16th. Transcript sections with material covering a specific day were assigned the associated case value, and days were grouped into the phases described in section 3.2.3, to facilitate temporal phase analysis (Table 8 and Table 9). The proportional magnitude of each code was then examined inside of each phase, facilitating the assessment of trends in decision making as they relate to the operational phases (Figure 18). We use the Incident Management Phases described above to disaggregate the decision making framework, allowing us to infer the relationship between the fire-environment, incident management, and on-the-ground decision making illustrated by changes in magnitude and qualitative details of the framework components over time.

8.3 RESULTS

8.3.1 Framework Description

Here, we begin with a brief explanation of the decision factors, types, and outcomes described in detail in Johnson *et al* (*In Review*). Decision factors are inputs to decision types and can be categorized into environmental, operational, institutional, resource, and risk information bins. Decision factor descriptive criteria (e.g. is fire progression slow or rapid?) influenced whether interviewees entered reactive (rapid fire progression) or anticipatory (slow fire progression) decision types. Anticipatory decisions involved actions proportional to expected fire behavior or effects, which were typically preceded by hierarchical sequencing of action, the consideration of actions necessary to achieve subsequent goals. Conversely, reactive decisions were in response to immediately perceived hazards rather than a proportional response to current and predicted fire behavior. The pursued outcomes of tactical decisions included perimeter control, protection of property and life, and preventing fire from breaching established firelines.

Below, we elaborate on how these decisions, decision factors, and outcomes changed over time on the Caldor Fire.

8.3.2 Tactical Decisions Over Time

The relative magnitudes of decisions across operational phases reveal how decisions changed as the Caldor Fire progressed, incident complexity increased, and incident management transitioned (Figure 18). Phase names were derived from their density of decision types with greater amounts of anticipatory decisions indicating movement towards stability (i.e. decreasing levels of uncertainty). Below we present the thematic composition of each phase, justifying phase separation and explaining the impact of incident complexity on tactical decision making.

8.3.2.1 Phase 1: Reactive-Initial

Relative to other phases, the Reactive-Initial Phase (Aug 14-Aug 17) is characterized by a large magnitude of operational decision factors, reactive decision types, and life and property protection objectives. During this phase, red flag conditions on August 15th coincided with a large spread event when the fire grew to approximately 21,600 ha (Figure 15). During this time the US Forest Service and CAL FIRE organized a Unified Command structure to manage the fire (Table 8). Values at risk included the communities of Grizzly Flats and Leoni Meadows, and the Consumnes River watershed. The fire remained 0% contained for the duration of this phase (ONCC, 2021).

Interviewees reported that attempts toward perimeter control were repeatedly unsuccessful in this phase. During initial attack efforts, interviewees described how priorities shifted as firefighters Reactively disengaged, re-engaged, and ultimately abandoned suppression efforts. When suppression operations resumed the following morning, environmental, operational, and resource factors emerged as firefighters struggled to determine the fire's exact location due to rapid rates of spread through dense forest fuels. This hampered communication among resources and created hazardous working conditions. As the fire expanded from its origin on the 15th, the lack of suppression resources created additional challenges during attempts toward perimeter control and structure protection (Table 10).

The fire spotted over Dogtown Creek on the 16th and approached the communities of Grizzly Flats and Leoni Meadows. On the evening of the 16th, interviewees reported that planning for the defense of these communities began in earnest in Anticipation of the fire's arrival. Tactical decisions included a Reactive attempt to stop the fire using roads that had been buffered by previous fuels thinning and broadcast burning treatments (Table 8). In reference to the attempted perimeter control directly adjacent to structures at Leoni Meadows one interviewee observed that *"he took the folks back down in there to try again and they barely made it back out."* Another described fire behavior that exceeded expectations set over the course of a long firefighting career *"30 years in my career, and we'd never had a fire spread at night even close to that."* As the fire impacted Leoni Meadows and Grizzly Flats in the late night and early morning of August 16th and 17th, interviewees Reactively attempted to complete evacuations of the remaining residents. Intersecting sources of risk converged as firefighters simultaneously dealt with burned evacuees and attempted structure defense. Some US Forest Service personnel left Grizzly Flats as the fire impacted the community due to poor communication from their

supervisors and institutional policy requirements mandating work to rest ratios ensuring that they would be available for work during the following shift.

Interviewees reported a mixed influence of fuel treatment on tactical decisions and effectiveness during this phase. One interviewee not assigned as a DIVS at the time reported that the extensive private and federal fuel treatments around communities mitigated the worst outcomes because they increased firefighter safety and structure protection effectiveness *“a lot of the stuff we did in Leoni Meadows and in and around Grizzly Flats we wouldn't have even tried. A lot of this stuff along Sly Park. We used the areas that we did based on where the fuel treatments were. I'm not sure what we would have done had they not been there.”* When leveraged explicitly for perimeter control, treatments were reportedly much less effective. Interviewees reported instances where industrial clearcuts burned through too quickly to be leveraged for fireline placement, and areas on federal land initially treated with prescribed fire but not subsequent canopy fuel removal were reburned too intensely to be effective.

While some successful containment line was constructed near the heel of the fire, the general thematic patterns we found are encapsulated by this interviewee: *“there wasn't a lot of [successful] perimeter control at the time. We were just over stressed with [a lack of] resources and the amount of fire on the ground... that was almost a 72 hour shift by the time we got released.”* The extreme fire growth during this phase and impact it was having on communities prompted the ordering of a Type 1 IMT on the morning of Aug 17th.

8.3.2.2 Phase 2: Stabilizing Organization

The Stabilizing Organization Phase (Aug 18-Aug 28) features an increased magnitude of environmental and firefighting resource factors, as long term planning and resource quantity increased. Consequently, more sequencing of action, anticipatory decisions, and perimeter control are observed (Figure 18, Table 10). Red flag conditions persisted Aug 18th-19th, Aug 21st, and a fire weather watch was reported on the 28th. The fire grew by 38,990 ha, reaching 60,604 ha in total size, threatening communities and recreational areas along Highway 50 and Highway 88 (Figure 14). A Type 1 CAL FIRE IMT assumed unified command with the El Dorado National Forest on Aug 18th. On Aug 27th, a National Incident Management Organization IMT composed of full-time incident managers who specialize in innovative management approaches, supplanted the Eldorado National Forest in the Unified Command structure (Table 6). During this phase the fire's reported containment reached 19% (ONCC, 2021).

Line progression extended from an anchor near the heel of the fire, south of the origin, to the west, north, and east. Interviewees described how progress was facilitated by environmental and institutional factors including subsiding fire weather, stabilizing atmospheric conditions, and institutional support from the IMT that began long term planning of perimeter control operations. Anticipatory planning provided time to evaluate and leverage improving conditions and control opportunities, access local knowledge, increase situational awareness, and improve resource allocation.

Interviewees reported concerns about an east wind event, which are common in the area, could threaten communities west of the fire including Somerset and Pleasant Valley. In Anticipation, a specialized firing plan was developed that leveraged local knowledge to contain

the western perimeter. The plan connected federal fuel treatments, agricultural areas, a large fuel break constructed by community members during the fire, roads, and ridgetops. It was described by one interviewee as *“probably the hardest burn we’ve ever pulled off, I’ve ever pulled off, in my career. Not only did you have the complexities of the burn, the extreme fire behavior, but it’s your backyard.”* Planning took place over multiple shifts, and the group was split between multiple DIVS qualified personnel due to the large area, number of resources, and values at risk. Operations took place over approximately seven “swing” shifts, starting late in the day and ending early in the morning to capitalize on advantageous fire weather conditions. In addition to being strategic locations for containment lines, treatments facilitated Anticipatory decisions to initiate interior firing operations. Reducing negative ecological fire effects from high intensity fire, and creating a convective heating column which pulled ignitions along the perimeter away from containment lines. Much of the firing took place directly adjacent to structures and leveraged homeowner constructed defensible space which decreased the likelihood of structure loss. Some Reactive decisions did emerge in response to difficult to contain spot fires, which were successfully suppressed. The successful completion of this operation coincided with an increase in fire behavior along the northeastern fire perimeter and firing resources were immediately reallocated to assist with structure protection at the Sierra-at-Tahoe ski resort.

Perimeter control operations along the southern, southeastern, and eastern fire perimeter north of Highway 88 progressed along fuel treatment laden ridge tops (Figure 14). Interviewees learned the location of fuels treatments from local resources and used this knowledge to plan perimeter control operations in Anticipation of future fire growth. Construction of an indirect fireline connecting Highway 50 to the 2019 Caples prescribed fire footprint began during this phase. However, environmental conditions and insufficient supervision for nighttime heavy equipment operations challenged progress. While a high-pressure system temporarily decreased fire behavior, other environmental factors such as dense vegetation and rocky soils challenged forward progress for hand crews and bulldozers. A low pressure system moved over the fire on the 28th and large machine piles of activity fuels from commercial forest thinning caused spot fires and the breaching of firelines (Table 10). Inside of some fuel treatments, diminished rates of spread caused interviewees to underestimate fire behavior during this forecasted weather event, which contributed toward compromised perimeter control.

Interviewees familiar with operations to contain a large spot fire across Highway 50 along the northern fire perimeter described primarily Anticipatory decisions and challenges due to resource and environmental factors. Structure protection operations dominated tactical decisions on the south side of Highway 50, but this area exhibited minimal fire behavior compared to the adjacent spot fire. In this area, a night time inversion would lift unusually early in the morning, which consistently caused fire behavior to increase. Efforts to contain the western perimeter of the spot fire were aided by older salvage logging/clear cutting, but in other locations firing operations would not carry through the same treatment type. A firing operation to contain the eastward spread of the spot fire escaped due to reportedly low numbers of resources. The escaped firing operation grew into a neighboring division and interviewees Reactively focused efforts on structure protection south of highway 50 where structure loss was attributed to low numbers of firefighting resources and increasing fire behavior.

During this phase, interviewees reported institutional friction between the USFS and CAL FIRE due to policy and cultural differences. USFS and CAL FIRE personnel respectively

work 16 and 24 hour shifts during wildfire response, with state employees receiving 24 hours off between shifts and federal employees working every day. This dynamic influences resource availability during night time shifts, when fewer federal employees are available for firefighting duties. Interviewees felt that this caused night-time resource shortages. Cultural differences included a preference for direct attack by CAL FIRE leadership who did not want to conduct some firing operations. This tension is illustrated by the case of a USFS interviewee, who was working as an engine captain during this shift. The interviewee described how CAL FIRE colleagues preferred direct fireline construction during a night shift. The interviewee viewed the operation as unsafe due to hazards from fire weakened trees. The issue was overcome when another CAL FIRE employee convinced colleagues to conduct a firing operation in lieu of direct attack because firing would provide a greater likelihood of success.

8.3.2.3 Phase 3: Challenging Stabilization

The Challenging Stabilization Phase (Aug 29-Sep 1) caused increased uncertainty from unpredictable fire behavior and impacts on HVRAs (Table 7). On Aug 29th, incident managers closed Highway 50 as South Lake Tahoe and adjacent communities became threatened. This event caused the Caldor Fire to become the priority wildfire in the nation, facilitating further institutional support and greater numbers of resources. Compared to the Initial-Reactive Phase (Aug 14-17) when fire growth overwhelmed efforts, interviewees considered environmental and fewer operational decision factors, and much greater proportions of Sequenced Actions and Anticipatory decisions. Tactics were mostly in pursuit of protection of life and property, however, perimeter control was pursued and achieved when facilitated by fire behavior, resource availability, and coordination between resources (Figure 18). Red flag conditions persisted through the evening of September 1st (Figure 15). The fire grew by 22,146 ha, reaching 82,749 ha in size and reported containment dropped to 13% on the 29th, but rose to 23% by the end of Sep 1st (ONCC, 2021).

Operations on the southern and southeastern fire perimeter, adjacent to Highway 88 and Kirkwood Ski Resort, were dominated by environmental, risk, and operational factors. North of Highway 88, a firing operation successfully connected multiple ridgetop and roadside thinning treatments, stopping fire progression in that area. Further to the east, spot fires crossed Highway 88, threatening structures in the Kirkwood Ski Resort area. Interviewees reported that the predicted winds and fire's proximity to structures elevated the priority of this section of the fire, resulting in increased firefighting resources to be allocated. The indirect fireline between Highway 50 and the Caples prescribed burn was incomplete during this phase, and burned over as the fire spread east. We found a large proportion of operational decision factors related to communication, including for the planning of multi-day firing operations and coordinating operations in Anticipation of predicted fire conditions. For example, one interviewee pre-empted extreme conditions by attempting to apply retardant in granitic areas with sparse clusters of forest vegetation. Under historical conditions these areas are unlikely to burn, but the interviewee indicated that the extreme conditions during the 2021 fire season caused them to Anticipate that the fire would spot between pockets of vegetation in the granite, allowing the fire to spread.

Interviewees on the Caldor Fire's northeastern perimeter reported operations near Echo Summit and along Highway 50, where the fire impacted structures. Interviewees reported resource, operational, and risk factors in reference to their decisions, as large numbers of

incoming resources, contingency firefighting operations, and coordination between DIVS occurred. Resources from other sections of the fire, including the crews responsible for the firing operations along the western perimeter described in Phase 2, relocated to assist in structure defense. These operations included Reactive structure protection using direct line construction and firing operations. In Anticipation of the fire's impact on Echo Summit, Meyers, and Christmas Valley, interviewees utilized large numbers of heavy equipment to create contingency firelines through numerous thinning and mastication treatments.

On the night of the 29th, the Caldor Fire crossed Echo Summit and spotted below Trimmer Peak. Large numbers of resources were positioned inside of communities to perform structure defense in Anticipation of the fire's arrival (Table 11). Firefighters leveraged treatments to contain spot fires, defending structures. At least one unauthorized firing operation occurred in the Meyers area, burning from fuel treatments to halt the spread of the spot fire below Trimmer Peak towards structures. During the following shifts, the fire continued toward Trimmer Peak, and resources pivoted to perimeter control and mop-up around structures.

Thematic patterns during this phase were consistent relative to the previous two phases across sections of the fire, potentially because the large spread characterizing this phase involved all interviewees. Interviewees described coordinating with adjacent forces and supervisors, developing plans to Sequence Actions, and conducting operations in Anticipation of future fire behavior. Resource movement toward the northeastern and southeastern flanks of the fire, including moving resources who had completed assignments in other fire areas, and increasing supervision to ensure appropriate span of control, was completed before the worst fire impacts occurred. Sequencing of Action was consistent across interviewee experiences, as the potential risks of future fire spread on South Lake Tahoe were clearly understood.

During this phase, which featured highly uncertain impacts on values at risk and compressed decision making time, all interviewees described instances of conflict attributable to resource allocation and operations. One interviewee reported disagreements about moving large quantities of water to conduct nighttime perimeter control operations. To resolve the issue, a branch supervisor intervened, commanding a DIVS to share structure protection resources. Another interviewee reported being repeatedly refused retardant applying aircraft which caused frustration with managers responsible for coordinating aerial firefighting. All interviewees reported direct involvement or familiarity with contentious firing operations. Due to red flag conditions, many CAL FIRE interviewees reportedly disagreed with firing operations to protect structures. Conversely, USFS interviewees viewed these operations as necessary to achieve protection of property and life outcomes and described how CAL FIRE IMTs were less likely to place division supervisors in the same location across continuous shifts, challenging the ability to gain situational awareness. Additionally, interviewees across agencies again described nighttime resource shortages due to agency policy differences.

Approximately 320 structures were lost along Highway 50 during Phase 3, while approximately two structures were destroyed in Meyers and Christmas Valley and another three along the southeastern perimeter. Interviewees believed the outcomes in Meyers and Christmas Valley were attributable to the increased presence of natural fire spread barriers, communication, resource management, decreasing fire weather, the angle of fire spread, and fuel treatments. Firefighting effectiveness increased as rock features provided anchor points and safety zones,

especially along the southeast perimeter and on Trimmer Peak. As the fire crossed Echo Summit, nighttime conditions had a diminishing effect on fire behavior and the area is naturally shielded from west winds (Table 9). While many spot fires ignited near structures, interviewees attributed successful outcomes to the combination of a large resource presence and fuel treatments. Some interviewees reported that an initial concern discussed during planning was the potential for the fire to spread south of the community and then funnel up Christmas Valley (Table 9). Two interviewees attributed this outcome to the Caples prescribed fire, which split the Caldor fire (Figure 14).

8.3.2.4 Phase 4: Stabilized Recovery

The Stabilized Recovery Phase (Sep 2-Oct 20) initiated when the fire was bisected into an Eastern (USFS) and Western (CAL FIRE) zone with a Type 1 IMT managing each (Table 7). Continuing firefighting operations focused on the Trimmer Peak spot fire, perimeter containment, and structure protection near Echo Lake on the northeastern side with perimeter control near Kirkwood and the Caples Prescribed Burn occurring on the southeastern side. The fire grew by 6,212 ha, with most growth occurring during the first two days of this phase. On Sep 8-9th, a fire weather watch occurred over the fire area and a red flag warning was declared on Sep 10th. Despite these conditions, percent containment continued to increase until full containment was declared on Oct 20th (interview content ends on Sep 16th). Holding established fireline and increasing containment dominated the decision making rationale during this phase. As potential sources of uncertainty continued to decrease and the incident continued to stabilize, daily operations became repetitive (Table 11).

Interviewees assigned to the southeast fire perimeter near Kirkwood described plentiful resources, adequate communication, support from the incident management team, and improving fire environment conditions. Directly after the fire was split into zones, division supervisors Anticipated the fire would breach indirect control lines near the zone boundary and requested to complete a firing operation. The request was denied and the next day the fire escaped containment in that location. This portion of the fire contains the longest lasting operations of the fire around the Caples prescribed fire footprint. Interviewees exhibited different perspectives on how the Caples burn influenced fire management (Table 11). While some reported that the change in the Caldor Fire's perimeter may have prevented the worst possible outcome to the Christmas Valley area, others reported that the logistical challenges of accessing that portion of the fire perimeter greatly increased the fire's length. Ultimately, a firing operation was conducted to contain that portion of the fire, which took place outside of the interview window (past Sep 16th).

Operations on the eastern fire perimeter in the Trimmer Peak area continued, although minimal perimeter expansion occurred after Sep 2nd. Interviewees reported access and logistical challenges for resources containing fire spread. While the area was well staffed, resource numbers fluctuated between night and day shifts. Shifting resource quantities between shifts combined with hazards from fire damaged trees that are difficult to see at night slowed containment on this portion of the fire. After containment lines had been established, interviewees reported concerns from spot fires outside of the main perimeter as a continuing concern, which required frequent patrol and mop-up. Additionally, a contentious firing operation was completed to remove unburned fuel between an indirect fireline and a portion of the fire

perimeter. One interviewee reported that this firing operation required additional resources to ensure that control lines held long past when the operation took place.

During this phase, operations took place to protect remote cabins near Echo Lake from fire backing downslope. These operations occurred for several days and challenges included logistical support and contentious firing operations in this remote area. The firing operations, conducted to keep the fire that was backing towards the lake from impacting structures, were viewed as problematic by an interviewee because they required increased numbers of resources to patrol and ensure the operation remained inside of containment lines.

As perimeter control operations were completed, mop-up operations to hold established firelines increased. As this occurred, any division supervisors were reassigned to assist in repopulation of communities in the western section of the fire. The increase in focus was intended to establish a presence for and assist homeowners, who were allowed to repopulate evacuated areas. These tasks were generally described as “house calls”, with interviewees reportedly Reactively responding to reports of smoldering material sometimes well inside of the fire perimeter and away from structures (Table 11). One interviewee reported challenges with motivating resources to remain engaged as fire activity decreased. Resources also became available for use in suppression repair operations, and interviewees reported sharing their assigned resources to complete these tasks as the risks to established fireline subsided and resources began to demobilize from the fire. Interviewees also mitigated risks around structures and recreational areas by coordinating tree falling teams to remove hazardous trees near structures. This resource was only mentioned by interviewees during this phase.

Fuel treatments served a much smaller role in operations during the Stabilized Recovery Phase. Two interviewees noted that mop-up and other tasks completed after perimeter control operations were complete, such as hazard tree falling, was easier inside of fuel treatments. The former due to the increased ease of finding smoldering material and the latter due to the decreased canopy density and number of fire damaged trees in treated areas.

8.4 DISCUSSION

When the Caldor Fire was split into four Operational Phases using incident and fire progression data, trends in decisions are apparent (Table 8, Table 9, Figure 15, Figure 18). Early in the fire, when the fire was managed under a local Unified Command structure and growth was rapid, Reactive decisions dominated. When an IMT supplanted the local management structure more Anticipatory decisions were made as long-term planning, greater numbers of resources arrived, and communication improved. When the fire grew rapidly during the 3rd phase, this stability was challenged, but interviewees still described more Anticipatory decisions relative to the first phase. In the fourth phase, firefighters achieved full containment of the fire as weather conditions allowed and the fire burned into areas of sparse fuels (Finney *et al.*, 2009). During this phase, interviewees continued to make Anticipatory decisions as mop-up, repopulation of evacuated areas, and fire suppression repair became the dominant operations across the fire area.

Researchers separating wildfires into operational “phases” have investigated resource efficiency and use in relation to wildfire perimeter control progress (Thompson *et al.*, 2017; Katuwal *et al.*, 2017; Simpson *et al.*, 2019). Challenging these investigations is the fact that

firefighting resources engage in many operations beyond perimeter control such as structure protection, mop-up, and logistical support and little is known about resource productivity beyond containment construction rates (Dunn *et al.*, 2017). Our study sheds light on the prevalence of these other tactics. During periods of large fire growth, when perimeter control is known to be ineffective (Finney *et al.*, 2009), we found that IMTs and abundant resources support successful tactical decisions pursuing structure protection. Previous research findings have also described how operations across large wildfires are heterogeneous, with some sections achieving containment well before a wildfire stops spreading (Katuwal *et al.*, 2017; Simpson *et al.*, 2019). These are in alignment with our interviewees, who described how western sections of the Caldor Fire were contained in advance of the eastward growth that threatened South Lake Tahoe.

8.4.1 Fire Management Flexibility, Culture and Wildfire Outcomes

Modern incident management has evolved to include the perspectives of stakeholders with jurisdiction in areas impacted by wildfires, such as local law enforcement, agriculture, and community leadership (Nowell and Steelman, 2019; Essen *et al.*, 2023; Buettner *et al.*, 2025). While there is concern that the consideration of diverse perspectives may inhibit the speed of incident management decisions, they should increase the ability of IMTs to adapt to changing conditions and emergent uncertainty on long duration complex incidents (Walton, 2014; Essen *et al.*, 2023). Our findings indicate that ICS facilitated the achievement of the pursued outcomes of tactical decisions when qualified IMTs were in place on a large, full suppression wildfire, which is evident in the change in decision types and factors across Operational Phases of the Caldor Fire.

The default strategy for wildfires threatening communities is typically full suppression, with the objective of halting fire spread as far away from structures as possible (Pietruszka *et al.*, 2023). The Caldor Fire experienced two large growth events, the first resulted in the destruction of Grizzly Flats, the second resulted in substantially less structure loss despite large numbers of structures laying in the path of the fire. While our interviews reveal multiple reasons for the disparity between these events, such as fire weather differences and the angle of fire spread, there were also coordinated efforts deploying firefighting resources to defensively leverage fuel treatments South of Lake Tahoe. Institutional bias towards perimeter control may contribute toward adverse Wildland Urban Interface (WUI) outcomes when there is less decision-making support from IMTs to divert resources towards structure protection in a timely manner.

WUI fires can occur during extreme weather events when fire becomes established and quickly spreads into communities, overwhelming firefighting resources as the fire transitions from vegetation and many homes burn at once (Cohen, 2010; Balch *et al.*, 2024). We suggest two types of WUI fires, ones that begin during the initial attack period and ones that occur during ongoing incidents. While reducing WUI fire risk by preventatively reducing flammable material immediately on and adjacent to structures is likely the most effective approach in terms of cost and structure survival, firefighting resources protecting structures do reduce losses (Cohen, 2010; Calkin *et al.*, 2014; Link, 2024). Future WUI fire studies should investigate alternative response strategies for wildfires threatening communities in the context of the number of available resources and existing incident management structures. Alternatives should be developed to assist IMTs to reallocate resources towards communities and away from perimeter control well in advance of WUI fire disasters.

Agencies responsible for wildfire response are also responsible for pre-fire risk mitigation including the construction of fuel treatments to assist firefighting efforts near structures and across landscapes (Calkin *et al.*, 2014). While fuel treatments on public and private land may not slow fire spread during extreme conditions, adjacent fuel treatments have been shown to decrease structure loss (Cruz *et al.*, 2022; Gibbons *et al.*, 2025). These benefits are likely due to the opportunities they provide for firefighters conducting structure defense and decreased ember sources which cause spot fires near structures (Calkin *et al.*, 2014; Gibbons *et al.*, 2025). However, budget and policy constraints impede the completion of some community defense zones, as was the case with the Trestle Project planned to protect Grizzly Flats, which was incomplete at the time of the Caldor Fire. The existing fuel treatments did allow firefighters to perform some structure protection, and interviewees reported that completed fuels reduction around Leoni Meadows contributed to positive outcomes at that location.

Institutional and operational decision factor themes revealed the importance of agency culture and incident command on fireline tactical decision making. Shift length differences, different perceptions around the riskiness of firing operations, and differing priorities of pursued outcomes were the primary differences interviewees described between USFS and CAL FIRE management approaches. The numerous differences described by interviewees indicate that substantial cultural and policy differences existing between agencies may disrupt incident management and cause conflict during large wildfires management (Nowell and Steelman, 2015). While previous literature has established the importance of cross-agency relationship building for effective response and the general differences these agencies exhibit in terms of incident response, additional research is needed to understand the influence of collaborative decision making across individuals motivated by different agency missions and cultures (Stelman and McCaffrey, 2011; Nowell and Steelman, 2015; Starrs *et al.*, 2018).

8.4.2 Future Research and Management Implications

To our knowledge, this is the first interview-based wildfire research using event-centered calendar interviewing of a single fire with an ArcGIS mapping application to aid memory recall (Figure 17) (Moore-Cherry *et al.*, 2015; Jackman *et al.*, 2022). While we conducted interviews as soon as we received institutional approval, future studies could conduct interviews directly after a wildfire. Future studies should also use perimeter maps reflecting conditions at the end of the shift being recorded. Our use of perimeters reflecting the fire's location for the morning of the shift in question resulted in some interviewees becoming confused about which day specific events occurred, requiring triangulation of specific dates using incident maps and other data post-interview.

Interviewee access is a key consideration in future research leveraging similar methodologies. Interviewing firefighters about tactical decisions on a specific fire can be challenging considering insular agency culture (Stelman and McCaffrey, 2011). We partially overcame this issue by expanding our sampling frame, and we would be remiss to not mention that this may influence our final results. Specifically, the magnitude of themes across phases would be influenced when interviewees who had been division supervisors assumed a position in the IMT command staff or as an engine captain. Future studies may conduct interviews over multiple fires, which may overcome sample size limitations and contribute towards the generalization of these findings.

8.5 TABLES

Phase 1: Reactive-Initial (Aug 14-17)		Phase 2: Stabilizing Organization (Aug 18-28)	
Time of Event	Event	Time of Event	Event
Evening Aug 14th	Fire reported near Omo Ranch. Resources are dispatched to suppress the Caldor Fire. Local US Forest Service and CAL FIRE units establish Unified Command.	Aug 18th	Type 1 IMT assumes command.
Aug 15 th to 16 th	Initial containment attempts fail. Firefighters continue to attempt perimeter control and assess threatened structures.	Aug 21 st to 28 th	Large firing operation contains the western fire perimeter between Jenkinson Reservoir and Gold Note Ridge.
Aug 16 th	Planning begins for fire to impact Grizzly Flats and Leoni Meadows	Aug 22 nd	National Incident Management Organization (NIMO) is ordered to assist with fire and resource management.
		Aug 27 th	Containment progress along Southern perimeter encounters Caples wildfire footprint.
		Aug 27 th	NIMO assumes partial management of resources.
Aug 17 th	Fire impacts Grizzly Flats and Leoni Meadows. A Type 1 IMT is ordered. Substantial structure loss occurs.	Aug 28 th	Fire impacts Strawberry. Prompting movement of resources to assist with structure protection.

Table 8: Operational events and transitions used to separate the 2021 Caldor Fire into separate Phases representing a transition towards incident stability. Details in this table are from Phase 1: Initial-Reactive and Phase 2: Stabilizing Organization. Bolded text is used to highlight the events which indicate the beginning of a new phase. Information in this table was compiled from Northern California Geographic Area Coordination Center Incident Updates and triangulation of events with interview and fire progression data.

Phase 3: Challenging Stabilization (Aug 29-Sep 1)		Phase 4: Stabilized Recovery (Sep 2-Oct 20)	
Time of Event	Event	Time of Event	Event
Evening Aug 29 th	Fire crosses Echo Summit, running up Trimmer Peak. Communities are impacted. Massive resource movement occurs. Minimal structure loss in Christmas Valley. Substantial structure loss along Hwy 50.	Sep 2	The fire is split into two zones with separate Type 1 IMTs.
		Sep 3 rd - 6 th	Remote structure protection occurs near Echo Lake. No structures are lost.
		Sep 17 th	A Type 2 IMT takes command of the fire. Collapsing the East and West zones under one management team.
		Phase Duration	Mop up operations transition to suppression rehabilitation.
Aug 29- Sep1	Efforts to contain spot fire on Trimmer Peak are successful.	Phase Duration	Repopulation of impacted areas begins.
		Phase Duration	Containment operations continue along the Caples Wildfire perimeter. A firing operation connects the wildfire perimeter around the Caples area.
Aug 28- Sep 1	Firing operations and direct attack near Kirkwood mitigate structure loss.		

Table 9: Operational events and transitions used to separate the 2021 Caldor Fire into separate Phases representing a transition towards incident stability. Details in this table are from Phase 3: Challenging Stabilization and Phase 4: Stabilized Recovery. Bolded text is used to highlight the events which indicate the beginning of a new phase. Information in this table was compiled from Northern California Geographic Area Coordination Center Incident Updates and triangulation of events with interview and fire progression data.

Phase 1: Reactive-Initial (Aug 14-17)		Phase 2: Stabilizing Organization (Aug 18-28)	
Framework	Quotation	Framework	Quotation
Decision Factors	<i>There was no new resources that came in on the 15th or the 16th for the most part. So that was probably the biggest failure of the whole thing was not being able to provide a good extended attack. We went from kind of initial attack for four days to a major incident. – Interviewee (Resources)</i>	Decision Factors	<i>The branch director.. just doesn't know the area. So I went out there and worked with him and the division and basically started tying in roads.. and building our control lines that way. – Interviewee (Institutional)</i>
Leveraging Treatments	<i>We would not have left folks in Leoni Meadows had they not had extensive fuels work in there, and Grizzly Flats we would not have been near as aggressive as we were. – Interviewee (Increase firefighter safety)</i>	Leveraging Treatments	<i>They had a ton of log decks or slash piles whatever you want to call them. Probably, you know 100 by 115 feet tall. So once fire got inside those things, they started spotting across the line that evening. – Interviewee (Treatment Characteristics)</i>
Decision Processes	<i>We tried to hold the Caldor Road, which runs just parallel with the Steely Fork Canyon right here. Once it crossed that then we were just going into a structure protection mode in Leoni Meadows. And then within a couple hours, it pushed it into Grizzly Flat. – Interviewee (Reactive)</i>	Decision Processes	<i>We were working within the divisions and we did support division alpha and delta with some other opportunities for direct suppression, because we had, you know, hotshot crews and resources, but our primary focus was firing.. – Interviewee (Sequencing of Action)</i>
Outcomes	<i>No tactics were effective. Especially the indirect, which the fire consistently overran. – Interviewee (Perimeter Control)</i>	Outcomes	<i>When the sun came up, everything was good. I don't think it seemed real effective to them at the time because they got knocked around pretty good, but when the sun came up, they were in a pretty good spot. – Interviewee (Perimeter Control)</i>

Table 10: Quotations from interviews of operational personnel used to illustrate categories of the decision making framework and fuel treatment leverage during the first two incident management Phases of the Caldor Fire. The theme associated with the quotation is provided in parentheses.

Phase 3: Challenging Stabilization (Aug 29-Sep 1)		Phase 4: Stabilized Recovery (Sep 2-Oct 20)	
Framework	Quotation	Framework	Quotation
Decision Factors	<i>The other gentleman decided to go with the line there, but it was basically just a road, it was 20ft wide with full mature trees... And their plan was to fire that piece off. I felt like it was more of a risk to do it that way versus getting into that treatment area. He was looking at that treatment area as a secondary fallback.. There's more than one way to skin a cat. – Interviewee (Operational)</i>	Decision Factors	<i>We had repopulated Grizzly Flats. And so there was a strike team in there that was just staged there in case something was needed from homeowners, or something happened... Then service calls, where people see a smoke it could be three miles in there, and it's like, hey, well, that's going to burn until it rains. – Interviewee (Risk)</i>
Leveraging Treatments	<i>It hit the fuel treatment as dark came. So it definitely went down... it could have also been relative humidities coming up... you know, all those nighttime factors starting to come into play. The wind reversals... So I think it was a combination of everything, but it definitely moderated when it hit the echo summit fuel breaks that I saw. Interviewee - (Approaching Fire Behavior and Treatments)</i>	Leveraging Treatments	<i>The Caples burn was kind of a thorn in our side in some respects. This is where that comes into play because it didn't burn through there, and it did hold it up, but it burned around. We had to build handline all the way to there. – Interviewee (Treatment Alignment With Decisions in Time and Space)</i>
Decision Processes	<i>The objective was to hold all fire, which would be north of Highway 88 and then that slop had occurred prior to me getting there. So they were holding the slop and stopping it there, because if it had outflanked us there the box was going to get a lot bigger. There was no nowhere to stop it out farther. – Interviewee (Anticipatory)</i>	Decision Processes	<i>My next shift out there. I went to the exact same place and did the exact same thing. And we just mopped up and held what we had, and there wasn't any significant changes in fire behavior. – Interviewee (Sequencing of Action)</i>
Outcomes	<i>There are cabins in there, so there was structure defense going on as well. But that was that was done via direct attack with handline construction. It was effective. They were able to hold the fire in that area as directed. And there was overall good effectiveness. Good success. – Interviewee (Protecting Property and Life)</i>	Outcomes	<i>I don't believe we had any issues on that third night. Any like spots outside the line or holding concerns. It had already been worked over for almost 48 hours at that point with the fire burning down and securing and mopping up. – Interviewee (Holding Established Fireline)</i>

Table 11: Quotations from interviews of operational personnel used to illustrate categories of the decision making framework and fuel treatment leverage during the second two incident management Phases of the Caldor Fire. The theme associated with the quote is provided in parentheses.

8.6 FIGURES

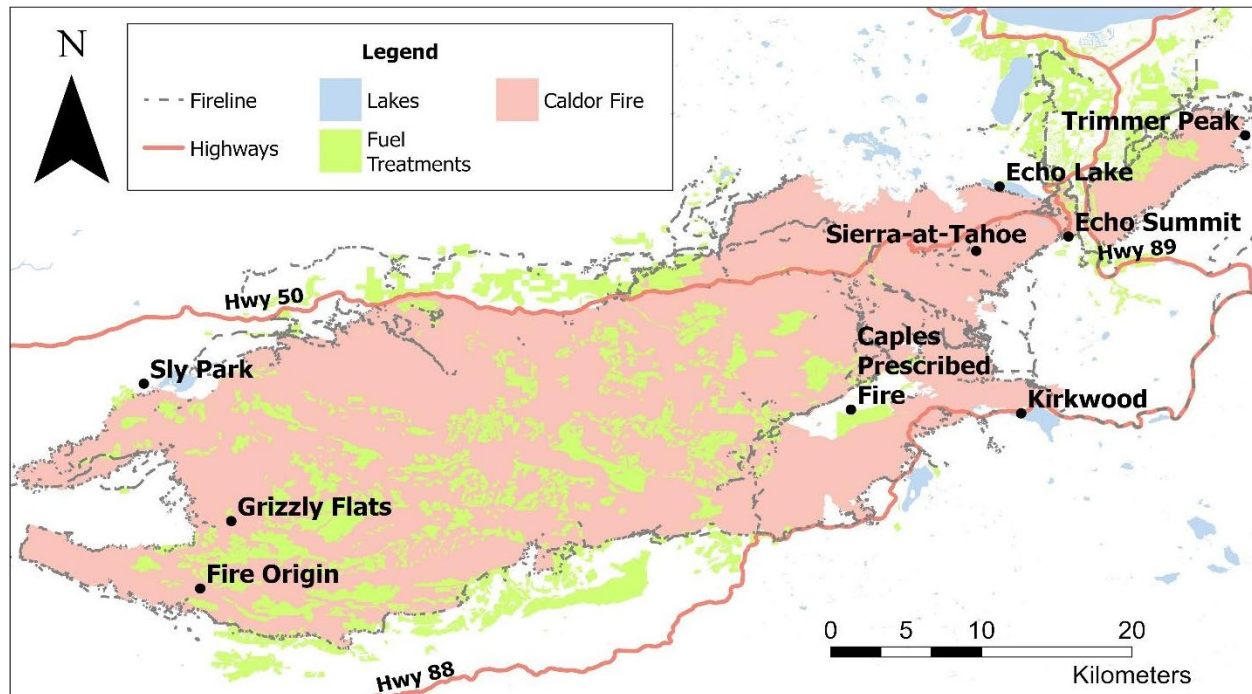


Figure 14: Map of the 2021 Caldor Fire's final perimeter with operationally relevant locations, fuel treatments completed less than 20 years before the fire from the US Forest Service Activity Tracking System, highways, firelines, and bodies of water. The escaped Caples Prescribed Fire, which caused the southeast section of the fire to split, burned the majority of the white area around the fuel treatment labeled as the Caples Prescribed Fire.

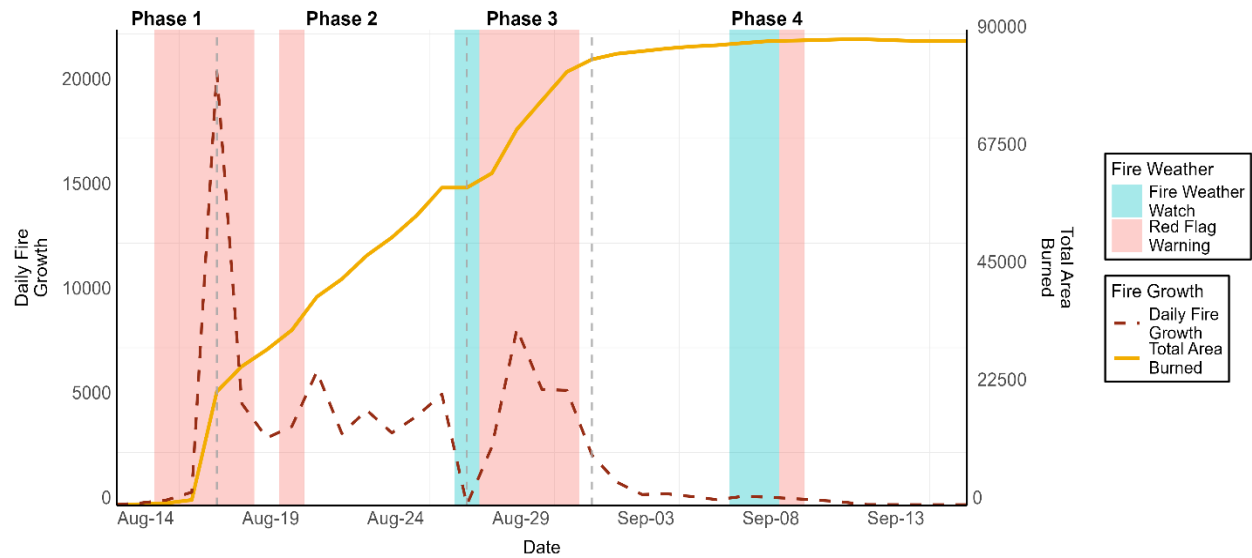


Figure 15: The Caldor Fire's daily growth (dashed line, left y-axis) and total area burned (solid yellow line, right y-axis) over the time covered by interviews of operational personnel. The x-axis begins on the ignition date (August 14, 2021) and ends on September 16, 2021. Background rectangles represent the duration of the Red Flag Warnings and Fire Weather Watches that occurred during the interview period. Dashed vertical lines represent the incident management phases established using operational events and transitions to examine changes in decision making over time (Table 8, Table 9). Increases in burned area occurring after September 16th are due to planned ignitions to contain the open fire's edge along the Caples prescribed burn perimeter (Figure 1), and are not the result of uncontrolled spread.

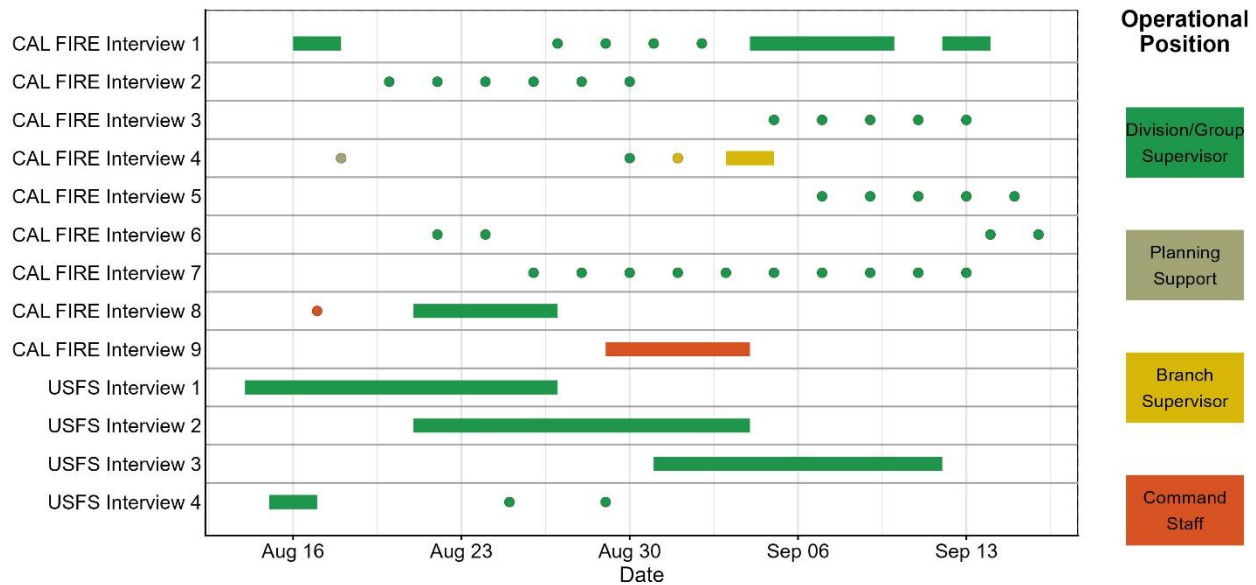


Figure 16: Dates covered by the interviews of operational personnel on the Caldor Fire. Each row represents an interviewee. Rows are labelled by the employing agency of the interviewee and the interview number which begins at one for both agencies. The x-axis represents time on the Caldor Fire, with interview coverage beginning during the Initial Attack period. Dots represent interviews for single days, which are common for CAL FIRE interviewees due to their shift lengths. Each observation is color coded to indicate the position of the interviewee on the specific day of the fire.

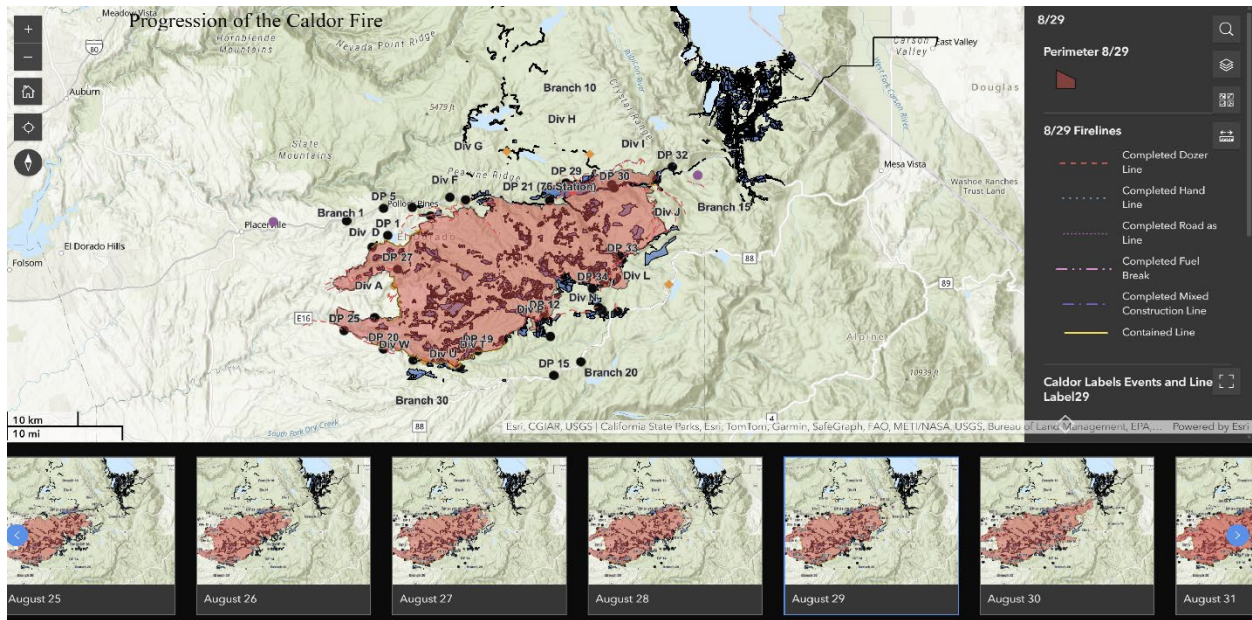


Figure 17: Screenshot of the ArcGIS Online Map used as a visual elicitation tool during fireline supervisor interviews. The map features include daily fire perimeters, firelines, division breaks, drop points, and fuel treatments from federal and local government databases.

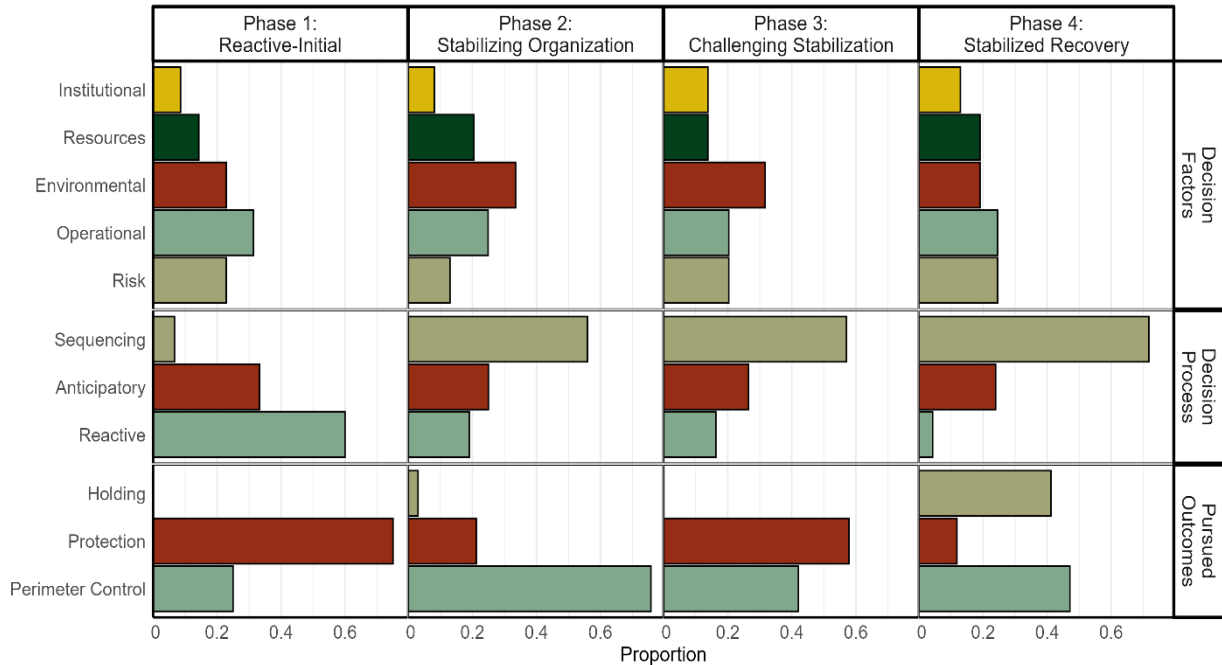


Figure 18: Proportions of themes aligned with framework categories (Decision Factors, Decision Processes, and Pursued Outcomes), of fire management decision making during the Caldor Fire's four incident management phases (Table 8, Table 9). The y-axis includes labels for the themes under the main framework categories (Decision factors, processes, and outcomes) and the x-axis represents the proportional magnitude of text coded to each theme relative to the total number of codes in the main framework category during each phase. Environmental decision factors increased and then decreased over time, operational factors decrease, and risk and institutional factors increased. Trends in Decision Processes during the Reactive Initial Phase were typically reactive with low instances of Sequencing of Action, which inverted during subsequent Phases. Over time Protection Outcomes were sought during periods of large fire growth (Phases 2 and 3), while Perimeter Control increased during Phase 2 and interviewee pursuit of Holding was negligible until Phase 4 when the incident stabilized.

9 CONCLUSION

In California, fire and fuels managers describe fuel breaks as an on-the-landscape risk reduction tool with multiple co-benefits. Their construction is influenced by multiple factors, including public opinion, regulatory hurdles, and environmental constraints. Once constructed, either by removing or rearranging fuels with prescribed fire or mechanical methods, fuel breaks primarily act as a pre-established location for containment lines. Managers went beyond this description though, describing how fuel breaks may increase the speed at which suppression work can be accomplished, while increasing time and decision space for operations in adjacent areas by slowing fire spread. The outcomes of manager experiences with fuel breaks influences how they plan them in the future.

Taking the theories developed in the first chapter, we produced a novel fire risk metric to reflect the risk of uncontrollable wildfire, an especially relevant measurement for fuel break evaluations. We used this metric to assess the effectiveness of four fuel break configurations, finding how geometry and fuel break “leverage” influence risk across landscapes. Importantly, unstaffed fuel breaks composed of grass fuels increased fire risk in this study, which presents an important management implication for future fuel break construction.

Similar to fuel breaks, large wildfire management and the increasingly challenging conditions under which these events occur present an important lens through which to view current fire management paradigms. Large wildfire management is conducted using a system developed for fire suppression decades ago (Auf der Heide, 1989). While ICS has allowed first responders to coordinate logistics, resources, strategy, and tactics on wildfires well, changing wildfire conditions and management approaches present challenges (Bigley and Roberts, 2001; Buettner *et al.*, 2025). As instances of quickly growing wildfires increase in fuel types where fire persists for weeks or months, hierarchical decision making is challenged. Additionally, ICS may be poorly suited for the incorporation of multiple stakeholder inputs in fire management decision making. While tools to adapt it to this new operating paradigm exist, governing agencies may re-evaluate current approaches to confront current dynamics.

The shortcomings of ICS, and the benefits, were displayed in the tactical decision-making studies of the Caldor Fire. During times of rapid growth, before a qualified IMT took charge of the fire, firefighters were often conducting operations reactively and poor outcomes occurred, including the destruction of the community of Grizzly Flats. The exact reasons for these outcomes are challenging to parse, but like most outcomes, they are a result of multiple influential factors, including the challenges of hierarchical decision making in rapidly changing environments. In later stages of the fire, although more structures were destroyed, the worst outcomes may have been avoided in areas like Meyers and Christmas Valley due to incident management, the presence of fuels reduction work, and advantageous environmental conditions; thus exemplifying the complexity of determining wildfire outcomes, while offering a success story for preventative wildfire risk reduction in the context of incident management when ample time for decision making exists.

Linear fuel treatments and large wildfires exemplify the challenging dynamics faced by fire and fuels managers when confronting the problems posed by contemporary fire regimes. Faced with increasing wildfire activity and frequency of high impact events, previously

established best practices will be stress-tested. This will require innovation in many areas, some of which is already ongoing (Buettner *et al.*, 2025). Current explorations of fuel treatment effectiveness typically stop at the ecological (did fuel treatments reduce burn severity?) or the operational binary (did the fire stop there?). As explored in the work above, opportunities abound for additional research. While attempts toward quantification may be limited by the data currently available, innovation in fire management and ecology research are required to tackle the problem at hand, which will continue to challenge society's ability to adapt to rapid change (North *et al.*, 2015; Thompson *et al.*, 2018b).

As wildfire impacts to valuable human resources increase, research that fully accounts for the complex systems that create and influence fire management is required to present novel insights and solutions. Future endeavors should continue to account for the voices of fire managers in research, who at the time of writing, are often the only witness to this ecosystem-shaping process that is, often unintentionally, a product of human behavior. Accounting for these complexities and perspectives will improve outcomes for ecosystems and the communities that rely on their services in California and beyond.

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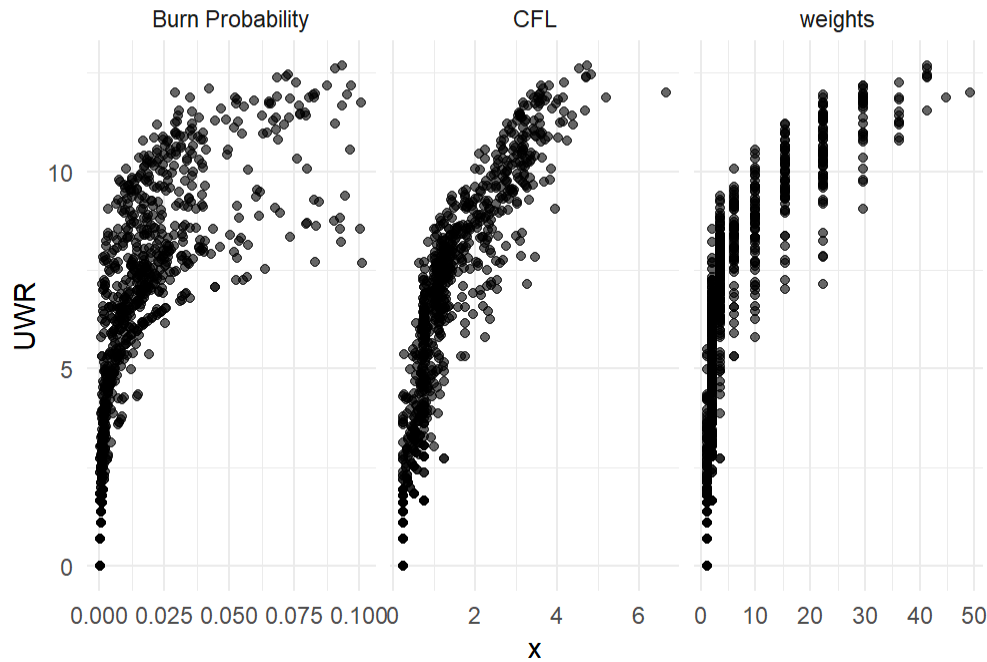
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11 SUPPLEMENTARY MATERIALS FOR “CONFIGURATIONS OF FUEL BREAK NETWORKS INFLUENCE LANDSCAPE-LEVEL FIRE-RISK IN CALIFORNIA”

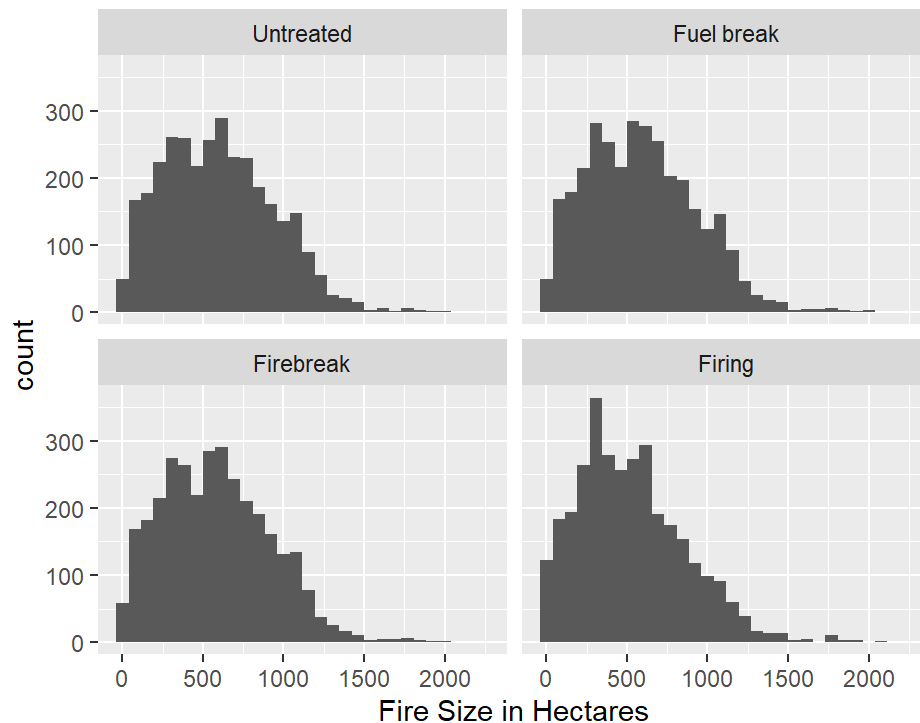
UWR over covariates



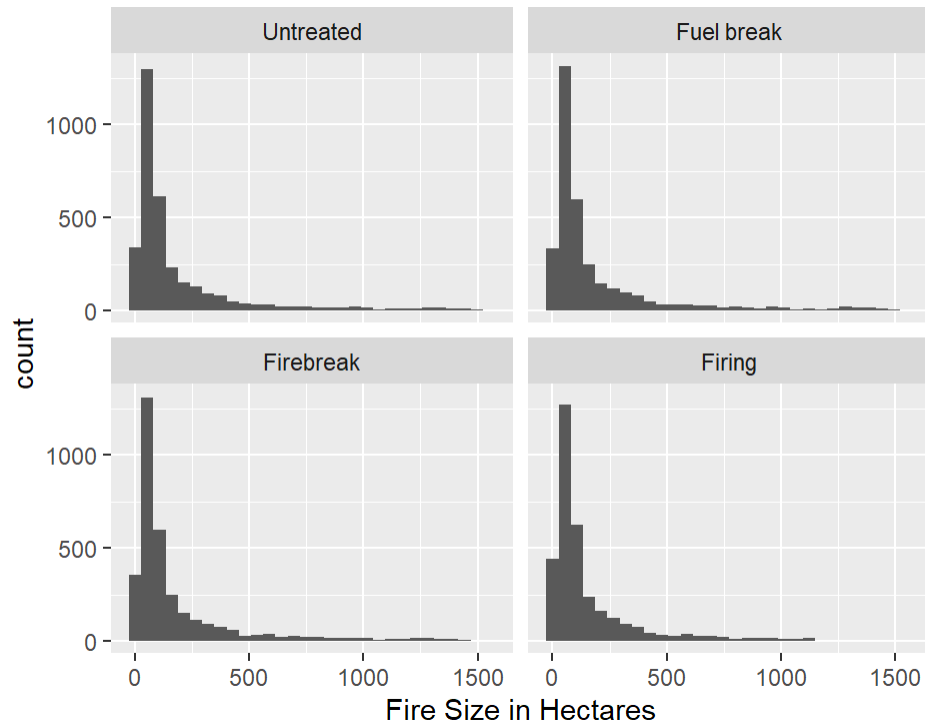
Supplementary Figure 1: Dot plots of input variables and Uncontrollable Wildfire Risk. Uncontrollable Wildfire Risk's relationship with the two fire modeling outputs (Conditional Flame Length and Burn Probability) and hazard weights. UWR maps more closely onto CFL than burn probability, High values occur over UWR 10, where flame lengths exceed two meters and burn probability values exceed 0.02.



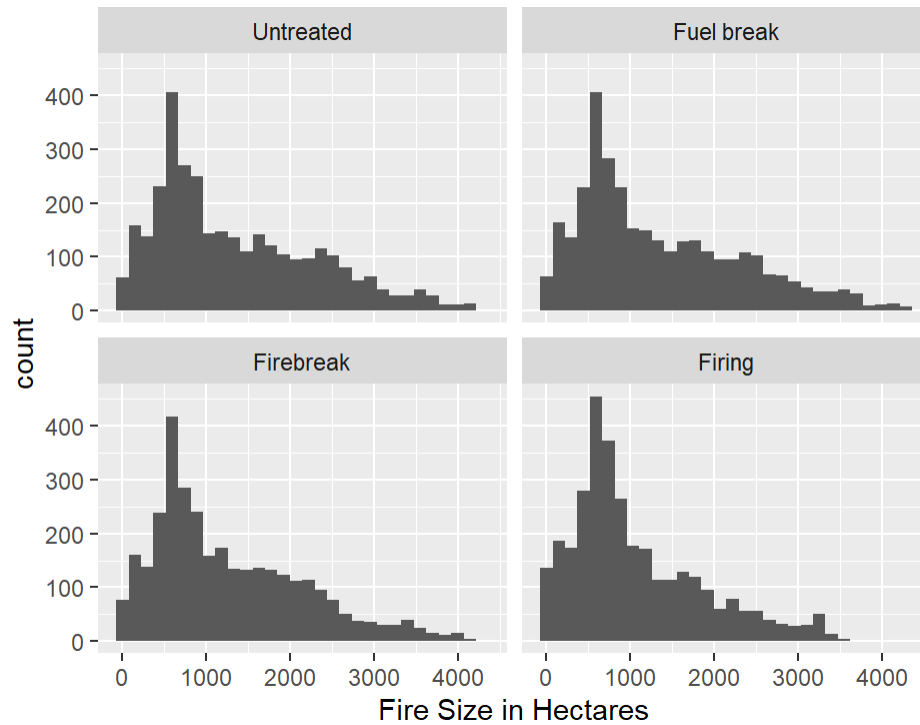
Supplementary Figure 2: Fire size distribution of the Single Segment Fuel Break Limestone Ridge Landscape. Generally, fire sizes shift left as leverage intensity increases, while the histogram shape remains mostly unchanged.



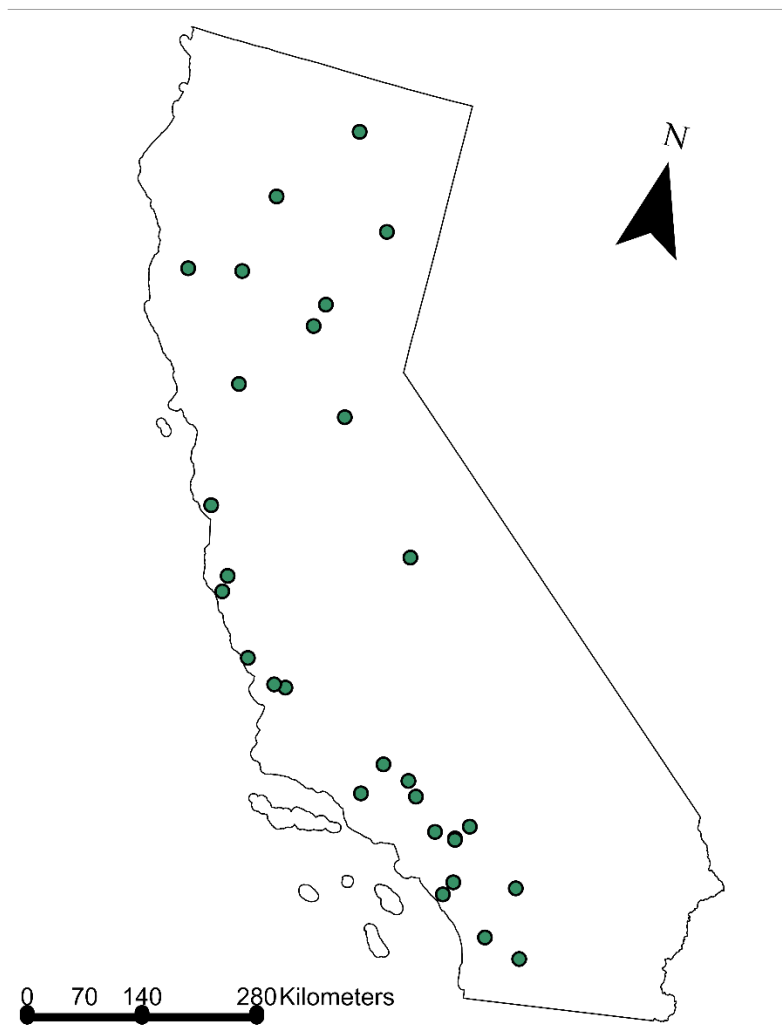
Supplementary Figure 3: Fire size distribution of the Branching Fuel Break Boundary Ridge Landscape. Generally, fire sizes shift left as leverage intensity increases, while the histogram shape remains mostly unchanged.



Supplementary Figure 4: Fire size distribution of the Enclosed Fuel Break Mount Lowe Landscape. Generally, fire sizes shift left as leverage intensity increases, while the histogram shape remains mostly unchanged. The right tail of the distribution disappears in the firing leverage scenario.



Supplementary Figure 5: Fire size distribution of the Multiple Segment Fuel Break North Mountain Landscape. Generally, fire sizes shift left as leverage intensity increases, while the histogram shape remains mostly unchanged. The right tail of the distribution disappears in the firing leverage scenario.



Supplementary Figure 6: Map of 30 fuel break locations used for categorization. Points represent the locations of fuel breaks collected from the survey of fire and fuels managers in California in Spring 2021.

Landscape	Boundary Ridge	Limestone Ridge	North Mountain	Mount Lowe
Landscape Resolution	30m	30m	30m	30m
Number of Fires	5000	10000	5000	5000
Burn Period	360 minutes	360 minutes	360 minutes	360 minutes
MTT Travel Path Interval	500	500	500	500
MTT Spot Probability	0.2	0.2	0.2	0.2
MTT Spot Delay	0	0	0	0
Wind Speed	13	20	20	13
Wind Direction	225	225	225	315
Wind Speed Units	mph @ 20'	mph @ 20'	mph @ 20'	mph @ 20'
Gridded Winds (Y/N)	Y	Y	Y	Y
Gridded Wind Resolution	60m	60m	60m	60m
Foliar Moisture Content	100	100	100	100
Crown Fire Method	ScottReinhardt	ScottReinhardt	ScottReinhardt	ScottReinhardt

Supplementary Table 1: Flammap input parameters for all landscapes. Inputs for Flammap runs used to create UWR on fuel break landscapes. Inputs are derived from 97th fire weather percentile RAWS data. Fire Family Plus was used to extract percentiles from the previous 10 years of weather data.

<u>Modeling Landscapes</u>	<u>Fuel Models Numbers</u>	<u>1 Hour</u>	<u>10 Hour</u>	<u>100 Hour</u>	<u>Live Herbaceous</u>	<u>Live Woody</u>
Boundary Ridge – Branching Network	101-147	2	2	4	30	60
	161-202	3	6	8	30	60
Limestone Ridge – Single Segment	101-147	3	4	6	43	78
	161-189	3	5	8	43	78
Mount Lowe – Enclosed Network	101-147	3	3	7	97	129
	161-202	4	8	10	97	129
North Mountain – Multiple Segment Network	101-147	3	4	5	63	88
	161-201	4	6	8	63	88

Supplementary Table 2: Live and dead fuel moistures for FBN fire models. The table is grouped by modeling landscapes. Every two rows after the column names are the 97th percentile ERC live and dead fuel moistures for modeling landscapes calculated in Fire Family Plus from RAWS station data from the past 10 years.

Beta Term	Variable Name
β_0	Intercept
β_1	Scenario [Unstaffed]
β_2	Scenario [Firebreak]
β_3	Scenario [Firing Operation]
β_4	Log10(Distance)
β_5	Wind Alignment
β_6	TPI
β_7	Width
β_8	Sinuosity
β_9	Proximity
β_{10}	Length
β_{11}	Slope
β_{12}	FB Cat GS
β_{13}	FB Cat SH
β_{14}	FB Cat TU
β_{15}	FB Cat TL
β_{16}	Distance x Unstaffed
β_{17}	Distance x Firebreak
β_{18}	Distance x Firing Operation
β_{19}	Wind x Unstaffed
β_{20}	Wind x Firebreak
β_{21}	Wind x Firing Operation
β_{22}	TPI x Unstaffed
β_{23}	TPI x Firebreak
β_{24}	TPI x Firing Operation
β_{25}	Width x Unstaffed
β_{26}	Width x Firebreak
β_{27}	Width x Firing Operation
β_{28}	Sinuosity x Unstaffed
β_{29}	Sinuosity x Firebreak
β_{30}	Sinuosity x Firing Operation
β_{31}	Proximity x Unstaffed
β_{32}	Proximity x Firebreak
β_{33}	Proximity x Firing Operation
β_{34}	Length x Unstaffed
β_{35}	Length x Firebreak
β_{36}	Length x Firing Operation

Supplementary Table 3: Table of coefficient terms and associated predictor variables names. Model coefficient betas and associated variable names for all model parameters. The 3 Fuel Break Networks include all terms listed. The Single Segment configuration model excludes length and proximity to other treatments.

Fire Size Class	Control Counts	Unstaffed Counts	Unstaffed Change	Firebreak Counts	Firebreak Change	Firing Counts	Firing Change
[0.09,219]	347	345	-2	357	10	451	104
(219,387]	346	342	-4	361	15	319	-27
(387,537]	347	355	8	342	-5	312	-35
(537,2.8e+03]	346	346	0	330	-16	307	-39
(2.8e+03,4.37e+03]	347	345	-2	343	-4	344	-3

Supplementary Table 4: Fire size quantiles of the Single Segment Fuel Break Limestone Ridge Landscape. Generally, fire the number of large fires decreases slightly as leverage intensity increases and the number of small fires increases.

Fire Size Class	Control Counts	Unstaffed Counts	Unstaffed Change	Firebreak Counts	Firebreak Change	Firing Counts	Firing Change
[0.09,278]	646	639	-7	657	11	804	158
(278,479]	645	662	17	662	17	779	134
(479,668]	646	673	27	680	34	679	33
(668,899]	644	631	-13	625	-19	509	-135
(899,2.23e+03]	646	622	-24	603	-43	456	-190

Supplementary Table 5: Fire size quantiles of the Branching Fuel Break Boundary Ridge Landscape. Generally, fire the number of large fires decreases slightly as leverage intensity increases and the number of small fires increases.

Fire Size Class	Control Counts	Unstaffed Counts	Unstaffed Change	Firebreak Counts	Firebreak Change	Firing Counts	Firing Change
[0.09,41.9]	675	672	-3	700	25	769	94
(41.9,69.4]	672	687	15	679	7	665	-7
(69.4,102]	676	660	-16	652	-24	661	-15
(102,262]	670	675	5	676	6	700	30
(262,1.55e+03]	674	673	-1	660	-14	572	-102

Supplementary Table 6: Fire size quantiles of the Enclosed Fuel Break Mount Lowe Landscape. Generally, fire the number of large fires decreases slightly as leverage intensity increases and the number of small fires increases.

Fire Size Class	Control Counts	Unstaffed Counts	Unstaffed Change	Firebreak Counts	Firebreak Change	Firing Counts	Firing Change
[0.09,545]	648	659	11	676	28	845	197
(545,828]	648	652	4	669	21	785	137
(828,1.4e+03]	647	631	-16	677	30	699	52
(1.4e+03,2.26e+03]	648	652	4	735	87	584	-64
(2.26e+03,4.29e+03]	648	645	-3	482	-166	326	-322

Supplementary Table 7: Fire size quantiles of the Multiple Segment Fuel Break North Mountain Landscape. Generally, fire the number of large fires decreases slightly as leverage intensity increases and the number of small fires increases.

Model Terms	Fuel Break Configuration			
	Segment	Enclosed	Branching	Multiple
<i>Observations</i>	14160	81128	64864	57604
<i>Sample Points</i>	3540	20287	16216	14401
<i>Marginal R²/Conditional R²</i>	0.33/0.99	0.60/0.99	0.42/0.99	0.66/0.99
Intercept	7.57 ± 0.09*	2.90 ± 0.02*	6.97 ± 0.03*	6.78 ± 0.02*
Scenario [Unstaffed]	<0.01 ± 0.01	>-0.01 ± <0.01	-0.01 ± <0.01*	<0.01 ± <0.01
Scenario [Firebreak]	-0.02 ± 0.01**	-0.01 ± <0.01*	-0.02 ± <0.01*	-0.04 ± <0.01*
Scenario [Firing Operation]	-0.14 ± 0.01*	-0.06 ± <0.01*	-0.13 ± <0.01*	-0.16 ± <0.01*
Distance	0.14 ± 0.03*	-0.15 ± 0.01*	0.07 ± 0.01*	-0.58 ± 0.01*
Distance x Unstaffed	<0.01 ± <0.01	<0.01 ± <0.01	0.01 ± <0.01*	>-0.01 ± <0.01
Distance x Firebreak	0.01 ± <0.01**	0.03 ± <0.01*	0.03 ± <0.01*	0.05 ± <0.01*
Distance x Firing Operation	0.16 ± <0.01*	0.13 ± <0.01*	0.24 ± <0.01*	0.22 ± <0.01*
Wind	0.29 ± 0.03*	-0.18 ± 0.01*	-0.42 ± 0.02*	0.47 ± 0.01*
Wind x Unstaffed	<0.01 ± <0.01	-0.01 ± <0.01**	>-0.01 ± <0.01	>-0.01 ± <0.01
Wind x Firebreak	-0.02 ± <0.01*	<0.01 ± <0.01***	>-0.01 ± <0.01**	-0.03 ± <0.01*
Wind x Firing Operation	-0.13 ± <0.01*	-0.01 ± <0.01*	-0.06 ± <0.01*	-0.12 ± <0.01*

TPI	$-0.08 \pm 0.01^*$	$-0.11 \pm 0.01^*$	$0.04 \pm 0.02^{***}$	$0.25 \pm 0.02^*$
TPI x Unstaffed	$<0.01 \pm <0.01$	$>-0.01 \pm <0.01^{**}$	$<0.01 \pm <0.01$	$>-0.01 \pm <0.01$
TPI x Firebreak	$<0.01 \pm <0.01$	$>-0.01 \pm <0.01^{***}$	$<0.01 \pm <0.01^{****}$	$-0.02 \pm <0.01^*$
TPI x Firing Operation	$<0.01 \pm <0.01^*$	$0.02 \pm <0.01^*$	$-0.02 \pm <0.01^*$	$-0.04 \pm <0.01^*$
Width	$0.12 \pm 0.03^*$	$-0.10 \pm 0.01^*$	$-0.08 \pm 0.01^*$	$-0.30 \pm 0.01^*$
Width x Unstaffed	$<0.01 \pm <0.01$	$>-0.01 \pm <0.01$	$>-0.01 \pm <0.01$	$>-0.01 \pm <0.01$
Width x Firebreak	$<0.01 \pm <0.01$	$<0.01 \pm <0.01$	$>-0.01 \pm <0.01$	$0.01 \pm <0.01^{***}$
Width x Firing Operation	$-0.01 \pm <0.01^{***}$	$<0.01 \pm <0.01^{***}$	$0.01 \pm <0.01^{**}$	$0.01 \pm <0.01^*$
Sinuosity	$0.59 \pm 0.04^*$	$-0.03 \pm 0.01^{****}$	$0.14 \pm 0.01^*$	$0.32 \pm 0.02^*$
Sinuosity x Unstaffed	$<0.01 \pm 0.01$	$<0.01 \pm <0.01$	$>-0.01 \pm <0.01^{****}$	$<0.01 \pm <0.01$
Sinuosity x Firebreak	-0.01 ± 0.01	$0.01 \pm <0.01^*$	$>-0.01 \pm <0.01^{***}$	$<0.01 \pm <0.01$
Sinuosity x Firing Operation	$-0.10 \pm 0.01^*$	$0.02 \pm <0.01^*$	$-0.04 \pm <0.01^*$	$0.03 \pm <0.01^*$
Proximity	-	$0.06 \pm 0.02^*$	$<0.01 \pm 0.01$	$0.21 \pm 0.02^*$
Proximity x Unstaffed	-	$-0.01 \pm <0.01^{***}$	$<0.01 \pm <0.01$	$<0.01 \pm <0.01$
Proximity x Firebreak	-	$0.01 \pm <0.01^*$	$0.01 \pm <0.01^*$	$-0.01 \pm <0.01^{***}$
Proximity x Firing Operation	-	$0.05 \pm <0.01^*$	$0.03 \pm <0.01^*$	$>-0.01 \pm <0.01$
Length	-	$-0.07 \pm 0.02^*$	$0.05 \pm 0.01^*$	-0.02 ± 0.02
Length x Unstaffed	-	$>-0.01 \pm <0.01$	$<0.01 \pm <0.01$	$>-0.01 \pm <0.01$

Length x Firebreak	-	$0.01 \pm <0.01^*$	$<0.01 \pm <0.01^{***}$	$-0.01 \pm <0.01^{**}$
Length x Firing Operation	-	$0.08 \pm <0.01^*$	$-0.03 \pm <0.01^*$	$-0.07 \pm <0.01^*$
Slope	$0.13 \pm 0.03^*$	$0.16 \pm 0.01^*$	$0.48 \pm <0.01^*$	$0.06 \pm 0.01^*$
FB Cat GS	$0.30 \pm 0.08^*$	$0.20 \pm 0.03^*$	$0.38 \pm 0.03^*$	$0.80 \pm 0.03^*$
FB Cat SH	$1.99 \pm 0.10^*$	$4.39 \pm 0.03^*$	$1.20 \pm 0.03^*$	$3.73 \pm 0.03^*$
FB Cat TU	$1.05 \pm 0.28^*$	$2.80 \pm 0.06^*$	$1.57 \pm 0.04^*$	$2.91 \pm 0.03^*$
FB Cat TL	$-0.98 \pm 0.28^*$	$0.13 \pm 0.04^{**}$	$-1.50 \pm 0.08^*$	$0.97 \pm 0.1^*$

*P-value < 0.001, **P-value < 0.01, ***P-value < 0.05, ****P-value < 0.1

Supplementary Table 8: Table of model coefficients and standard errors for fuel break configurations. Model coefficients and standard errors from generalized linear models used to examine the influence of fuel break characteristics on mean fire management risk. To aid in readability, we have listed the interaction term coefficients for each treatment scenario under the main effect.

Model Name	Bias-adjusted MSE	95% CI for Bias-adjusted MSE	Full-sample MSE
Limestone Ridge (Segment)	0.04	0.03 - 0.04	0.02
Boundary Ridge (Branching)	0.04	0.03 – 0.04	0.02
Mount Lowe (Enclosed)	0.03	0.03 – 0.04	0.02
North Mountain (Multiple Segment)	0.07	0.06 – 0.07	0.04

Supplementary Table 9: Table of model cross validation results. Cross validation was performed across 10 segments of data and the entire model to calculate mean squared error between model outputs and observed UWR.

Fuel Break Name	Unburnable	Grass	Grass-Shrub	Shrub	Timber Litter	Timber Understory
Limestone Ridge (Segment)	1	3	69	27	0	0
Boundary Ridge (Branching)	12	30	18	23	1	17
Mount Lowe (Enclosed)	18	27	27	13	8	7
North Mountain (Multiple Segment)	10	26	22	3	9	29

Supplementary Table 10: Pre-treatment fuel models inside of each fuel break polygon. Percent of the total fuel break polygon area covered by coarsened 40 fire behavior fuel models (Scott and Burgan 2005) calculated from LANDFIRE 2020 fire modeling inputs.

Fuel Break Name	Area (ha)	Average Width (m)	Length (km)	Ignitions within 2km 2011-2020	Number of segments
Limestone Ridge (Segment)	18	46	3.9	3	1
Boundary Ridge (Branching)	282	100	28	40	2
Mount Lowe (Enclosed)	204	35	43	0	4
North Mountain (Multiple Segment)	135.63	35.7	35.4	17	6

Supplementary Table 11: Case Study Fuel Break Descriptive Table. This table includes some general descriptive statistics of case study fuel breaks.

Southern California Mountains	Central California Foothills and Coastal Mountains	Southern California/Northern Baja Coast	Cascades	Coast Range	Klamath Mountains	Sierra Nevada
11	10	4	2	1	1	1

Supplementary Table 12: EPA Level III Ecoregions of categorized fuel breaks. The top row is the ecoregion that fuel breaks overlay, while the number below is the number of fuel breaks in that ecoregion.

12 SUPPLEMENTARY MATERIALS FOR “TACTICAL DECISION FACTORS, TYPES, AND OUTCOMES ON THE 2021 CALDOR FIRE IN THE CONTEXT OF FUEL TREATMENTS”

Caldor Fire Interview Protocol

This interview protocol was used for interviews of fireline decision makers on the 2021 Caldor Fire. The second block of questions was conducted for each day an interviewee was assigned to the fire. While the protocol contains many closed-questions, interviewees were encouraged to narrate experiences and probing questions were used to elucidate additional information. The questions on risk tolerance were asked, but not analyzed for the publication.

Start of Block: Block 1: Introduction Questions

Q38

I'm going to ask you questions about your risk tolerance as well. Some of the questions will be open ended and others will have options that you can choose from. Several of these questions you will answer for each day of the fire, these questions are about fire behavior, location, and tactics. Your input is totally anonymous, your name and personally identifiable will not be disclosed and you can end or opt out of the interview at any time. Let's get started.

I referenced IAPs to get your Division assignment during the fire, can you confirm that you supervised Division(s) (X) From the dates of (X) to (X)?

addtl_assnmnts Any additional assignments?

Agency What is your employing agency?

dayjob What is your job title?

home_unit What is your home unit?

career How long have you been a firefighter?

top_qual What is your "highest" IQCS Qualification?

caldor_startdate When were you assigned to the Caldor fire?

ft_supprn_opn Please rate how much you agree or disagree with this statement: Fuel treatments are not helpful in increasing suppression effectiveness.

risk_1 Please rate how much you agree or disagree with the following statement: I take risks

Q35

I'm going to ask you about day to day operations one day at a time, referencing this mapping application. I understand you might not remember all of these days, but I appreciate your trying. Please tell me if you

can't recall the answer to a question.

*(Skip fuel treatment questions if they did not utilize fuel treatments or do not remember)

Division Division Format "Div X"

location Landmarks (communities, geographic features)

Date DD/MM/YYYY

12_24 Was day (x) on Division (x) a 12 or 24 hour shift?

objectives Objectives

Tactics Tactics

tctc_effctv Were tactics effective?

tactics_fts Did these tactics use fuel treatments?

fb_ft_rateb4 Please rate fire behavior on a scale of 1-7 outside fuel treatments with 1 being a creeping ground fire and seven being an independent crown fire?

fb_ft_ratein Please rate fire behavior on a scale of 1-7 inside of the fuel treatment with 1 being a creeping ground fire and seven being an independent crown fire?

Div_resources What resources were you working with during this operation? (Aerial, Engines, Type 1 or 2 crews)

ft_uses Were fuel treatments used to?(Select all that apply)

Repeat_shift Did respondent Answer "Same as last shift" for all questions

another_shift Repeat:

☐ Yes, there is another shift (1)

☐ No, move on to final question block (2)

End of Block: Block 2: Repeated Questions

Start of Block: Block 3: General Questions

risk_2 Please rate how much you agree or disagree with the following statement: I avoid dangerous situations

ft_locations Were you informed of fuel treatment locations prior to engaging with the fire?

ft_coordination Please rate how strongly you agree or disagree with this statement: fuel treatments improve coordination among ground forces.

ft_confidenceout On a scale of 1-7, how confident were you that your forces could hold the fire inside of fuel treatments? With 1 being completely unsure and 7 being completely confident.

ft_confidencein On a scale of 1-7, how confident were you that your forces could hold the fire outside of fuel treatments? With 1 being completely unsure and 7 being completely confident.

ft_WTAin On a scale of 1-7 how willing were resources to accept assignments inside of fuel treatments? With 1 being completely unwilling and 7 being completely willing.

ft_WTAout On a scale of 1-7 how willing were resources to accept assignments outside of fuel treatments? With 1 being completely unwilling and 7 being completely willing.

ft_safety Please rate how strongly you agree or disagree with this statement: I feel safer conducting operations inside of a fuel treatment.

risk_3 Please rate how much you agree or disagree with the following statement: I seek adventure

End of Block: Block 3: General Questions
