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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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NIST Technical Note
NIST TN 2262

# WUI Fire Evacuation and Sheltering Considerations

*Assessment, Planning, and Execution (ESCAPE)*

Alexander Maranghides
Eric D. Link

This publication is available free of charge from:
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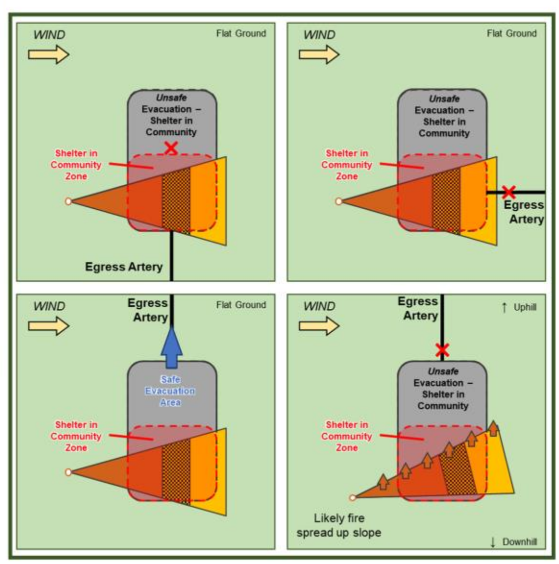


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**NIST Technical Note**
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# WUI Fire Evacuation and Sheltering Considerations

*Assessment, Planning, and Execution (ESCAPE)*

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*Engineering Laboratory*

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**Cover Page Photos**

Left set: Photographs from the Camp Fire, 8 November 2018. Clockwise from top left:

- Evacuating civilian vehicles exposed to fire on Pearson Rd, 09:41 (CAL FIRE);
- Evacuation traffic on Skyway, 10:57 (Paradise Police Department);
- Burned vehicles abandoned on Pearson Rd, 15:28 (U.S. Forest Service);
- Civilians at the Optimo TRA, 12:07 (CAL FIRE).

Right set: Diagrams depicting four scenarios of fire impact to a WUI community and egress artery. See Fig. 11.

## Abstract

Impacts of wildland-urban interface (WUI) fires continue to rise in the U.S., as evidenced by the string of devastating and record-breaking events occurring since 2017. As seen in several events in recent years, WUI fires can impact communities quickly, leaving little to no time for civilians to evacuate. Numerous events have also occurred internationally, including Australia, Canada, Chile, Greece, and Portugal.

One example is the Camp Fire that occurred on November 8, 2018, in Butte County, CA. The fire resulted in 85 fatalities and the destruction and damage of over 18 000 buildings, destroying over 90 % of the buildings in the town of Paradise. Following the fire, NIST initiated a case study to document and analyze fire spread and behavior, notifications, evacuations, and defensive actions to support preparedness for future WUI fires. The NIST Camp Fire case study has highlighted a number of potential challenges that intermix communities may face during WUI fire events. The purpose of this report is to use the lessons learned from the NIST Camp Fire case study to present a methodology and other considerations about WUI fire incidents that can be used by small and intermediate-sized WUI communities to help develop notification and evacuation plans.

The proposed methodology considers the spatial and temporal components of fire spread and the resulting impacts of fire on evacuation to develop an evacuation triangle that can be used as the foundation for notification and evacuation decisions by emergency managers. This report provides communities a path forward for assessing, planning, and implementing a notification/evacuation plan that leverages pre-fire conditions, local knowledge, and during-event information to enhance the life safety of civilians and first responders.

While additional research will provide further refinements, specifically in the areas of weather forecasting, fire spread modeling, and evacuation modeling, the proposed system outlines a path for community leaders to effectively work with first responders before a fire to assess and prepare the community for WUI fire events that can strike with little or no notice. The methodology provides community leaders with a temporal context of WUI fire events that will enable them to better evaluate different hazard reduction and risk management strategies to enhance the life safety of residents and first responders.

## Keywords

Camp Fire; community hazard reduction; disaster resilience; emergency notification; evacuation; intermix; interface; notification; pre-fire planning; public safety; wildland-urban interface; WUI

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## List of Symbols, Abbreviations, and Acronyms

**AHJ**
authority having jurisdiction

**BO**
burnover

**FFL**
fire front length

**IC**
incident commander

**ICS**
Incident Command System

**IL**
interface length

**LE**
law enforcement

**PPE**
personal protective equipment

**SIP**
shelter in place

**TRA**
temporary refuge area

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## Acknowledgments

The authors would like to acknowledge and thank Steve Hawks (California Department of Forestry and Fire Protection, retired) for his thoughtful discussions, experience, and review of this document. He also compiled the fire loss statistics for California, presented in Appendix A. Thanks go to Karen Jackson (Texas A&M Forest Service, retired) for assistance with the literature search and review of the document.

The authors appreciate the review and feedback from NIST WUI Fire Group colleagues Drs. Glenn Forney and Kathryn Butler, WUI Fire Group Leader Tom Cleary, and Fire Research Division Chief Matthew Hoehler.

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## Executive Summary

Impacts of wildland-urban interface (WUI) fires continue to rise in the U.S., as evidenced by the string of devastating and record-breaking events occurring since 2017. As seen in several events in recent years, WUI fires can impact communities quickly, leaving little to no time for civilians to evacuate. Numerous events have also occurred internationally, including Australia, Canada, Chile, Greece, and Portugal.

Minutes matter during WUI fires. Fire can rapidly impact a community, impede evacuation operations, and result in burnovers of evacuees and first responders. It is essential for communities in fire-prone WUI areas to have pre-existing evacuation plans to efficiently use the potentially limited available time during incidents. Pre-fire development of evacuation plans has the added benefit of enhancing communication with surrounding/participating jurisdictions and enabling effective communication pathways during rapidly developing WUI fire events.

Frequently, pre-planning is focused on scenarios where sufficient time for evacuation exists, and solutions for scenarios where the fire will impact the community before there is sufficient time to safely evacuate are underdeveloped or not considered. Community evacuations in response to WUI fires are complex; they are influenced by dynamic conditions and numerous variables ranging from fire behavior to human behavior. Findings from previous WUI fire case studies indicate that even individuals who were well prepared for their primary response action to a WUI fire, either to evacuate or to remain on their property, were overcome by fire when their primary plan was not successful and they had not considered contingency plans. Similarly, at the community level, citizens will benefit from a well-developed, pre-planned, community evacuation response that includes contingencies to accommodate a wide range of scenarios and random complications.

WUI intermix communities contain a significant amount of vegetative fuel scattered throughout the community, and many also contain areas of moderate to high density structures and other WUI fuels. Fire spread under these conditions can overcome the limited benefits of the small areas of defensible space available on small parcels, and exposures can exceed structure hardening and ignition mitigation attempts. The wide range of potential fire and ember exposure intensities renders stay-and-defend or shelter-in-place responses at residences hazardous at best, and deadly at worst.

WUI fires are different from other disasters primarily because the fuel that drives the event is also the asset that is being protected. This presents a unique opportunity to influence both the intensity and the impact of the disaster, with direct benefit to life safety. Targeted fuel reduction and management to reduce potential exposures is an important aspect of community evacuation preparedness and capability. Such approaches are particularly beneficial along egress arteries and around pre-planned refuge areas for contingency use as a last resort.

In this report, technical challenges related to community evacuations are discussed with respect to WUI fire event progression and life safety issues due to fire exposures potentially encountered during evacuation. Lessons learned from a detailed case study of the evacuations during the 2018 Camp Fire in Butte County, CA highlight critical concepts of WUI fire evacuations, including:

- the relationship between the time and location of ignition and the time the fire will impact the community,

- the number of civilians that can become trapped in intense fire exposures (i.e., burnovers) during evacuation,
- the widespread use of temporary refuge areas (TRAs) in urgent attempts to shelter from dangerous fire exposures and also as an evacuation and traffic management tool, and
- the benefits of a pre-disaster evacuation drill that provides a training opportunity for first responders to implement traffic management tools like counterflow and to coordinate with relevant partner agencies.

Twenty-four examples from the Camp Fire included throughout the report provide context for the developed methodology and highlight real incident outcomes, complications, and considerations.

While research has been conducted to further the understanding of different parts of the evacuation process, standardized methodologies do not yet exist for defining trigger zones to support evacuation response decision-making, specifically in the context of what communities can accomplish during WUI fire conditions. This report outlines a technical approach to help communities develop a comprehensive evacuation strategy that addresses spatiotemporal considerations and constraints associated with WUI community evacuations. The methodology and framework to develop these evacuation trigger zones are based on potential fire spread rates and the required evacuation time specific to the local community. Finally, concepts for planning and decision-making support tools that can be used in development of community notification and evacuation plans are presented.

The trigger zone concept is based on a comparison between the required safe egress time of a WUI community, WUI RSET or WRSET, and the available safe egress time, WASET. Both measures are determined by fire spread parameters and expected impacts to the community and egress pathways. Determining the elapsed time from fire ignition to the activation of emergency notifications and evacuation orders (ITA) and the subsequent community evacuation time (ET) can establish the minimum amount of time from ignition to safety (ITS), or WRSET. Successful evacuation planning will require data collection of both ITA and ET values through training and drills. Modeling may also be used to augment drills, but at this time will likely not be a substitute for full community evacuation drills. Comparing RSET to the anticipated timeline of fire progression (ASET) can determine the requisite evacuation (or alternative) response. In dire scenarios, when WASET < WRSET, evacuation will not be possible without exposing civilians to hazardous conditions. For these scenarios, implementation of pre-planned alternatives will be necessary. Linking these critical evacuation timescales to the distance fire may spread in that time can create designated geographic fire-evacuation trigger zones that correspond to different responses.

This report is intended for existing small and intermediate-sized intermix communities and isolated interface communities, although many concepts and incident considerations apply to larger communities and urban interface areas as well. Specific emphasis is given to providing a methodology to address fire events that impact a major portion of the community, resulting in limited or no options available for safe evacuation. This is particularly important for communities that may not have the resources or expertise to conduct or evaluate a more complex evacuation analysis. While additional research is needed to optimize the concepts discussed here, the presented information can inform communities and help develop/improve community sheltering and evacuation planning.

## 1. Introduction

Fires at the wildland-urban interface/intermix (WUI) pose a serious threat to the life safety of residents, evacuees, and first responders, as evidenced from numerous events within the past decade requiring rapid large-scale evacuations and resulting in destroyed communities and loss of life.

Wildland fires can impact communities within minutes or hours after ignition. If a fire ignites within a community, whether as an initial ignition or as a spot fire from a larger fire, it can rapidly grow and significantly impact civilian evacuations within and from the community. Fires in intermix communities are driven by both the built environment and the vegetative fuels located throughout. While there are often efforts to manage fuels and fire exposures through structure and parcel hardening, fires occurring in environments with high fuel densities can result in dangerous fire exposures to evacuating civilians. Fire can block—or worse, entrap—evacuating traffic and hinder first responder operations. There is a need to understand the spatiotemporal relationships among fire ignition location, fire rate of spread, and community evacuation.

Community evacuations in response to WUI fires are complex; they are influenced by dynamic conditions and numerous variables. Evacuation has often been considered as a binary decision made by civilians—either evacuate or stay, with those who choose to stay taking shelter or protecting property. In the U.S., significant emphasis has been placed on the "Ready, Set, Go!" [1, 2] education campaign that encourages awareness and evacuation, while a limited number of communities have adopted variations of shelter-in-place responses [3]. In Australia, a "stay and defend" approach is more widely considered as an option within the "Prepare Act Survive" campaign [4, 5], which encourages advanced planning and deliberate action whether one decides to stay or evacuate.

While research has been conducted to further the understanding of different parts of the evacuation process, standardized methodologies do not yet exist for defining trigger zones to support evacuation response decision-making, specifically in the context of what communities can accomplish during WUI fire conditions. Advances in computing power are improving the capability to run complex evacuation and fire spread models. However, limitations and uncertainties persist in current state-of-the-art models. Uncertainties are compounded with each step when models are combined and linked to capture the entire evolution of the event more completely. Weather, fire spread, impact of fire on roads, and evacuation are all linked, making attempts to precisely account for and predict the individual components difficult. Not every specific outcome can be evaluated; changes in evacuation conditions, including road blockages from varying fire behavior, are very difficult to predict before an ignition occurs or to model in real time. Additionally, human behavior and response is influenced by many factors, making predictions of the outcome from complex events difficult. The overall complexities call for a simplified general approach with a heavy emphasis on flexible and adaptive pre-planning.

Lessons learned from a detailed case study of the evacuations during the 2018 Camp Fire in Butte County, CA [6] highlight critical concepts of WUI fire evacuations, including:

- the relationship between the time and location of ignition and the time the fire will impact the community,

- the number of civilians that can become trapped in intense fire exposures (i.e., burnovers) during evacuation,
- the widespread use of temporary refuge areas (TRAs) in urgent attempts to shelter from dangerous fire exposures and also as an evacuation and traffic management tool, and
- the benefits of a pre-disaster evacuation drill that provides a training opportunity for first responders to implement traffic management tools like contraflow and to coordinate with relevant partner agencies.

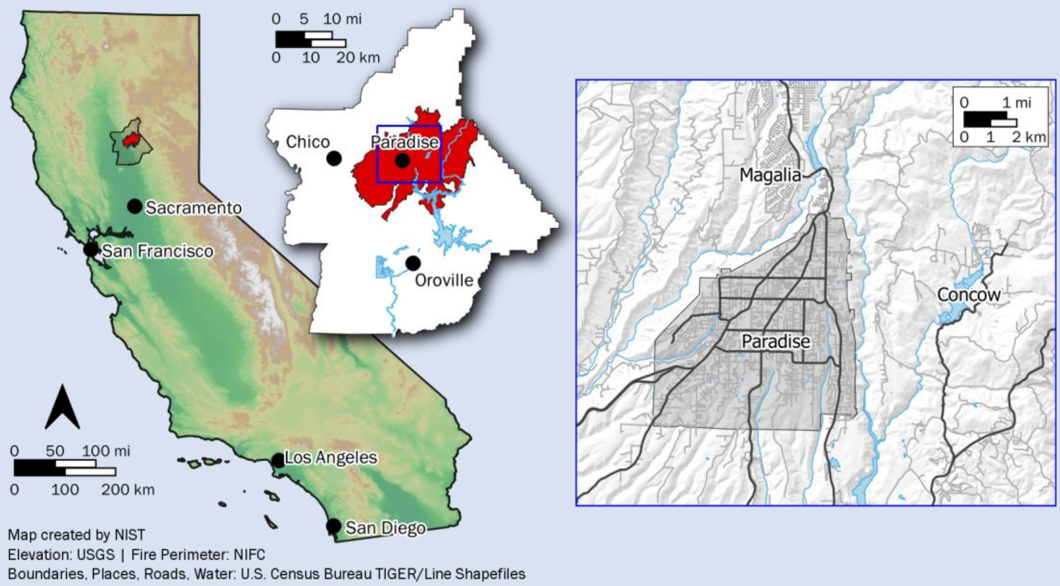
This report expands on these ideas in two parts. First, technical challenges related to community evacuations are discussed with respect to WUI fire event progression and life safety issues due to fire exposures potentially encountered during evacuation. Then, a technical approach is outlined that can be used to help develop a comprehensive evacuation strategy that addresses spatiotemporal considerations and constraints associated with WUI community evacuations. Planning and decision-making support concepts for the development of community notification and evacuation plans are then presented.

This report is intended for existing small and intermediate-sized[1] intermix communities and isolated interface communities, although many concepts and incident considerations apply to larger communities and urban interface areas as well. Specific emphasis is given to providing a methodology to address fire events that impact a major portion of the community resulting in limited or no options available for safe evacuation. This is particularly important for communities that may not have the resources or expertise to conduct or evaluate a more complex evacuation analysis. While additional research is needed to optimize the concepts discussed here, the presented information can inform communities and help develop/improve community sheltering and evacuation planning.

Throughout this report, specific examples from the Camp Fire are presented to provide context of real events from a WUI fire [6, 7]. They are presented in the following format, with this first example containing background about the incident.

[1] defined by the authors as communities with a total population less than approximately 30 000

**Camp Fire Example 1.** Introduction to the 2018 Camp Fire.




The 2018 Camp Fire in Butte County, California rapidly impacted the communities of Concow, Paradise, and Magalia, triggering widespread evacuation of 40 000 people. The maps above show the location of Butte County in California, the final fire perimeter, and the local area around Paradise.

The fire was the most deadly and destructive fire in California history, resulting in 85 fatalities and more than 18 000 destroyed structures. The Camp Fire ignited at approximately 06:20 off Camp Creek Road near the small community of Pulga in the Feather River Canyon, northeast of Concow. After immediately impacting Pulga, the fire spread southwest over a ridge, spotting and burning into Concow by 07:30, 6.4 km (4 mi) away. By 08:00 spot fires were igniting in Paradise, an additional 6 km (3.75 mi) west of Concow. The fire front impacted eastern Paradise forty minutes later.

A post-fire case study was conducted, resulting in two primary reports to date: the first on the fire progression timeline, fire behavior, and identified civilian burnover events [7], and the second on life safety aspects including notification, evacuation, traffic, temporary refuge areas, rescues, and fatalities (collectively, NETTRA) [6]. Various examples from the Camp Fire are introduced in this report to provide recent real-world examples that illustrate some of the considerations and challenges that are presented here.

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## 2. Community Evacuation and Alternatives

This section highlights different aspects of community planning and response to WUI fires that are important components of a comprehensive community response plan. Evacuation itself is a key component, of course; however, alternatives are also an important consideration for scenarios when evacuation is not possible. Such actions are commonly referred to as stay and defend and shelter in place. The following sections present important life-safety considerations and hazards of these approaches, including the concept of temporary refuge areas and areas of last resort. Defensible space is a critical contributor to life safety in WUI fires, including for evacuation and alternatives. However, defensible space alone is generally not a sufficient solution.

Due to the dynamic nature of WUI fire evacuations, situational awareness is an important component of the incident management. Traditional information updates come from sources including radio reports from personnel in the field and 911 operators. Technology advancements are increasing the amount of data potentially available, including live video feeds showing traffic conditions, real-time observation of the current fire location via remote sensing, and social media. There is a need to develop new systems to effectively gather, interpret, and use these information streams. Planning for the dissemination of this information is an important component of using these new technologies.

Computer models of fire spread and evacuations are becoming more sophisticated, with potential to support advance planning and scenario development. This section includes a basic introduction to models and references several recent research efforts to combine or couple fire and evacuation models.

### 2.1. Evacuation

The most common life-safety response policy to WUI fires is evacuation of the threatened population located in the anticipated path of the fire. This is the standard response implemented by officials in the U.S. and Canada, and is the preferred action in Australia [8]. Successful evacuation away from the hazard is the surest way to avoid exposure to flames, embers, heat, or smoke.

There is limited standardization for both the planning and execution of evacuations for WUI fires, although generalized conceptual guidance is available for all-hazards planning. The Federal Emergency Management Agency (FEMA) has a document [9] that outlines planning considerations. The document briefly touches on important aspects ranging from accessibility and medical facilities to accommodating pets to evacuation shelters out of the hazard area. The Federal Highway Administration (FHWA) also has a primer document describing general planning and operations concepts for no-notice evacuations such as those due to wildfires [10]. While the document highlights the transportation component of evacuations, the report includes additional background on no-notice incidents and general considerations for planning and operations.

Evacuations are often initiated by emergency officials who issue notifications and instructions to the affected populations using various tools such as reverse-911, the Integrated Public Alert & Warning System (IPAWS), and the internet. Sirens and door-to-door notifications may also be utilized. If time allows, evacuations may be conducted in phases, starting by notifying and evacuating areas of the community that may be affected first. This is often facilitated by establishing predetermined evacuation zones. In the U.S., most people evacuate using personal vehicles. Communities may include provisions for mass evacuation transportation for individuals without access or ability to utilize personal vehicles, whether via public transportation or more specific arrangements for evacuation procedures.

A critical public safety aspect of evacuations is that they are done early, when conditions are favorable before the fire impacts the community. Past fires have shown that attempting evacuation when there is not enough time to do so safely can result in evacuees being overrun by fire before reaching safety. Late evacuation can be generally defined as "an evacuation that puts an individual, or group of individuals, at risk of encountering dangers associated with the passage of a [wildfire]" [11], and may occur due to fast-moving fire, extended duration of evacuation procedures, or delayed decision-making. Deaths due to fire exposures experienced during evacuations have occurred in fires across the globe, with examples in the U.S. [12], Australia [11, 13], and Europe [14-16]. The hazard associated with smoke exposure and inhalation is complex and more widespread. Beyond acute exposures in the fire, smoke from wildfires and WUI fires can travel for tens or even hundreds of kilometers downwind and can impact civilians with preexisting respiratory conditions as well as the general population.

Adding to the challenges of timely evacuation is that, in many WUI fire events, evacuations are initiated with little notice before the onset of hazardous conditions. While fire weather alerts, such as Red Flag Warnings in the U.S., indicate conditions conducive to ignitions and rapid fire spread [17, 18], these are only generalized pre-event advisories. Initial orders for evacuation are typically reactionary, issued after a fire ignites. Alternatively, some individuals, or even entire communities, may consider evacuation before the most hazardous fire weather conditions are forecast to begin. This approach to "leave early" is recommended in Australia for days with Extreme or Catastrophic Fire Danger Ratings [4, 19]. However, this approach may not be feasible in all areas or for a large fraction of the population due to various socioeconomic burdens imposed by evacuations.

The no-notice nature of many WUI fire evacuation events requires significant pre-planning [10]. During an incident, emergency officials will likely have to make decisions with incomplete information and without time to develop a course of action coordinated with all the response agencies involved. Development of a comprehensive evacuation/sheltering plan *before an event* can increase the likelihood of an effective response, enhancing the safety of community members. Even in the event of a catastrophic incident that exceeds the capacity of the written plan, the existence of a plan can provide a foundation from which an appropriate response can be enacted.

## 2.2. Evacuation Alternatives

In response to a threatening WUI fire, residents must decide to take protective action or not, generally involving evacuation or sheltering. While early evacuation removes citizens from the hazards presented by WUI fires, alternatives to evacuation may be beneficial in some circumstances, either as contingency plans for individual citizens or for specific community/fire scenarios [3, 20-22]. The variability of ignition locations, fire spread, and community specifics dictate that evacuation cannot be implemented as a "one solution fits all" approach. Individuals (and by extension, communities) must have multiple response plans for various scenarios or eventualities depending on the actual fire event progression. Fatalities have occurred in instances where a person's primary plan to evacuate was not possible or successful and they were not prepared for an alternative action [23].

In the U.S., wildfire evacuations are predominantly achieved by use of personal vehicles, often at the rate of two vehicles per household [24]. This can lead to significant traffic delays, further increasing time required to evacuate and potentially exposing evacuees to the advancing fire. Additionally, background traffic and various intermediate trips [25] that civilians may make in response to a fire, including retrieving or meeting with family members [26, 27] or returning home [28] to gather belongings, may further extend evacuation times. In some communities, the evacuation of the residents to safety may not be a feasible response when evacuation capacity is considered against the anticipated fire spread rate, and alternatives should be considered [3, 20, 29].

Two often-discussed alternatives to evacuation include "stay and defend" and "shelter-in-place" (SIP) frameworks [22, 30]. There is some overlap between the approaches, however SIP is generally regarded as more passive compared to the actions required by a stay and defend approach [30, 31]. Sheltering choices may include staying at home (often including attempts to protect the home) or heading to a refuge area or other safer space [20]. How people ultimately decide what to do is an important component of ongoing research [32-34].

It is important to note that these approaches are not universal and may not work in all scenarios [20, 22, 23, 30, 35]. Decisions about whether a home is defensible, whether a civilian is physically able and prepared to defend a home, and whether it is safe to evacuate are nontrivial, dynamic, and variable from individual to individual and location to location [20]. These considerations cause difficulty for widespread implementation, including who determines (and how) what conditions, locations, and personal preparedness are appropriate for SIP.

Consideration of alternatives to a complete evacuation are necessary as part of contingency planning, primarily in response to situations where there is not enough time for safe evacuation to occur. These are referred to as dire scenarios [36]. The idea of shelter-in-place is typically employed under three circumstances: when it is the only option (i.e., entrapment), when evacuating would lead to entrapment, or as a pre-determined course of action for refuge or to protect the home [20]. Depending on the size of a community and the available evacuation capacity, community response/evacuation plans could implement a hybrid of evacuation and SIP [20]. For this to be a reasonable and safe path forward, additional research is required to identify and design safe areas for community refuge, and to standardize an approach for assessing whether a structure is defensible.

Comparisons of exposures experienced during evacuation should be considered with respect to potential exposures in other places of refuge. In many WUI communities, the fuel density (both vegetative and built environment) leads to high exposure hazards, making it unsafe to seek refuge there, necessitating evacuation. Even if there is a risk of exposure during evacuation, this may be less hazardous than taking refuge in the available locations. However, there may be instances where combinations of roadside fuels, evacuation routes, or heavy traffic delays increase the hazard to evacuees, and seeking refuge may be a better option.

### 2.2.1. Stay and Defend

“Stay and defend” refers to an alternative to evacuation in which residents prepare and intend to remain at their property to defend against the fire and ember exposures, with the goal of saving structures and lives. In Australia, stay and defend was gradually adopted into policy during the 1960s as a civil defense-like approach to public safety as development expanded into fire-prone rural areas beyond the capacity of the existing fire service [37]. Subsequent disastrous bushfires resulted in an increasing emphasis on individual responsibility and decision-making, with the stay and defend approach evolving into “Stay or Go” after the 1983 Ash Wednesday bushfires, and into “Prepare Act Survive” after the 2009 Black Saturday fires.

While not advocated by emergency officials in the U.S., some residents invariably decide to stay during a wildfire and defend their property and surrounding neighboring properties.

The “stay and defend” approach can work under certain scenarios where there is an appropriate balance among actual fire exposure levels, structure/parcel ignition resistance, and effective defensive actions. Proponents of the stay and defend approach acknowledge the important concept of suitability for staying and defending. Some structures or locations may not be defensible [29]. There are many places in the interface and intermix where the density of structures and other WUI fuels render a parcel indefensible, even by trained and equipped firefighters. Building construction and local attributes of terrain and weather further influence defensibility.

Significant preparations are necessary to implement this approach [38]; not all civilians will be capable of defending their property, especially against high intensity exposures. However, this crucial aspect of the “stay and defend” mantra was found to be largely misunderstood and oversimplified by the public. Roughly one third of the 173 fatalities in the 2009 Black Saturday fires occurred at homes that were not defensible [31, 39], including conditions where structures were located close to significant wildland vegetation.

Furthermore, just because a structure may be deemed defensible, that does not address the need for the resident to have appropriate training, fitness, and equipment to successfully defend the structure [20]. The stay and defend approach essentially requires a civilian to undertake a skilled and physically demanding professional job—firefighting. Miscommunication or misunderstanding of the potential risks and exposure conditions that may be encountered can result in inadequate preparation, which greatly increases the risk to life safety [31]. It should be clear to residents that staying within the path of a WUI fire, whether planned or unplanned, can have serious or fatal consequences. In past fires, even individuals who were well prepared to defend their properties (including those with fire service training, firefighting equipment and water supply, personal protective equipment [PPE], and defensible space) have died, indicating the difficulty of this approach [23, 31]. Decisions to abandon plans to defend one’s structure (for example, after determining the situation is beyond the capability of the resident to defend) and then evacuating late can lead to some of the most dangerous scenarios in the middle of peak fire activity.

While there are successful cases of civilians defending their properties, there has been no systematic study to assess how many fatalities are associated specifically with stay and defend practices or intentions. With some exceptions, e.g. Ref. [31], the intentions of those making this decision are unknown. Additionally, information about harmful effects of smoke inhalation and other delayed significant health issues after staying behind and defending residential properties is primarily anecdotal. No comprehensive analysis has yet been conducted to assess the effectiveness of defensive actions by civilians, which would be especially useful within the context of local conditions (fuels, topography, and local weather), quantification of fire and ember exposures, and life safety.

All of this leads to important aspects of this approach—what is defensible, and what training and equipment are required to do so effectively and safely?

Conceptually, defensibility includes exposure levels, structure construction and ignition resistance, and the capacity to defend [38]. The level of potential exposures vary so dramatically that it is difficult to summarize or know the conditions that residents will ultimately encounter. Exposures can range from minimal fire and small ember fluxes to direct flame impingement from a neighboring home that is fully involved. Even experienced firefighters can be surprised by the intensity of the WUI fire front, especially in catastrophic events.

The capacity to defend is subject to personal capacity (physical and mental), equipment, and local conditions of the property [38]. Physical fitness, water supply, and equipment availability require long-term pre-planning and financial investment. In rural locations, exposures may be more readily managed, as space may be available for fuel relocation, reduction, or removal. Hazard reduction by individual property owners, even when implemented at a parcel level, does not address overall exposures from adjacent parcels [40], which may be significant in intermix or interface communities with increased fuel density.

Differences between a civilian, including all but the most well-prepared individuals, and firefighters are listed in Table 1. From basics like appropriate firefighting training, experience, and physical fitness, to details such as firefighting equipment (including tools, water supply, and PPE) and situational awareness, there is a large gap between the two groups. The differences point to the high potential for civilians to encounter situations that compromise their life safety. Work is needed to develop explicit requirements that can be used by AHJs and civilians to prepare residences, infrastructure, and communities for the safe implementation of stay and defend policies and regulations [41].

When applied to today's WUI, particularly in contrast to rural ranch settings, further challenges arise, such as whether the property owner is present at home when the fire ignites, or whether they will have to return toward or into the fire to get home and enact their defense plan.

If the expectation of stay and defend is to help put out spot fires, this is a very different exposure level than an intense fire front with heavy ember shower and flame exposures from parcel and neighboring parcel fuels, or even suppressing the structure after it potentially ignites. Residents were surprised by the lengthy amount of time it took the fire front to pass in the 2009 Victoria fires [39]. This can be the case in intermix and interface fires where the types of fuels present can continue to burn for long durations, generate embers, and continually ignite additional fuels for a long time, requiring continuous defensive and suppression efforts, likely in unhealthy conditions.

**Table 1.** Differences between private civilians and firefighters.

| Preparedness/Response Attribute | Typical Civilian | Firefighter |
|---|---|---|
| Training and maintenance of proficiency of WUI/wildland firefighting strategies and tactics | Limited | Mandatory training; experience gained through practice and annual recertification |
| Physical fitness | Variable | Required, tested |
| Equipment | Limited | Available, maintained, tested, and specialized |
| Standalone water supply (independent of community infrastructure) | Variable | Available on apparatus and locally accessible sources |
| PPE and safety training, including wildland fire shelter use | Likely inadequate | Standard and required |
| Situational awareness | Limited to media, internet, and radio scanners, and may be dependent on electrical power supply | Fully integrated in ICS with an incident action plan (IAP) |
| Lookouts, Communication, Escape Routes, and Safety Zones (LCES) | Unlikely | Yes |
| Operational support | No | Yes |

### 2.2.2. Shelter-in-Place

Shelter-in-place is a protective action where individuals quickly shelter indoors in response to an emergency. This action is accomplished faster than an evacuation because the person is already located in or near the sheltering location and does not require travel. It is a common response for other no-notice hazards, such as tornadoes or chemical releases. In special cases, shelter-in-place may be a response during interior structure fires (e.g., high-rises, hospitals), but this action depends on the specific design of engineered buildings, the fire scenario, and fire protection systems (i.e., passive barriers and active suppression).

Currently, FEMA does not include wildfire in its guidance for SIP that includes other emergencies including earthquakes, floods, hurricanes, and tornados [42, 43]; evacuation is the recommended protective action [44]. Due to combustible construction materials, fuel accumulation and agglomeration, high structure density, and existing ignition vulnerabilities [40], many communities are not generally suitable for stay and defend, and nearly all are unsuitable for a more passive SIP approach.

Shelter-in-place requires homes to stand alone through a WUI fire event without intervention. In nearly all cases, current structures are not built to a standard where passive sheltering is a reliable way to survive. Even in locations where fuels have been removed to avoid direct flame contact and high radiative exposures, the threat of ignition from embers is very high. Using SIP as a last resort, where a structure may provide temporary refuge from exterior exposures before it ignites, has also been done in the past, sometimes as part of a stay and defend strategy. This is an important option to keep in mind; however, significant risks are involved with sheltering inside a burning building. Conditions can rapidly deteriorate once a home ignites, forcing occupants to escape outside where the initial exposures they were trying to avoid may still be hazardous. Injuries and deaths of even experienced fire service personnel have occurred when determining the transition point between sheltering inside and exiting into the outdoor fire [23].

Few communities in the U.S. have adopted a SIP approach for WUI fires. The community of Rancho Santa Fe in San Diego County, California is often referenced as an example [3, 20, 30, 35]. However, even within the community where this approach is implemented there is variable interpretation of the shelter-in-place terminology. Officials disagree whether shelter-in-place means a) building construction and pre-fire preparations alone versus b) a default approach for residents to remain at home during a wildfire. While the community was built to higher building standards[2] to resist ignitions, the current official guidance from the Rancho Santa Fe Fire Protection District is to first evacuate if safely possible [45].

### 2.2.3. Areas of Last Resort and Temporary Refuge Areas

In some cases, such as in fast-moving fire scenarios, there may not be enough time to return to one's property to carry out a stay and defend or shelter-in-place plan, let alone evacuate. In other scenarios, plans to stay and defend or shelter in place may fail, or evacuees may be overcome by fire during evacuation. These outcomes have been observed in several past fires; the most detailed analysis followed the 2009 Victoria bushfires in Australia when a royal commission investigated the devastating fires [39].

One result of the Commission's findings was that people must have contingency plans and alternatives of last resort if their plan to leave early or stay and defend fails. Subsequently, Australians formalized the Neighborhood Safer Place [46-48] and Community Fire Refuge [49] ideas. Similar concepts have been implemented by local communities in the U.S., including the community of Concow, CA involved in the 2018 Camp Fire, with pre-designated Wild Fire Safety Zones and public assembly areas. While comparatively safer than surrounding areas, these locations do not guarantee safety. It is not guaranteed that access to these locations will be possible, or that they will be able to accommodate everybody seeking refuge there. Further, there is no guarantee of the presence of first responders to facilitate or protect those taking refuge.

Similarly, open spaces (i.e., parks, parking lots) or select structures may be chosen in the moment as temporary refuge areas (TRAs). Many of the same challenges regarding shelter-in-place also apply to areas of last resort or TRAs.

## 2.3. Defensible Space

This section provides context on the implications of the concept of defensible space on structure accessibility and defensibility as they relate to evacuation and rescue operations.

Defensible space is a structure-centric approach where fuels are managed/removed from the surrounding parcel with differing specifications at increasing distances from the structure, often a primary residential structure. The defensible space concept was conceived in large part to provide a safer space for first responders to defend a structure and has been implemented for decades. For example, it was first added to California state law in 1965 [50]. Several

[2] While comparatively higher than other existing building codes, exact requirements are unspecified, as is the degree to which compliance of these standards has been maintained years later. Many vulnerabilities remain even after WUI fire provisions in existing building codes are implemented [40].

amendments have been made in the years since, with the most recent in 2021. The “home ignition zone” and the Firewise program [51] were introduced in 1986 to educate homeowners and communities about fuel reduction and vegetation maintenance within 200 ft (60 m) of structures.

Two primary benefits of defensive space fuel reduction are:

1. exposure reduction to the structure and surrounding parcel area, and
2. a safer environment for trained firefighters to defend the residence.

While defensible space is an important component of structure survival and stay and defend or shelter-in-place responses, defensible space alone is not sufficient to support these actions. A few limitations of defensible space should be considered. Defensible space, although conceptually presented as a single approach, is not defined by a one-size-fits-all distance or fuel treatment for every structure; it requires adjustments based on the footprint of the structure and surrounding fuels and topography [52]. One prominent limitation is that there are often discontinuities on defensible space at property boundaries, and home ignition zones often overlap or extend beyond property lines [29, 53]. Another is that, within a community, varying degrees of defensible space may be implemented or maintained by property owners, and regulations and enforcement may differ across jurisdictions.

Parcel-to-parcel exposures and fuel agglomeration can have significant impact on structure survivability and access for evacuation and rescue operations [40]. Fire and ember exposures in WUI settings can come from burning buildings, vegetation, and other parcel-level combustibles. The parcel-to-parcel fire and ember exposures in high density construction (i.e., structures separated by less than 25 ft [7.6 m]) can result in significant life safety hazards and should be considered when planning for the evacuation of civilians; special attention should be placed on the evacuation of civilians with reduced mobility. High exposures can also be encountered in moderate density intermix settings with limited fire history, where fire exposures can impact a residence from adjacent parcels with high parcel fuel loadings.

Wildland vegetation can also have a significant impact on residential properties, resident evacuation, and first responder access. Intense fire exposures from wildland fuels can occur on parcels where there is limited setback from property lines for the creation of effective defensible space and no mechanisms are in place for a resident to manage the fuel loading beyond their property line.

**Camp Fire Example 2.** Defensible space and exposures from neighboring parcels.


Exposures from neighboring parcels must be accounted for when assessing the defensibility of a property. The fully involved parcel (including structure, vehicle, and vegetation) seen above illustrates the very high fire exposures that can be generated during WUI fires. Fully involved fuels with flame lengths greater than 6 m (20 ft), as in the image above, would be difficult to contain even with several firefighting apparatus and cannot be contained by defensive actions by residents.

In this scenario, the structure separation distance (SSD) was 13 m (43 ft) from the burning home shown in the image to the neighboring structure. The structure to property line distance (SPLD) was 8 m (26 ft). Defensible space may be difficult to implement in moderate and high-density communities where significant fire exposures can originate from neighboring parcels and structures are spaced even closer than in this example.

Defensible space is an important component of a stay and defend or shelter-in-place approach, but the life safety risks can be very high. In the context of evacuation and rescues, there is significant value in managing the fuels around a residence. There is a fundamental difference between designing, building, and maintaining a structure to meet existing minimum code requirements and making a structure standalone with the necessary hardening to address both the expected exposures from fire (flames) and embers [40]. Many existing building codes for residential construction in the WUI are designed to work together with defensible space to allow first responders safe access to defend the property. Defensible space can provide significant value during assistance and rescue operations by creating a safer environment for assisted/rescued civilians and first responders. Defensible space practices are therefore important for residences, commercial facilities, and critical care facilities where additional time may be necessary to evacuate mobility impaired residents.

Beyond the impacts on firefighter access and rescues from residences, fire exposures can pose a hazard to evacuating civilians by causing the local closure of egress arteries. Closure of a main roadway during community evacuation will impact civilian egress and first responder access even if neither group becomes entrapped in a burnover event. While defensible space is often focused on protecting structures, similar fuel reductions along egress arteries play a critical role in limiting the potential exposures encountered during evacuations.

## 2.4. WUI Fire and Evacuation Modeling

WUI fires are community and incident specific. Extrapolation and generalization of results from one incident to another community or scenario are limited due to sensitivity to local conditions [54], including the fire scenario, community demographics, evacuation capacity and egress routes, and many other factors. Previous case studies and generalized findings can identify possible scenarios and challenges to look out for, but assessing how an individual community can and will respond to those events must be focused on the local community in question. This provides an opportunity for use of computer modeling as a tool to support decision-making and advance planning by public safety officials by providing insight into potential scenarios and outcomes.

Evacuation planning lies at the intersection between fire spread and evacuation modeling. To provide a comprehensive approach, an integrated, coupled set of models is desired. A computational tool that combines the relevant components of an evacuation event, namely the fire, pedestrian movement, and vehicular traffic, would support evacuation plan development and the decision-making of emergency officials [55]. Recently, Ronchi et al. have developed a modular framework (called WUI-NITY) [56, 57] that integrates these three layers of modeling. Through this framework, any of several models might be selected to accomplish prediction of each fire or evacuation component. Ronchi et al. [55] present a broad comparison and evaluation of many of the existing models in each of these three areas. Furthermore, they have developed a list of important questions users/practitioners need to consider regarding the performance of different model components [55, 58].

One major challenge is the amount of complexity in each layer of the combined modeling. For the fire component these include aspects of fire spread uncertainty and factors like weather forecasting and fire-weather coupling, spot fire ignitions, and treatment of structural/community fuel types in current models. For the evacuation component these include aspects of evacuee decision-making, departure timing, route choice, and destination choice [59]. Incorporation of human behavior and decision-making into the models is also an ongoing challenge. Several studies of human behavior during WUI fires have been done (see an overview [59] and detailed reviews of the field [33, 60]). These complexities in predicting fire spread and the evacuation process exist even before the fire impacts the evacuation routes or community; additional complications can arise that are not able to be specifically predicted due to their stochastic nature. Pre-planning and scenario gaming becomes key to understanding response options and the potential consequences. Evacuation models that are uncoupled from the fire spread models, specifically addressing scenarios where evacuation is not affected by fire, may provide valuable insight to traffic management and the time required for evacuation in the best conditions.

## 2.5. Evacuation Trigger Models

The decision to order evacuations must be made by fire officials in the face of complexities and uncertainties in evacuations and fire spread. Decision points are based on certain fire behavior or weather events or extent of fire progression, often linked to physical landmarks to aid in identification. When situation-specific criteria are met, response actions or evacuations are triggered [61]. Standardized guidance for determining triggers is limited or non-existent; it is often left to the experience and judgment of the incident commander or other emergency official to consider required evacuation time against estimates of fire arrival time.

Several models are in development to link components of fire and evacuation modeling to systematically identify trigger locations and buffers by linking fire and evacuation models. An early approach was introduced by Cova et al. [61] in 2005, inspired by a GIS-based decision support tool for hurricanes (HURREVAC [62]). The model, named WUIVAC, calculates fire spread predictions for an area of interest and determines buffers around the community corresponding to the different time periods over which the fire is predicted to spread into the community. These fire arrival times are compared to an estimated evacuation time, determined independently, to identify the buffer location(s) where an evacuation should be initiated if the fire reaches that specified location around the community. The model has been applied in a research capacity [63, 64] to Julian, CA, a community in San Diego County that was affected by the 2003 Cedar Fire. A traffic simulation model has recently been implemented in conjunction with the WUIVAC model to further develop the evacuation time component of the trigger buffer [65].

More recently, Mitchell et al. [66] explored defining evacuation trigger buffers using a method they called PERIL, developed using the WUI-NITY model framework [56, 57, 67]. To demonstrate the capabilities of this approach, the model was applied to two communities: one in the United Kingdom and one in Colorado. Kalogeropoulos et al. [68] advanced PERIL into k-PERIL. The new implementation generates a set of trigger buffers by stochastically changing the input conditions to a range of user specified values. The resulting set of trigger buffers indicates a confidence interval reflecting the variability and sensitivity of the wildfire/evacuation simulations. Sections of the boundary that exhibit more variable fire behavior and higher uncertainty result in a wider range of trigger buffers.

Both the WUIVAC and k-PERIL tools are promising research efforts that could provide a means to apply many of the evacuation planning concepts discussed in this report. This approach has not yet been implemented by communities in practice and is further discussed in this report in support of expanding options for community evacuation plans. However, when using modeling tools to plan and predict different aspects of community evacuation, model outputs need to be assessed and interpreted by subject matter experts of the tools used to understand the limitations and uncertainties associated with the predicted outcomes.

## 2.6. Evacuation Triangle

The evacuation triangle presented in Fig. 1 represents the connectivity among fire–evacuation trigger zones (ETZs), available time before the fire reaches the community (or associated egress routes depending on the geography and scenario), and evacuation decisions. The concepts of this evacuation triangle will be useful before a fire, during the design stage of a community evacuation plan, and during an actual fire event to link together these three key aspects of evacuation. The concept of the triangle is intended to be continuously evaluated during a WUI fire event, indicated by the arrows; all three aspects of the triangle are dynamic. Changing conditions in fire progression and available versus required evacuation time (i.e., fire–evacuation trigger zones) will influence evacuation decisions. It should be noted that, unless the fire is contained or slows down, the available time typically only decreases as fire approaches a community.

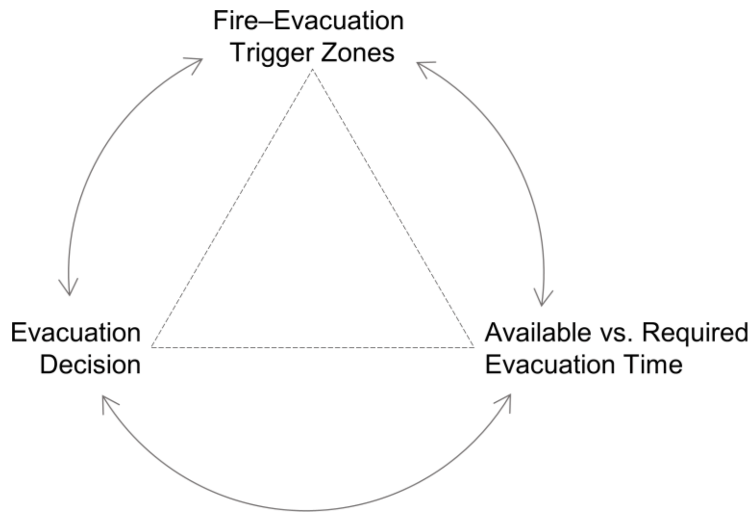



**Fig. 1.** Evacuation triangle illustrating connectivity among evacuation trigger zones, available time before fire reaches community, and evacuation decisions.

## 3. Technical Challenges of Community Evacuations from WUI Fire

WUI fires have important differences distinguishing them from other disasters. These differences have implications in managing the hazard of WUI fires, some of which can directly affect evacuations. This section presents challenges regarding community evacuations to be considered when planning community response to WUI fires.

Modeling of fire spread and evacuation may be able to assist with planning and decision-making by emergency management officials. However, a thorough understanding of the limitations and uncertainties of the modeling tool is required to adequately interpret the results.

A list of technical challenges is summarized at the end of this section.

### 3.1. Distinguishing Characteristics of WUI Fire Disasters

Several key aspects distinguish WUI fires from other natural disasters. Some characteristics that distinguish WUI fires from other natural events that can lead to evacuation are presented in Table 2. Each natural disaster included in this table can result in damage and destruction to a community and infrastructure (including egress arteries). However, WUI fires are unique in that the community itself is the fuel that propagates and, in many cases, intensifies the disaster. The extent of disaster propagation in WUI fires is driven by the complex interactions of the fuels, weather (wind, humidity), terrain, and defensive actions.

**Table 2.** Characteristics of WUI fires compared to other selected natural disasters.

| Characteristic | Hurricane | Flood | Tornado | Earthquake | WUI Fire |
|---|---|---|---|---|---|
| Built environment adds energy to fuel event | No | Yes [a] | No | No | Yes |
| Defensive actions during event change outcome [b] | No | No | No | No | Yes |
| Event energy can be managed beforehand | No | No [c] | No | No | Yes |
| Event starts other similar events | No | No | No | Yes | Yes |
| Notification period | Days | Variable [d] | Minutes | None | Variable [d] |
| Extent of evacuation | Region | Community/ Region | Shelter-in-place | Shelter-in-place | Community/ City/Region |
| Building construction or sheltering standards | Yes | Yes | Yes | Yes | Limited |

[a] infrastructure failure; dams, levee systems (not individual buildings)
[b] including residential and commercial structures or other infrastructure
[c] amount of precipitation cannot be controlled; flood water can potentially be managed
[d] minutes to hours to days

### 3.1.1. Defensive Actions Affect WUI Fire Outcomes

In WUI fires, the assets that are being protected (wildland vegetation and structures) are also the fuel and energy sources that drive and often intensify the disaster. This has significant implications on how WUI fire hazards can be mitigated and how WUI incidents can be approached in the context of evacuation and disaster response. First responders (specifically firefighters) can directly affect the outcome of WUI fires—defensive actions during the event may alter the event progression and ultimately stop the fire spread through the community and contain the fire in most cases. Therefore, it is critical that the specific defensive actions performed in the community and their impacts are accounted for in the context of exposure reduction as well as traffic management and rescue operations. This is different from the approach to other disasters in which emphasis is placed on pre-disaster evacuation support or rescues during and after the event.

### 3.1.2. The Asset is the Fuel

The fuel and asset being one and the same means that efforts to protect the community beforehand through fuel reduction and structure hardening can affect the energy available to the disaster, unlike the other events listed in Table 2. Wildland fires can be beneficial to the ecosystem and are a recurring natural event. Attempts to manage wildland fire intensity and frequency have been undertaken by federal, state, and local landowners for decades. The transition from wildland fires to WUI fires can be mitigated by fuel treatments around and within communities and by hardening structures and parcels throughout the entire community. These actions can decrease ignition potential and reduce the intensity of a fire in the community, potentially reducing losses from WUI disasters. Pre-fire hazard mitigation and its effects on exposure intensity expand the range of potential outcomes as a wildfire impacts a community, spanning from a reduction in intensity and interruption of fire spread to complete destruction of the community and significant loss of life.

### 3.1.3. Fires Can Start New Fires

An additional distinction among natural disasters is the potential for WUI fires to initiate additional incidents themselves. Spot fires ignited from firebrands, which can be transported kilometers ahead of the main fire front, effectively accelerate the anticipated or previously observed fire spread rate. These spot fires can generate new hazards in unexpected locations deeper within the community, dynamically expanding evacuation requirements and potentially impacting previously uncompromised evacuation routes.

### 3.1.4. Notification Times Range from Minutes to Days

On the continuum of notification periods, WUI fires are generally positioned between earthquakes and tornados, which give shorter notice, and flooding and hurricanes, which generally provide more lead time. In some instances, WUI fires may be characterized by a no-notice timeline, where an ignition occurs close enough to a community that immediate action is required, more akin to tornado timelines. In other cases, a fire burning in the wildlands may not pose an immediate risk and provide additional lead time for evacuations.

### 3.1.5. WUI Fires Have Limited Advanced Warning and Locally Variable Intensity

In the U.S., large-scale community and regional evacuations are commonly implemented when hurricanes (more generally, tropical cyclones) impact populated coastal areas. Many coastal states and communities have well-established evacuation plans and zones to guide preparation and response for varying levels of storm intensities and impacts. Some notable components associated with community evacuations ahead of a hurricane provide a contrast with WUI fires.

To inform the public about an approaching hurricane, a system of watches and warnings[3] has been established and implemented by the National Weather Service (NWS) [69, 70]. A watch is issued for a specific area when hurricane conditions are a possibility within 48 hours. A warning is issued when a hurricane is expected in an area within 36 hours. This is distinctly different from WUI fire disasters in several ways:

1. While Fire Weather Watches and Red Flag Warnings are issued ahead of qualifying weather days, these general warnings do not indicate that there *is* a fire. The actual ignition location, direction of fire spread, and fire intensity are not determined until after an ignition.
2. Hurricane watches and warnings are issued based on a standardized system for predicting the track of the hurricane, including confidence and uncertainty analyses.
3. The lead time of hurricanes is typically measured in days, not hours or minutes.
4. There is a national decision support tool with clear temporal thresholds in place for triggering evacuations for hurricanes (HURREVAC [62]).

Once a hurricane moves over land the storm decreases in intensity as the energy source (warm ocean water) stops feeding the hurricane. In contrast, WUI fire intensity and fire spread is solely dependent on local fuels, including the community itself, and therefore can decrease or increase in intensity and/or spread rate. Fire spread through a community is not characterized by widespread steady-state propagation; community fuels can generate very high local exposures. Furthermore, fire intensity can vary dramatically based on local fuels, wind, and topographic characteristics. Spot fire ignitions ahead of the main fire front can start new events or accelerate the timeline of fire spread. In contrast, a hurricane does not start new hurricanes, and the construction characteristics of the community do not affect the intensity of the hurricane. This is also true of tornadoes, earthquakes, and floods. These two fundamental differences have repercussions on the design and execution of evacuation plans for WUI fires as compared to other disasters.

### 3.1.6. No Standardized WUI Fire Shelters

The lack of reliable and effective shelter also makes WUI fires different from other natural disasters. There is no federal or state guidance available for the placement, construction, and maintenance of shelters than can be used to protect civilians during WUI fires. The lack of reliable community fire shelter design information, in addition to the concerns discussed in Sec. 2.2 regarding stay and defend and shelter-in-place, make the use of that approach difficult at this time. Without means to safely design and properly place and maintain WUI fire shelters in

[3] The NWS watch and warning system also encompasses weather impacts beyond tropical cyclones.

communities, authorities having jurisdiction (AHJs) have fewer options for addressing the life safety of civilians during WUI events compared to some of the other natural disasters like tornadoes and hurricanes.

Information is available to the public for how to generally prepare for disasters. Publications and websites like https://www.ready.gov/evacuation can provide useful information to the public for general evacuation information and are designed to work together with specific community and regional guidance; however, the differences highlighted above indicate a need to treat WUI fire disaster evacuations differently.

### 3.1.7. Wildfires Are Relatively Frequent

Finally, AHJs must contend with the high frequency of wildland and WUI fires that threaten communities relative to the frequency of some of the other natural disasters. The National Interagency Fire Center (NIFC) reported a total of 58 733 wildland fires in 2021, the year with the fifth fewest ignitions on record. This number includes all wildland fires, not just those that reached a WUI community, and it does not necessarily include all fires that started within communities. A closer look at wildfire statistics can provide insight into how many of this large number of ignitions may develop into significant events that can impact communities.

Overall numbers and statistics of evacuations for wildland fires are not generally tracked or available. One study by Beverly and Bothwell [71] identified 547 wildfire evacuation events in Canada between 1980 and 2007, averaging 20 per year with a high count of 53 events in one year. Updated data show approximately the same number of wildfire evacuation events (566) occurring in Canada between 2008 and 2018 [72], averaging 51 per year. Beverly and Bothwell point out that there are fundamental differences between Canada and locations such as California, where the overlap between populated areas and fire occurrence is more widespread. Based on data from the California Department of Forestry and Fire Protection (CAL FIRE) compiled in Appendix A, an average of 34 fires per year led to reported structural losses in the six-year period 2017–2022 in California, which may conservatively serve as a proxy for the minimum number of evacuations in California. At least 11 large-scale fires in California between 2017 and 2019 required evacuation of more than 10 000 people [24].

The number of incidents that require evacuation for wildfires is thus greater than for hurricanes. Historically, the upper bound for the number of Atlantic hurricanes in a season is 30 named storms (2020), with a 30-year average of 15 [73]. Not all hurricanes will impact land and require evacuation.

## 3.2. WUI Fire Evacuations

Evacuations encounter inherent constraints in the time available to evacuate and in the potential for compromised evacuation infrastructure. Planning for a community-wide evacuation is fundamentally different than that required for an evacuation from an indoor fire in a commercial building, or for evacuation of a corporate or university campus in response to non-WUI fire events such as a chemical spill or active shooter incident. Primary differences include:

1. The authority for mandatory evacuation;
2. Standards for exits, evacuation pathways, and building capacity;

3. How far the building or campus occupants must travel and whether they need a vehicle to evacuate;
4. The impact of evacuation on the surrounding local area and community; and
5. The extent of coordination required with the community.

Table 3 summarizes the differences listed above. The lack of standardization for community-scale evacuations affects the design of plans for these events. This is further reinforced by the limited accreditation infrastructure for the technical skills and tools necessary for the design of such plans. An ongoing international effort, led by the Society of Fire Protection Engineers (SFPE) Foundation, is working to address this issue for the WUI [74].

**Table 3.** Comparison of evacuations for individual buildings vs. a campus vs. a larger community.

| Aspect | Commercial building [a] | Campus | Community or part of community |
|---|---|---|---|
| Codes used in design and construction addressing fire | Yes | Yes | No |
| Regional coordination needed | No | No | Yes |
| Safety zone location | Outside assembly area, typically in parking lot | Variable/undetermined | Can be miles away and will likely require travel in vehicle(s) |
| Evacuation impact on overall community | Low | Low to Moderate | High |
| Community road capacity impact on evacuation | Low | Variable | High |
| Potential impact of evacuees | Parcel only or Local | Local/Community | Community to regional |

[a] selected for comparison due to specific code requirements for evacuation and construction compared to single-family residential type buildings

Evacuations in response to wildland or WUI fires need to address the life safety needs of both civilians and first responders. This also applies to other disasters; however, the building hardening standards currently available are typically not sufficient for buildings to withstand potential WUI fire and ember exposures [40]. Therefore, buildings cannot be treated as de facto shelters. Consequently, evacuation of the affected population is typically the key life safety strategy and goal rather than sheltering in buildings.

**Camp Fire Example 3.** Inadequacy of existing infrastructure buildings as fire shelters.

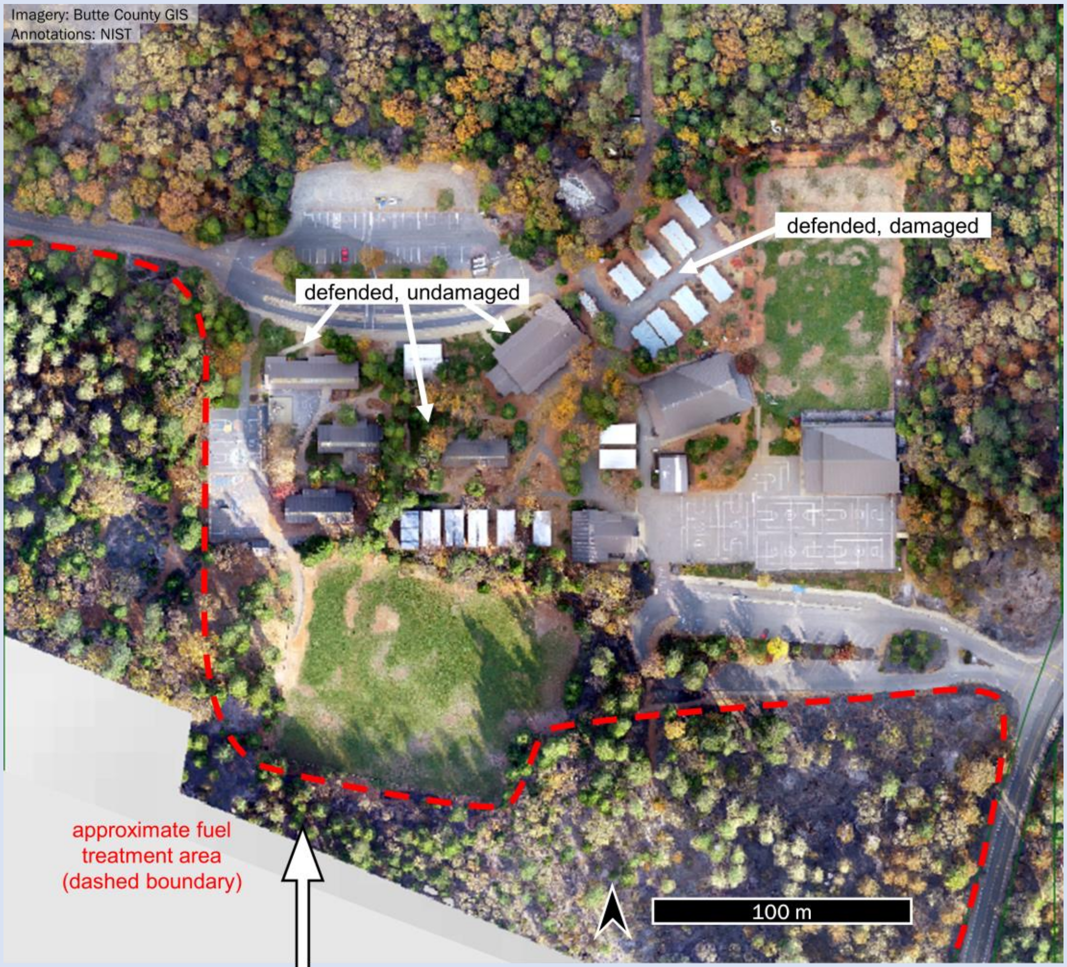

a) Ponderosa Elementary School


b) Feather River Hospital


c) Feather River Hospital

The damage to Ponderosa Elementary School (a) and Feather River Hospital (b and c) illustrate just two examples of existing infrastructure that were not adequate for use as WUI fire shelters during the Camp Fire. Despite having more robust construction than typical residential structures, they are not currently designed to withstand WUI fire exposures. Both the school and hospital buildings ignited and were actively defended by firefighters, largely saving the structures. The damage to the buildings was extensive, even with significant efforts by firefighters, and one defended hospital building was destroyed. School children, hospital patients, and other susceptible populations cannot shelter in place in existing infrastructure that is not designed specifically to withstand WUI fire and ember exposures.

**Camp Fire Example 4.** Fuel treatments alone are likely not sufficient to protect existing structures for use as shelters.





The parking area of the Pine Ridge School in Magalia was a pre-designated public assembly point (PAP) in the Paradise-Upper Ridge evacuation plan. The school campus, shown in the drone imagery above, experienced an intense period of fire spread on the morning of November 9, 2018. Before the fire, a fuel reduction and mastication program had recently been completed south of the school buildings, indicated by the red dashed border in the map above. The photograph shows the condition of the forest after the fire. The primary school buildings survived due to a combination of reduced fire exposures from the adjacent fuel treatment and defensive actions by firefighters who used the relative safety of the PAP to escape from a nearby burnover and were thus able to defend the structures. Auxiliary temporary classroom buildings were ignited but suffered limited damage owing to the actions of the firefighters.

A challenge arises from the combination of insufficiently hardened facilities and the potential for a no-notice event. Evacuations can occur during the day or at night, during business hours or on holidays. A key consideration is the ability of individuals to evacuate by their own means rather than shelter in place. The range of evacuation capabilities of civilians from different locations is presented in Table 4. Note that all types of locations might require specialized evacuation considerations; there are individuals who will potentially require assistance or not have the means to evacuate in all locations and population groups.

**Table 4.** Evacuation capabilities of civilians at different locations.

| Location | have means to evacuate | do not have means to evacuate | require assistance to evacuate |
|---|---|---|---|
| Residence | ✓ | ✓ | ✓ |
| Work | ✓ | ✓ | ✓ |
| Schools | variable | ✓ | ✓ |
| Care Facilities | employees | ✓ | ✓ |

WUI fire events can develop quickly. Where people will be and what the traffic conditions will be at the beginning of an evacuation is related to the time of day the incident occurs. As is the case with all disasters, Table 4 highlights that two key issues with evacuation of civilians are access to transportation and the ability to self-evacuate. The potential for rapidly developing events with short lead times presents several challenges for each of the civilian populations identified in Table 4:

- Residences pose a particular challenge for evacuation of civilians with mobility impairments because of the potential for many calls requesting evacuation assistance. This is especially the case in retirement communities or other areas where the demographics point to a less mobile population. The main evacuation challenge is that large numbers of first responders must be available to respond to all the homes where assistance is needed. Access to many residences may be compromised because some may not be readily reachable, or access may be prevented due to fire. Civilians with limited access to transportation but who are otherwise mobile also face challenges; however, in these cases their mobility can enable evacuation with neighbors or public transportation, or they could potentially walk to a safety zone or to a centralized evacuation location.
- Civilians at work can evacuate directly with their vehicles or with coworkers. However, a challenge arises from subsequent intermediate trips after leaving work; for example, when an individual decides to first return home to collect belongings or otherwise prepare their home, or must pick up dependents (e.g., mobility impaired relatives or children) from elsewhere. Traffic associated with these activities will impact road capacity and can slow down overall community evacuation. Social tools, such as remote work during high fire hazard weather events, may reduce road congestion and enhance evacuation.
- Evacuations of schools present several challenges, including that they can require parents or guardians to pick up the children, and they may require a staggered evacuation if the number of available buses is not enough to evacuate all students simultaneously. As

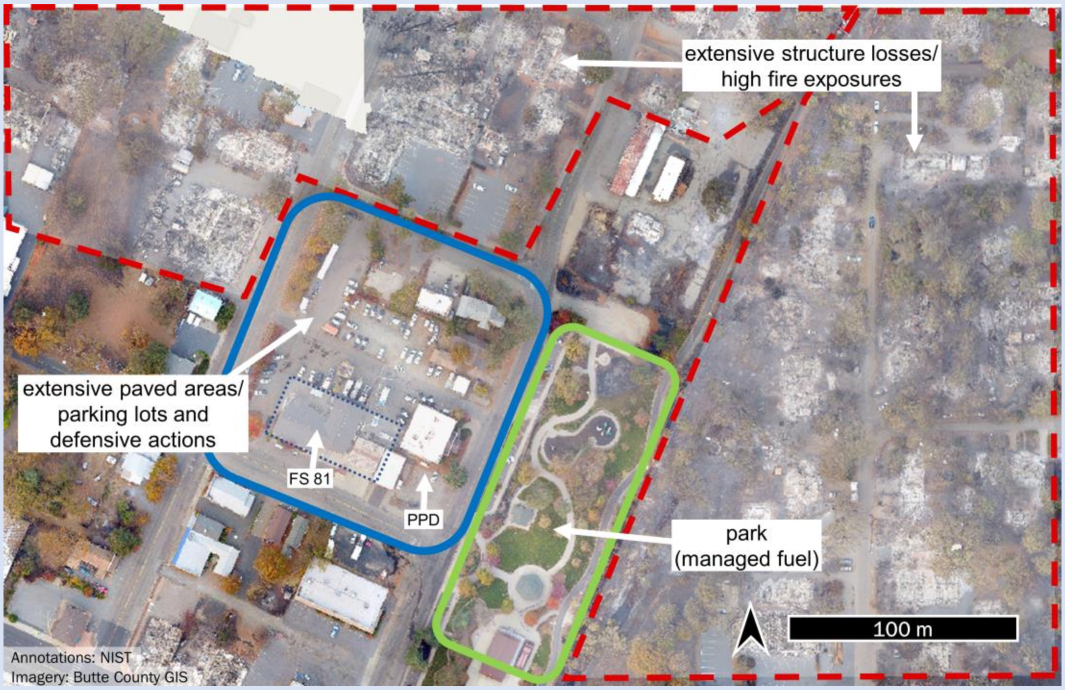
suggested above, social tools such as remote work (distance learning) during high fire hazard weather events may reduce road congestion and enhance evacuation.

- The evacuation of critical care facilities is a complex evacuation challenge for several reasons, including:
    - the need for specialized evacuation vehicles to transport patients with mobility impairments and medical conditions; the vehicles must have sufficient capacity to address all the facility residents.
    - the need for partner facilities to accommodate the evacuees; this can be particularly challenging when multiple facilities or an entire community is being evacuated.
    - the potential increase in time required for evacuation of these facilities owing to mobility impairments and medical conditions of the evacuees.

Special consideration must also be provided for the life safety and potential evacuation of emergency staff operating 911 dispatch and other communication and infrastructure facilities. The hardening of such facilities is beyond the scope of this report; however, the safety considerations for the life safety of evacuating civilians can also be used to address the evacuation of emergency officials. The evacuation of first responders can have a significant impact on response operations, for example, if 911 dispatch or the emergency operations center needs to be evacuated for the safety of the first responders. Continuity of operations may be impacted during evacuation, since these facilities have specialized equipment and infrastructure that cannot be readily transported or replicated.

Potential solutions to some of these challenges are discussed in the evacuation planning section of this report (Sec. 6.2). The authority to issue mandatory evacuations, enforcement of evacuation orders, and the rights of civilians to not evacuate [75] are beyond the scope of this report.

**Camp Fire Example 5.** Paradise Police Department 911 dispatch evacuated.




The Paradise Police Department (PPD) 911 operators/dispatchers started receiving calls related to the Camp Fire by 07:07. Dispatch operations from the PPD building were suspended at 10:30 due to the approaching fire, and the dispatch staff evacuated to Chico Police Department. It took them approximately two hours to travel the 27 km (17 mi) route (the shortest route of 20 km [13 mi] was blocked). Suspension of dispatch operations at PPD impacted response operations and public notification. Radio communications from Chico to Paradise were patchy, often requiring officers to relay messages between each other and with dispatch.

Fire reached the area surrounding the PPD building at 13:00. The parking lots around PPD, together with the park to the east, protected the building against direct fire exposures. To protect against firebrands, PPD was defended by several officers and firefighters. Defensive actions included removal of debris from the roof, active suppression with a garden hose, and patrol by a fire engine.

## 3.3. Compounded Uncertainties in Fire/Evacuation Predictions

To convey the complexities associated with predicting an evacuation event, this section is divided into two parts. The first part describes the general sequence of a WUI fire incident and gives an overview of variables and consequences. The second discusses the use of models as pre-event support tools and aids during WUI fire operations, in the context of the variables and consequences presented in the first section.

### 3.3.1. Progression of a WUI Fire Event

WUI or wildfire events that impact communities can occur in a variety of scenarios with different timelines and impacts to a community. A fire can start from a single point ignition and, under the right conditions, grow rapidly, breach initial containment attempts, and impact communities (recent example: Camp Fire [CA, 2018]). Alternatively, a fire may burn for several days with limited direct impacts to a community, before it quickly intensifies or shifts direction due to wind or weather changes and spreads into the community (Waldo Canyon Fire [CO, 2012]). Long-duration and large area fires may impact multiple communities in sequence as the fire continues to spread (Dixie Fire [CA, 2021]). Some fires may exhibit many of these timelines for surrounding communities (Caldor Fire [CA, 2021]).

Figure 2 illustrates the relationships among fire, evacuation orders, and fire effects on evacuation. The events are listed in a general chronological order from top to bottom, although event specifics may result in temporal overlaps or loops. The figure shows two key events/outcomes, one where fire affects evacuation the other where fire does not affect evacuation.

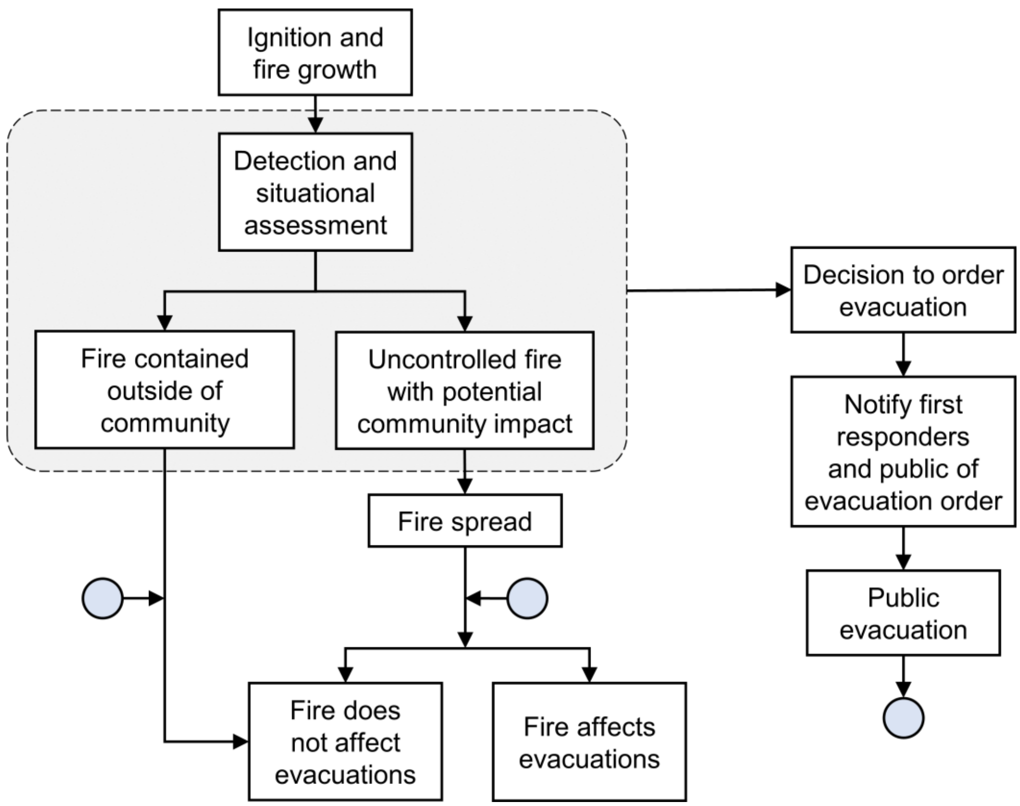



**Fig. 2.** Primary wildland/WUI fire event components leading to community evacuation.

Not captured in Fig. 2 are several challenges associated with the links connecting the different boxes, namely:

a) reliably determining which ignition scenarios will result in uncontrolled fires,

b) reliably determining whether a fire will pose a threat to one or more communities, and

c) reliably quantifying fire spread and its potential impacts on public evacuation.

Conditions that impact the capability to quickly contain a fire include the location of the ignition, the fuels present (type, quantity, moisture content), topography, weather conditions (wind and humidity), the accessibility and time needed to reach the area at or near the ignition location, and the extent of available suppression resources. The above list alludes to the number of possible scenarios that need to be considered.

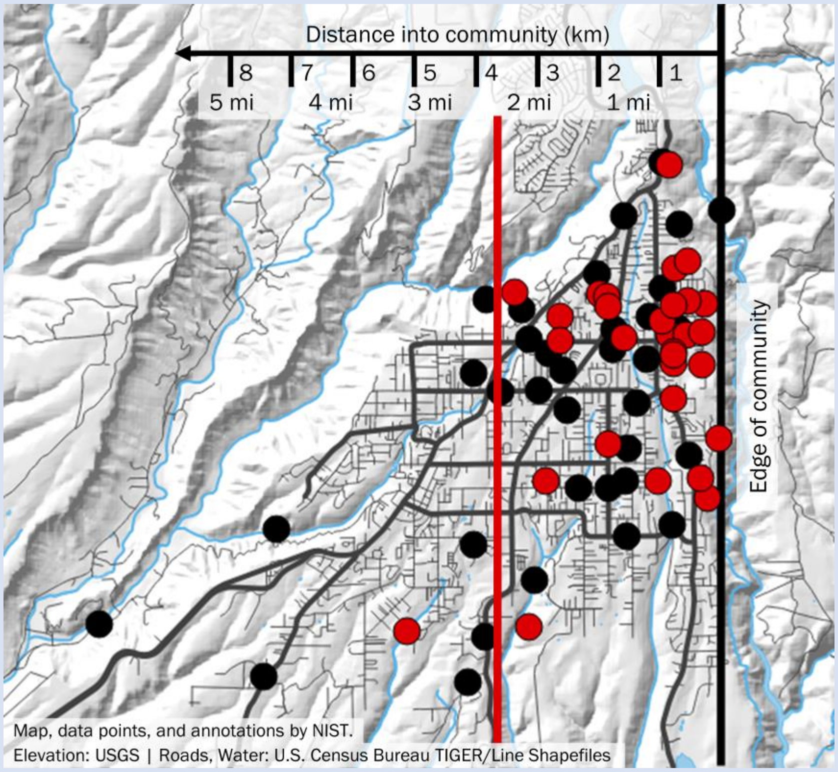
**Camp Fire Example 6.** Ignition location and rapid fire spread.


The ignition of the Camp Fire (at approximately 06:15) was located 1.6 km (1 mi) northeast of the community of Pulga in the Feather River Canyon. Visible from CA Highway 70 (photo above), the actual ignition location along the high voltage electrical transmission lines was only accessible via a narrow, winding, one-lane roadway difficult for emergency equipment to travel under the best conditions. Furthermore, while the nearest fire station was a 12 km (7.5 mi) drive away and the first engine arrived 13 minutes after being dispatched, additional resources had to travel more than 43 km (27 mi) to access the ignition location.

Despite the rapid detection (06:25) and dispatch response (06:31), the challenging access and location prevented the quick arrival of resources. Owing to the severe fire conditions at the time of ignition (drought and high winds), the initial fire spread rapidly. The fire spread rapidly to the west, cresting the ridge east of Concow, leaving little time to notify and evacuate the community. Attempts to contain the fire east of Concow were not achievable given the intensity and size of the main fire and long-distance spotting. Spot fires ignited within Concow by 07:20, 35 minutes after the first engine arrived near the origin 6 km (3.7 mi) away.

These three challenges can be viewed as the capability to predict detailed fire behavior, typically over a range of several kilometers. The smaller the community and the larger the distance from the fire origin, the harder the prediction. Overall fire spread direction can often be inferred by general wind and topography. The primary difficulty is the temporal component; quantifying the rate of spread is difficult since the main/original fire front may be augmented by far-field spotting on the order of kilometers ahead of the front, making the fire advance much faster. These spot fires can have significant impacts on community evacuation as discussed below related to challenge c). The spread rate will also impact the width of the fire front that may impact nearby communities.

**Camp Fire Example 7.** Spot fires in Paradise.




Thirty (30) confirmed spot fires ignited in Paradise between 07:49 and 08:30 (indicated by the red points in map above) from embers ahead of the fire front, which landed as far as 4 km (2.5 mi) into the community. Since the main fire front didn't arrive at the east side of Paradise until 08:30, these spot fires must have been ignited from fuels burning outside and upwind of the community. At least 35 additional spot fires ignited between 08:30 and 10:00 (black points), after the fire front arrival.

The spot fires were uncontained for four primary reasons:

1. high ignition potential of the fuels (drought),
2. amount of fuels present (intermix vegetation, limited/no fire history),
3. number and spatial distribution of spot fires compared to available firefighting resources, and
4. enhanced spread of spot fires due to weather conditions (low humidity and high wind).

Notably, only one of the four reasons, fuels management, is under the control of the community.

The widespread distribution of spot fires throughout the community forced the decision for the simultaneous evacuation of the entire community at 08:03, rather than the pre-planned phased evacuation of distinct zones. The widespread spot fires impacted the full-community evacuation and, in several cases, caused burnovers that entrapped first responders and evacuating civilians (see Camp Fire Example 9).

Challenges b) and c) differ in that a community may be impacted by fire after the community has been evacuated. If fire behavior and fire spread can be reliably quantified to determine whether one or more communities will be impacted by a fire, then the remaining task is to determine what the impacts of that fire will be on evacuation. Here, the challenges are threefold. First, from b), an estimate needs to be developed as to when the fire will reach the community. Then this information needs to be processed in the context of the evacuation status. Finally, an assessment needs to be made on the impact of that fire on an ongoing evacuation. How fire impacts a community is very specific to the local conditions. The ignition potential of fuels, type of exposure (fire vs. embers), locations of ignitions, availability of resources for defensive actions, and impact of all of the above on egress arteries is scenario specific. Fire can impact evacuation directly (smoke, flames [radiation, convection]) or indirectly (downed utility lines and poles, other burned or burning obstructions). These impacts can result in the restriction or closure of egress arteries, or worse, lead to civilian entrapments and burnovers. Evacuation flow restrictions can then propagate along roadways and create traffic problems that require active management during rapidly changing and deteriorating conditions.

**Camp Fire Example 8.** Escalation of traffic gridlock.

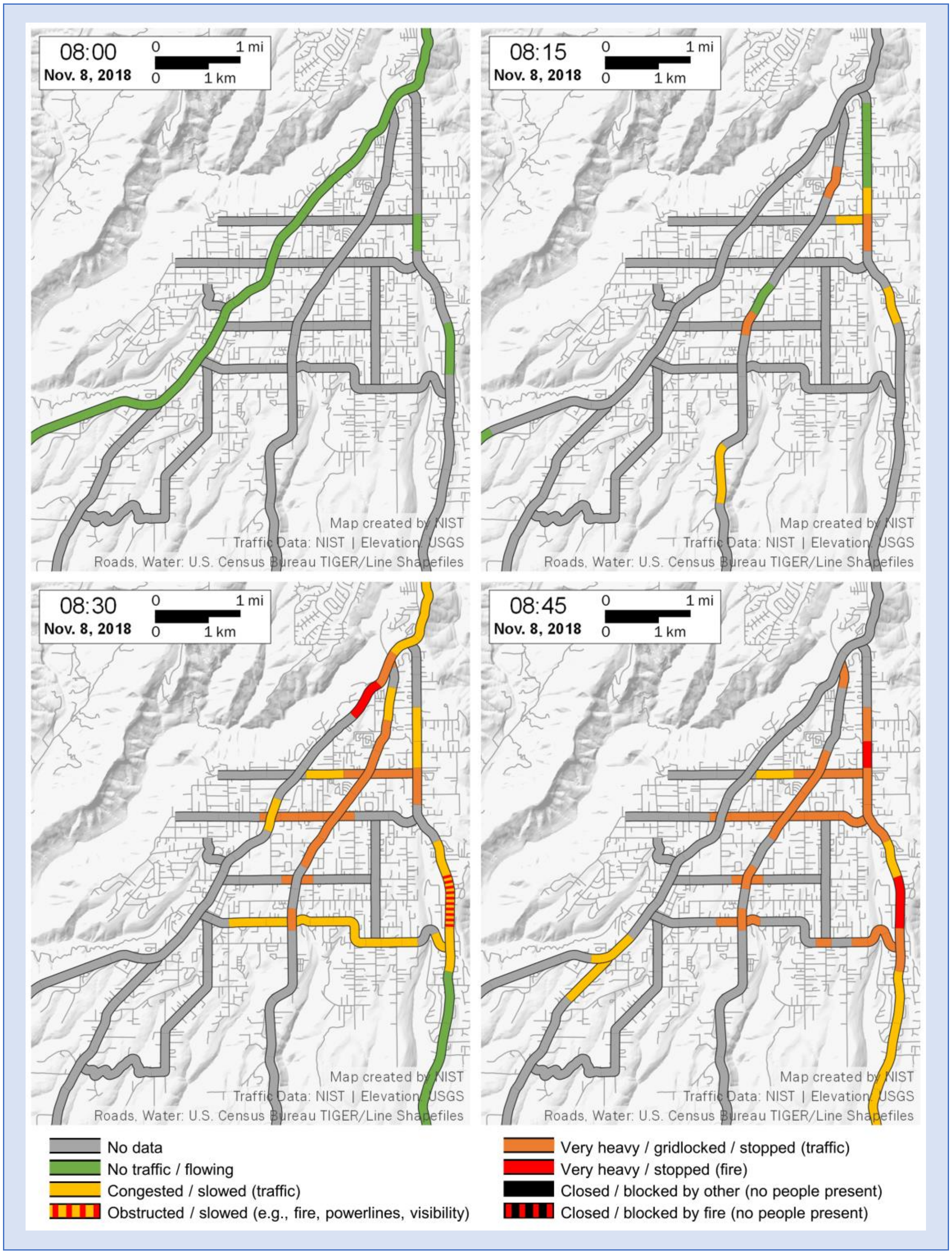
The Camp Fire impacted evacuation of Paradise, specifically the traffic, in two distinct ways. Firstly, the ember showers that resulted in 30 spot fires throughout Paradise before the arrival of the main fire front resulted in the need to evacuate the entire community simultaneously. Secondly, the fire front, which extended along almost the entire eastern edge of the community, resulted in rapidly deteriorating conditions in the eastern part of town, followed by the central and western parts.

The combination of traffic gridlock and fire impacts resulted in multiple burnovers that entrapped evacuees and restricted evacuation of civilians and ingress of first responders. The rapidly deteriorating egress conditions illustrate how difficult it is for civilians to travel though highly congested areas after a fire has impacted a community.

The map figures below illustrate how quickly the traffic conditions deteriorated in the hour after the first spot fire reached the community. At 08:00, traffic was flowing throughout Paradise (indicated by green segments) as the first spot fires ignited in eastern Paradise. By 08:30, traffic throughout Paradise had significantly deteriorated (indicated by yellow and orange segments), and fire overtook traffic both on Pentz Road and upper Skyway (indicated by the red segments). These two burnovers significantly affected traffic flow out of and through Paradise.

Each of the five egress arteries out of Paradise were closed due to fire at least once during the evacuations on November 8. At 09:00, the first evacuation route to close was Pentz Road (the easternmost artery). Conditions continued to deteriorate and between 11:30 and 13:00, three of the four southbound egress routes were closed simultaneously.

*(continues on next page)*


08:00
Nov. 8, 2018
0 1 mi
0 1 km
08:15
Nov. 8, 2018
08:30
Nov. 8, 2018
08:45
Nov. 8, 2018
Map created by NIST
Traffic Data: NIST | Elevation: USGS
Roads, Water: U.S. Census Bureau TIGER/Line Shapefiles
No data
No traffic / flowing
Congested / slowed (traffic)
Obstructed / slowed (e.g., fire, powerlines, visibility)
Very heavy / gridlocked / stopped (traffic)
Very heavy / stopped (fire)
Closed / blocked by other (no people present)
Closed / blocked by fire (no people present)

Considering the above three challenges, a) may be easiest to address. While there is significant uncertainty in reliably determining which ignitions will result in uncontrolled fires, data are available on both containment and non-containment events in many regions. Incorporation of local expert knowledge may be able to increase the reliability of anticipating either type of event; however, over-reliance on fire history may underpredict fire spread rates and intensity in future incidents.

### 3.3.2. Pre-fire vs. During Fire Modeling

The purpose of this section is to highlight high-level issues associated with fire modeling, both before and during the event, in the context of the challenges posed in the previous section. A variety of models are in development and use for fire spread prediction, evacuee behavior, and evacuation and traffic modeling. This section will not review all of the various types of models available for these tasks, neither will it review model output uncertainties. The main focus of this section is on the use of various models to address the challenges identified in Sec. 3.3.1, and how the use of these models may impact different aspects of evacuation. This highlights the challenges associated with linking multiple models (i.e., using the output from one as the input of the next).

Several global constraints apply to using models, with some variation in their importance among the different types of models. These constraints include:

1. The large number and broad range of scenarios to be considered
2. Trackable reliability (certification) of tools and accreditation of users
3. Individual component uncertainty and compounded total uncertainty
4. Interpretation and use of model outputs.

#### 3.3.2.1. The large number and broad range of scenarios to be considered

Regardless of any predictive model use, there are many potential fire event and evacuation scenarios. A very large number of possible scenarios may need to be considered as large geographic areas may be involved with many possible ignition locations, different fire spread directions, decisions on evacuation, and impacts of fire on evacuation. Planning decisions cannot hinge on individual scenarios and must be flexible to accommodate the broad range of outcomes.

While models present a path forward to facilitate advance planning, the large number of scenarios required may lead to exorbitant computational costs, especially for smaller communities. The other constraints discussed below also affect the benefits provided by fire/evacuation modeling.

#### 3.3.2.2. Certification of tools and accreditation of users

The issues of model performance, limitations, and validation apply independent of the model type or complexity. The same applies to the accreditation or training of the user. It should be noted that the availability of a model does not necessarily make it the appropriate choice for addressing a specific problem. This is particularly important to consider for models initially designed for one application that are later utilized for another. Examples include structural fire spread models expanded to the WUI as well as wildland fire models applied to the WUI. Models must be verified and validated for the new application before they can be trusted to provide correct and useful results.

#### 3.3.2.3. Individual component uncertainty and compounded total uncertainty

The effects of a wildland or WUI fire on the evacuation of a community are the outcome of a complex sequence of events. Small changes in one event or input may significantly affect the outcome. Quantifying the uncertainties of evacuation predictions requires an understanding of the uncertainties of all the key components that impact the evacuation. As fire spread impacts evacuation decisions and the evacuation impacts traffic, this entire system can be viewed as a linked system resulting in compounded uncertainties. Each step must account for the uncertainties associated with the input from the previous step.

Figure 3 illustrates the complex relationships among the various modules and how they ultimately affect community evacuations. The coupled weather and fire models impact AHJ notification and evacuation decisions, which impact civilian evacuation decisions. These individual decisions, together with the actualized impacts of fire on egress arteries, impact traffic management decisions and, finally, civilian evacuation.

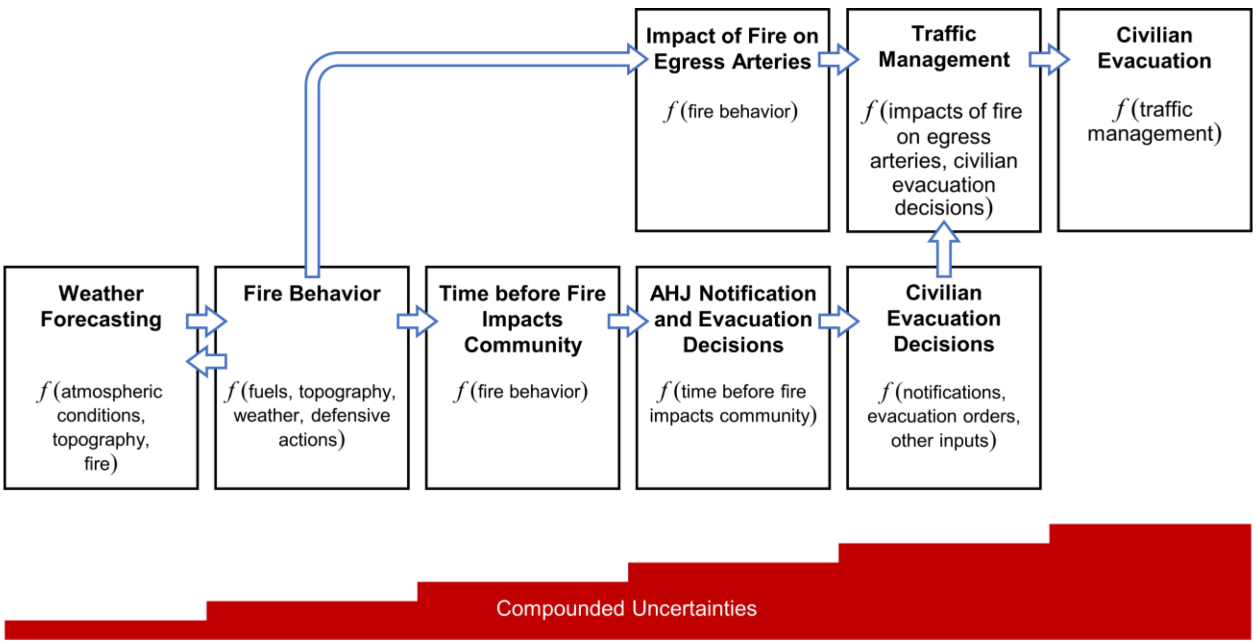



**Fig. 3.** Linked modules associated with evacuation predictions. Uncertainties are compounded and propagate from left to right and illustrated in red (not to scale).

Figure 3 illustrates the interconnectivity of the components that ultimately drive evacuation conditions. Note the two-way arrow between the weather module and the fire behavior module; large fires can affect local weather, and some models incorporate a feedback loop to address this coupling [76]. Each component listed in the figure (white boxes) represent complex systems. The polygon in red illustrates the ever-increasing prediction uncertainties (not drawn to scale in the figure). Note that there is an initial uncertainty associated with weather forecasting and the red polygon does not start at zero.

While wildfire modeling has been actively researched for close to 50 years, the number of variables, stochastic fire behavior, and ever-changing local fuel and weather conditions make it difficult to reliably predict landscape-scale fire spread at the resolution of interest to the evacuation problem. Furthermore, there is frequently a difference in the temporal scale of interest between wildland fires and WUI fires (days vs. hours or minutes, respectively), implying that the application of wildland fire models to specific WUI applications may not be as direct as it seems.

The limitations of spatially resolving wildland fire behavior can also have significant consequences on evacuations. In a large wildfire, far-field spotting ahead of the flaming front may ultimately have little impact on the overall wildfire; however, spot fires can have significant impact on a community. Spotting can result in multiple ignitions within the community that can directly or indirectly impact evacuations, challenge firefighting resources, and complicate evacuation decision-making and notifications.

### 3.3.2.4. Interpretation and use of model outputs

The interpretation and application of evacuation modeling results depends on the use of tools well-suited to address the specific module needs. It must account for the large number of scenarios and the compounded uncertainties as discussed above.

If a model is validated and tested for the conditions of interest and the uncertainties are known, modeling may provide insights for scoping different scenarios; however, the linking of multiple models may still result in large uncertainties, jeopardizing the utility of the results. The variability of fire behavior at the scale of interest to evacuation needs to be acknowledged, as small disturbances/changes can result in significant impacts on fire spread pathways. While past fires may provide validation opportunities if sufficient data is available, changing conditions (weather, drought, and fuels buildup) can result in unprecedented fire behavior, particularly for communities that have not experienced fire in a long time and have no directly applicable fire experience. Community evacuation drills may provide opportunities to collect non-emergency data to further support model development and validation, such as recent work by Gwynne et al. [54].

The inherent limitations of models with very large uncertainties may result in a more conservative evacuation approach as an understanding is gained of how variable WUI fire spread and evacuation events can be. The challenges and complexities associated with developing reliable evacuation predictions, which are highlighted in this section, point to a need for a simplified evacuation approach that leverages the known uncertainties to create an implementable evacuation system focused on life safety.

Interpretation of model outputs requires expert knowledge of the model inputs and architecture. For example, one desired output of a model may be an optimized evacuation time estimate. However, in cases where evacuation of the community is simultaneous with the fire, alternative traffic control strategies may need to be implemented to prioritize life safety and reduce the number of vehicles exposed to or stuck in hazardous conditions. This strategy was used by first responders during the Camp Fire when vehicles were ushered onto secondary roadways within the town of Paradise in order to move the end of the line of traffic away from the advancing fire front [6]. A recent study of evacuation traffic modeling found that evacuation strategies like phased (or zoned) evacuations and implementation of contraflow where feasible can effectively reduce the number of vehicles exposed, although they may not necessarily reduce overall evacuation times [77]. If the focus of the analysis is on reduced evacuation time, certain strategies or tangential goals may be overlooked.

## 3.4. List of WUI Community Evacuation Challenges

The following list summarizes the issues presented in this section that make planning for and executing WUI evacuations challenging. There is a need for a simplified adaptive approach to address the formulation of evacuation plans, particularly for small and medium-sized intermix communities. Additional components of a comprehensive evacuation plan include notification of civilians and first responders, and situational awareness of emergency officials and the public.

**Before the Fire**

1. Large number of possible fire scenarios (ignition location, fuel presence, fuel moisture content, weather).
2. Chaotic behavior, in which small perturbations of variables can result in large changes in predicted event outcomes.
3. Difficulty in characterizing, quantifying, and analyzing the large number of different fire scenarios.
4. Complexities of modeling and predicting human behavior in evacuations and response to emergency situations.
5. Difficulties in how to account for the uncertainties in the methods used to generate the different scenarios/predictions.
6. Difficulties in how to use/implement the findings from the above-mentioned scenarios/predictions.
7. Need to characterize and quantify the possibility of non-containment of the fire (to address the large number of ignitions that do not result in catastrophic events).
8. Need to develop contingencies for events like loss of communication and power.
9. Need to develop contingencies for potential closures or obstructions of egress arteries.
10. Need to evaluate evacuation through high-hazard wildland areas (which may result in burnovers), an issue that is particularly important for remote intermix communities.
11. Need to evaluate evacuation pathways that lead through urban areas for intermix communities adjacent to or near a large urban area.
12. Need to develop evacuation plans that address the above issues.
13. Need to disseminate the evacuation plans to first responders and the public.

**During the Fire**

1. Limits in situational awareness, including dynamic outages in data sources and communications.
2. Integration of rapidly changing conditions into ongoing evacuation activities.
3. Large uncertainty in fire spread during incidents.
4. Communication to first responders and civilians of any changes to the evacuation plan.

## 4. Fire-Evacuation Temporal Relationships and Evacuation Failures

Successful evacuation, meaning evacuees are not exposed to hazardous fire conditions during evacuation, is a function of the temporal relationship between fire spread and the evacuation process. To better understand the impact of this relationship, potential failure modes are presented, followed by sample timeline scenarios that may lead to these evacuation failures.

### 4.1. Primary Modes of Evacuation Failures

Recognizing different ways in which evacuations can fall short of their objectives can be useful in identifying potential contingencies to maintain life safety. The use of the term "evacuation failure" in this report is not intended to convey or assign blame but rather to highlight scenarios that result in undesirable outcomes. Such outcomes may be non-life threatening or can include injuries or fatalities.

#### 4.1.1. Defining Failure

Failures of evacuation events can be divided into two types based on whether the shortcomings impact life safety:

***Type 1: Undesirable Evacuation Consequences – No impacts to life safety***

This classification reflects situations where there were no direct threats to life safety of the general population[4] during the evacuation, but the evacuation was characterized by other undesirable results. Two examples of this include:

1. Prolonged evacuation, extending beyond the expected duration; this may highlight needs for adjustment to the existing evacuation plan.
2. Evacuation conducted when fire does not end up impacting the community, and the associated:
    a) economic cost of evacuation (personal and commercial), and
    b) evacuation fatigue, potentially resulting in resistance to evacuate in future events.

***Type 2: Evacuation Failures – Impacts to life safety***

This type of failure can be described when residents experience high fire exposures at their residences or during evacuation. Causes associated with these scenarios include:

1. Inability to effectively communicate evacuation orders to residents in a timely fashion, delaying the start of evacuation.
2. Fire ignition near the community resulting in only a short time to safely evacuate when the resulting fire behavior and rate of spread outpace the evacuation process.
3. Underestimation of the fire rate of spread, or changing conditions, resulting in fire arrival at the community sooner than anticipated.
4. Underestimation of the time required to evacuate the community or part of community.
5. Underestimation of the impact of fire on egress arteries.

[4] Note that evacuations may induce a larger health burden on susceptible subpopulations, such as hospital patients and individuals with disabilities, compared to the general population as a whole.

These types of failures will also impact first responder operations, primarily through prioritization of rescues ahead of fire suppression or control, including access for rescues that may be restricted by fire.

Residents can experience high fire exposure conditions in several situations. The three primary scenarios that can result in injuries or fatalities are:

1. An inability to evacuate owing to reduced mobility (e.g., physical or medical factors) or lack of access to a vehicle or other transportation.
2. High exposures at one's residence experienced after a decision to stay (whether to shelter in place or stay and defend).
3. High exposures experienced during egress (i.e., burnover)
    a. during a late or delayed evacuation after an initial decision to stay or after accomplishing specific tasks like getting kids from school.
    b. being overrun by fire due to rapid fire spread or due to traffic or other evacuation delay.

Injuries and fatalities of individuals can occur at or near residences or during evacuation. Exposure conditions can vary dramatically over short distances (on the order of 10 m [30 ft]) and within short time frames (on the order of a minute). Some fire exposures can be short in duration, such as from a burning bush, while others can last an hour or longer, such as from a burning structure. Smoke exposures can last for hours or days.

***High fire exposures at residences***

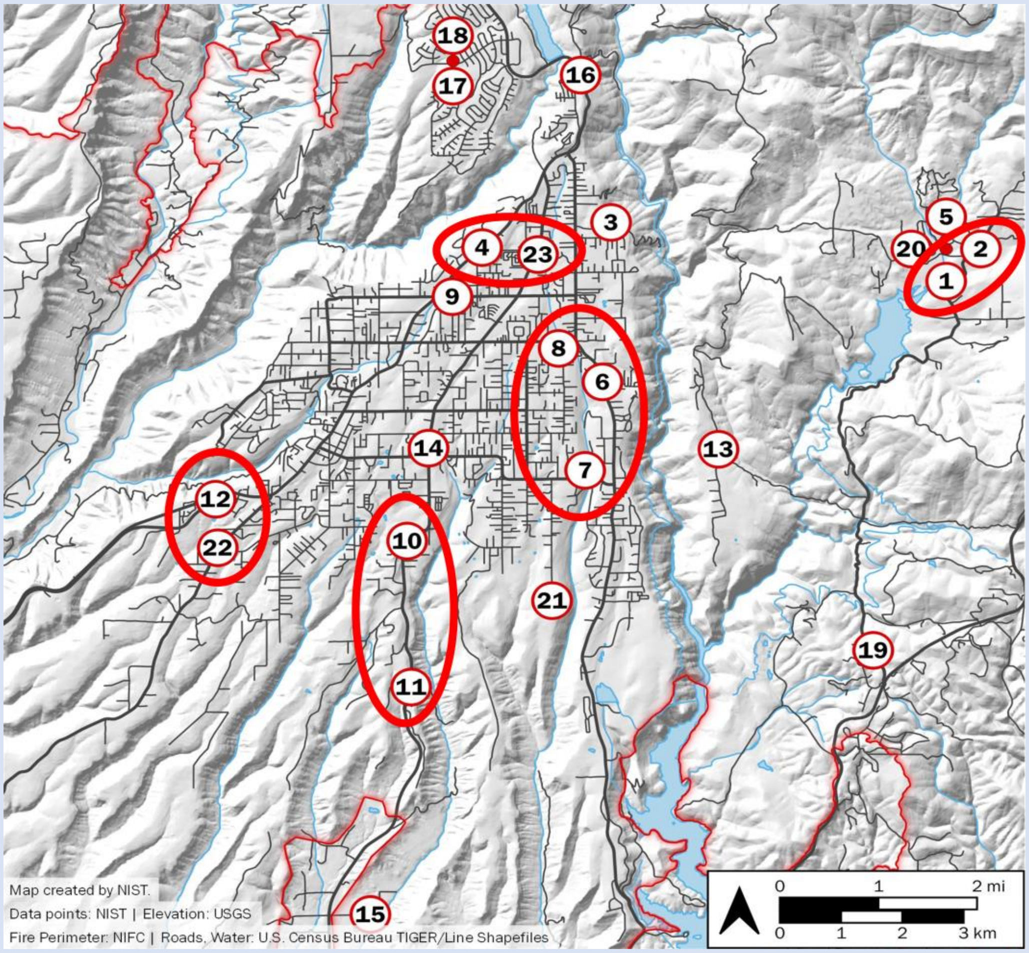
Injuries and fatalities at home can be associated with structure ignition or deteriorating local conditions. These high exposure conditions can occur when the structure cannot withstand the incoming exposures (fire and embers) or extensive burning occurs in the vicinity of the home (fire/smoke exposures). Affected residents may be inside or outside of the structure, whether taking shelter, conducting defensive actions, or attempting to evacuate.

***High fire exposures during egress***

Injuries and fatalities during travel can result from the burning of high fuel loads present along key egress roadways. Potential causes of high fire exposures for evacuees include:

- Traffic delays leading to extended time in high hazard areas.
- Road closures far ahead of the fire front (due to spot fires), causing delays and burnovers when traffic extends back into the fire area.
- Burnover conditions can occur even without heavy traffic, resulting in civilians getting trapped.

**Camp Fire Example 9.** Burnover events that impacted evacuating civilians and responding emergency personnel.




Entrapment/burnover events are defined as life-threatening situations where planned escape routes or safety zones are inadequate or compromised and individuals are overtaken or trapped by fire, often resulting in equipment damage and personal injury or death. The post-fire case study identified 23 such events that occurred in the first 26 hours of the Camp Fire [6, 7, 78], 17 of which involved an estimated combined total of up to 500 civilians. A total of seven civilians were killed in three of the 23 events. The locations of the 23 burnover incidents are shown in the map above, occurring throughout the fire area.

Out of the 23 identified burnovers, 11 impacted primary egress arteries during the peak of the evacuation, roughly between 08:00 and 12:00. These events are indicated by the circled burnover ID points in the map above. Fire overtook evacuees who were stuck in gridlocked traffic in five instances, and intense fire impeded or trapped moving traffic in six instances. The closure of Concow Road, the sole egress route in Concow, significantly affected the evacuation of that community. In Paradise, some egress arteries were closed for several hours, impacting both civilian egress and first responder access and operations. At 09:45, two hours after the first spot fire ignited in Paradise and a little over three hours after the fire was reported, two of the four southbound egress arteries were closed due to fire. By 11:45, during the peak of the Paradise evacuation, three of the four were closed due to fire, significantly impacting evacuation.

The concurrence of evacuation and fire impact on the community significantly affected the life safety of evacuating civilians. The formation and use of TRAs significantly enhanced the life safety of entrapped individuals.

### 4.1.2. Addressing Type 1 Evacuation Events

Type 1 failure events when fire does not end up impacting the community would ideally be avoided but should not be viewed only as “unnecessary evacuations.” Instances like this can benefit community preparedness and experience and identify improvements to the evacuation plan and execution. Given uncertainties in fire spread predictions, a small change may have resulted in a direct hit to the community. Improved fire spread predictions, coupled with improved evacuation modeling, may help to reduce the uncertainty of predictions in the overall evacuation system. However, this is difficult to achieve because of the chaotic nature of WUI events, the stochastic ignition and nonlinear impacts of spot fires, and the complexities associated with traffic redirection of evacuees occurring in real time. While advancements will be achieved in each component, an overall reduction in uncertainties to reliably predict what will happen is a long-term goal.

The quantification of the economic impacts of an evacuation when the community does not experience a fire are beyond the scope of this report. There is a need for economic modeling to provide guidance for the benefit cost of repeated evacuations compared to the probability of a community getting impacted by the fire. This information would help inform the public and help AHJs further refine community evacuation thresholds and education campaigns.

### 4.1.3. Addressing Type 2 Evacuation Events

Type 2 scenarios, when fire directly affects evacuations, can result in injuries or fatalities. This section addresses the three scenarios identified in Sec. 4.1.1.

***Inability to evacuate and exposed to fire***

Scenarios in which civilians are unable to evacuate owing to mobility impairments or a lack of access to transportation can be further divided into two separate categories:

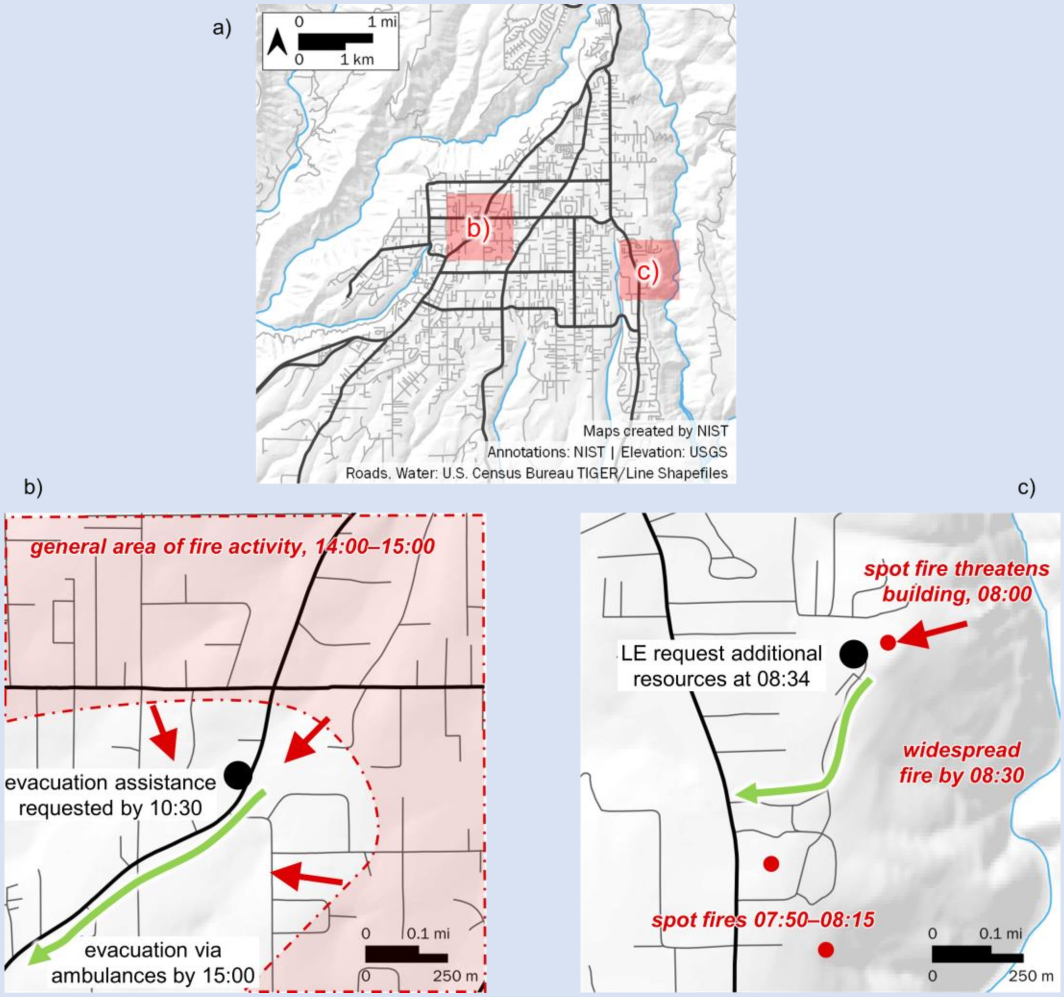
a) Events that occur when there is sufficient time to safely evacuate the community before the fire affects evacuation.
b) Events that occur when there is little or no time between when an evacuation order is issued and when the fire impacts the community.

Events in category a) might be addressed by implementation of evacuation programs for people who need assistance. A primary issue to address in this case is the potential need for simultaneous evacuation of many civilians and multiple care facilities. The transportation/evacuation resources in the community should be assessed together with the time necessary to get mutual aid resources on location.

Events in category b) are difficult to manage for three distinct reasons:

- Fire may rapidly restrict access to the area for first responders
- Fire and smoke may slow down evacuations of local civilians
- Traffic may be directed out of the area using contraflow to increase egress capacity, making ingress of first responders difficult and dangerous.

**Camp Fire Example 10.** Evacuation of assisted living facilities.




Two individual facilities illustrate a wide range of scenarios. One assisted living facility (c, above) on the eastern edge of Paradise was located in one of the first areas of town impacted by spot fires and the fire front (select nearby spot fires are indicated in the figure above). Urgent evacuation of 140 residents and staff was accomplished using various vehicles, including many first responder vehicles, concurrent with evacuation of the neighboring hospital and the community. Fire was observed spreading onto the property by 08:00. Law enforcement requested additional evacuation support by 08:34, and all residents were evacuated by 09:00. Firefighter actions at the main building extinguished several spot fires after the residents had been evacuated, and several detached residences were destroyed by the fire.

A second, smaller, skilled nursing facility located at the center of town (b, above) was not directly threatened by the initial fire impacts to Paradise. Evacuation assistance was first requested at 10:30. After several hours, presumably related to first responder prioritization, threat levels, and availability of transportation (vehicles and access), the facility was evacuated between 14:00 and 15:00 as fire was approaching. A mutual aid task force of a dozen ambulances arrived from two hours away and evacuated the patients. The building was reported to have ignited as the evacuation was being completed. The facility was destroyed by the fire.

An approach to address the Category b) events where evacuation is difficult is to harden the structure or facility. This is not to create a fire shelter, but rather to briefly extend the time available for evacuation by reducing the ignition potential as much as possible. The WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology (HMM) [40] is an example of a comprehensive approach to address structure and parcel hardening for both fire and ember exposures. While HMM was not developed explicitly for commercial facilities, the approach can be applied and adapted to assess the exposures and address the vulnerabilities. Hardening the facility against fire does not imply that the facility will necessarily be suitable as a fire shelter. Ventilation, power, and other tenability and access issues necessary to create a fire shelter are beyond the scope of this report. Examples of items that would need to be addressed beyond what is explicitly listed in the HMM include hardening of ventilation systems, hardening of the roofing assembly, and instituting a requirement for the parking of commercial transport vehicles (e.g., minibuses, ambulances) at a safe distance from the structure.

Along with the development of evacuation plans for individuals with disabilities, the hardening of individual residences is also necessary. Individual households and multi-patient care facilities can challenge first responders in different ways. Evacuating multiple individual households is intensive in time and resources, requiring many distinct stops. In many cases, evacuations from these residences or facilities may be accomplished by vehicles or fire engines; however, responding to many individual calls around the community is problematic because of the number of vehicles needed, the challenges in traveling to the locations, and the potential difficulties of getting the civilians out of the fire. For multi-patient facilities, large capacity vehicles are typically necessary for transport. If such vehicles are not present at the facility, they need to be located and driven there. Medically vulnerable patients require specialized transport and staff to support them. Evacuation of patients during high exposure conditions, potentially resulting in burnovers, is hazardous for the patients and first responders.

***High fire exposures after decision to stay***

High exposures may be experienced at a residence after a decision to stay, whether to shelter in place or to actively defend against fire. Cases that result in injuries or fatality can hopefully be avoided by appropriate education and individual planning. Education and information campaigns highlighting the dangers of wildfires, together with the limitations and priorities of first responders during these events, can be used to inform the public. It is likely that some people will chose not to evacuate; however, those people should be aware that these alternative approaches can be extremely dangerous even for well-prepared individuals, as discussed in Sec. 2.2.

***High fire exposures during egress***

Avoiding situations where evacuees experience high exposures during egress, i.e., burnovers, that result in injuries or fatality is a primary goal of an evacuation plan. One approach to mitigate these events is to reduce the potential for high fire exposure along the key egress routes and arteries. This maintains tenability of the routes and allows evacuees to remain in their vehicles to reach safety. Making this an effective approach requires fuel thinning and vegetation removal along evacuation corridors and continued maintenance of these fuel treatments over time. Hardening or burying utility infrastructure along roadways will also reduce potential for obstructions. Two challenges associated with mitigating exposures to egress routes are the access/rights to conduct the fuel treatments (involving rights-of-way and private property) and the expense, both short-term to perform the initial clean-up and long-term to maintain the treatments. Access for fuel treatments is particularly important, since high radiative and flame exposures can occur tens of feet from burning fuels and therefore will necessitate access to properties well beyond the typical rights-of-way. Some fuels, such as structures close to the road that may impact egress arteries when they burn, can be very difficult or effectively impossible to remove for multiple reasons (e.g., critical infrastructure, historical status, or ownership). Hardening may improve the fire behavior of these structures.

A second approach to mitigating the risk of high exposures for evacuees is to assemble residents at a wildfire safety zone or other preplanned and identified safer place. A distributed network of wildfire safety zones can reduce travel time for residents seeking shelter when there is no safe route for full evacuation.

## 4.2. Temporal Relationships Among Fire Progression, Notification, Evacuation, and Sheltering

The relationship between the time fire arrives the completion of evacuation influences how the fire may affect evacuees. Ideally, evacuations occur before being affected by the fire, both in the community and along the egress routes. This section presents the baseline minimum time required for evacuation, beginning from detection and extending through decision-making by emergency officials, notification of the public, and transportation out of the hazard area.

Five fire/notification scenarios are presented with varying times of fire arrival during the evacuation. Scenarios range from very dire situations where fire ignites or arrives very near a community without any notification, causing immediate threat to life safety, to scenarios where fire spreads into the community after evacuation.

Then, five evacuation scenarios are described and related to the fire/notification timelines. The evacuation scenarios range from immediate shelter in place to a safe evacuation from the community without evacuees being exposed to fire.

### 4.2.1. Minimum Time for Community Evacuation

There is a minimum amount of time needed to execute an evacuation. In fire protection engineering this is often referred to as the required safe egress time (RSET). RSET includes time for detection, alarm, pre-movement, and evacuation. In the WUI, the WUI RSET (WRSET) [55, 58, 66] includes additional steps not typically encountered or that are typically much shorter in building evacuation timelines, including the time required to assess the ignition/fire situation, communicate this information to the incident commander and emergency operations center, decide on the required evacuations, begin the notification and evacuation processes, and conduct the evacuation. A minimum WRSET is defined here as the time needed to evacuate a community utilizing all available tools (like contraflow) in the absence of any direct or indirect fire impacts. This is the best-case evacuation and would occur only in conditions where the fire reached the community *after* the entire evacuation was completed.

Ronchi et al. [58] proposed a WRSET time as

$$\mathrm{WRSET} = t_d + t_{FDS} + t_{FDI} + t_N + t_{prep} + t_{foot} + t_{veh} + t_{ref} \quad (1)$$

where $t_d$ is the time elapsed from ignition to detection, $t_{FDS}$ and $t_{FDI}$ represent time for fire department situational assessment and intervention, and $t_N$ is the time required for notification. The remaining terms relate to the evacuee timeline, including preparation time $t_{prep}$, movement time on foot and in vehicles, $t_{foot}$ and $t_{veh}$, and the time to be on-boarded at a place of refuge $t_{ref}$.

To make the timeline more salient to the incident commander (IC), Eq. (1) can be reformulated to expand some terms and condense others in order highlight different components of the evacuation timeline as viewed from the IC perspective:

$$\mathrm{WRSET2} = t_{order} + t_{IT} + t_{diss} + t_{prep} + t_{trans} \quad (2)$$

The first term of WRSET2 in Eq. (2), $t_{order}$, is the time it takes the IC to request an evacuation order. This term includes the time from ignition to detection plus the time for situational assessment and decision making. In relation to Eq. (1), $t_{order} = t_d + t_{FDS} + t_{FDI}$.

The time for information transfer $t_{IT}$ and dissemination $t_{diss}$ are terms representing how long it takes for the evacuation request to get to the agency responsible for the evacuation and how long it takes for that agency to implement the orders and disseminate the information to the public. For this time estimation, the $t_{diss}$ term represents the time to the start of the dissemination (e.g., the first notification or reverse-911 call), not the complete notification. This is intentional to provide an absolute minimum total time for evacuation for planning purposes. This information by itself does not provide an estimate for the time needed to inform the majority of a certain population. These terms are an expansion of Eq. (1); $t_N = t_{IT} + t_{diss}$.

The last two terms $t_{prep}$ and $t_{trans}$ represent the minimum time for civilians to get out of the fire, including preparation and transport, respectively. The transport term incorporates both movement on foot and in vehicles from Eq. (1); $t_{trans} = t_{foot} + t_{veh}$. To first order, a minimum $t_{trans}$ can be estimated or modeled based on scenarios in which evacuation is not impacted by fire (i.e., no burnovers or other road closures due to fire or fire effects), or it can be established through evacuation drills. The no-fire scenarios should account for traffic and the utilizations of traffic management systems, such as contraflow, where applicable. A full community evacuation drill may provide valuable information and insight towards quantifying an evacuation time $t_{trans}$.

WRSET2 also differs from WRSET in that WRSET includes the time to be onboarded at the place of refuge. While part of the overall evacuation process, this time is not directly related to the IC decision to order evacuations and has been omitted from WRSET2.

While WRSET2 represents a minimum time required for evacuation, there is no minimum time between a fire ignition and fire reaching a community. The worst case conditions are scenarios where there is not sufficient time to safely evacuate communities, referred to as dire scenarios [36]. These scenarios need to be characterized, understood, and incorporated into community evacuation plans. This report will highlight these scenarios and outline implementable solutions to manage the risk to evacuating civilians.

An additional consideration is the time of day when the evacuation takes place, which influences where people will be and what they may be doing. Equation (3) calculates $T_{evac}$, the time of day at which the evacuation is completed. The clock time is set by defining $T_{ig}$ as the time of day of ignition (24-hour hh:mm).

$$T_{evac} = T_{ig} + WRSET2 \tag{3}$$

Considering the actual time of day as well as the elapsed time may highlight evacuation/traffic issues like rush hour or dropping off/picking up children from school.

### 4.2.2. Fire/Notification Timing Scenarios

As discussed in the previous sections, exposures (fire and smoke) can impact ongoing evacuations in certain fire ignition/spread and evacuation scenarios. In some cases, rescues may be necessary. The timing between ignition and community impact has a direct effect on the time available to evacuate and the time for emergency personnel to respond to requests for evacuation assistance. In this section, five scenarios are defined in space and time by the presence of fire, notification status, and ability to safely egress. Fire/notification scenarios FN1, FN2, and FN3 have the potential to expose evacuees to high hazard conditions. To protect civilian and first responder life safety, the goal is to operate within scenarios FN4 or FN5.

The schematic in Fig. 4 denotes the general timelines for each scenario.

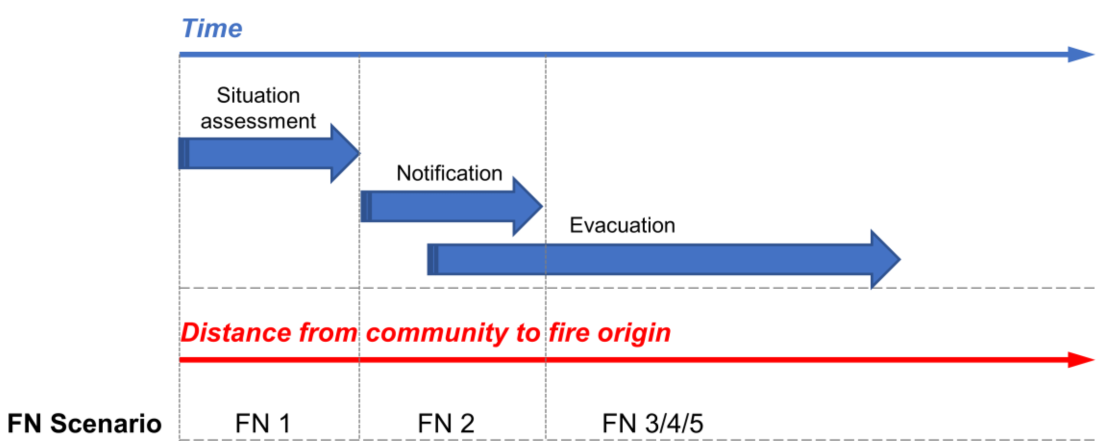
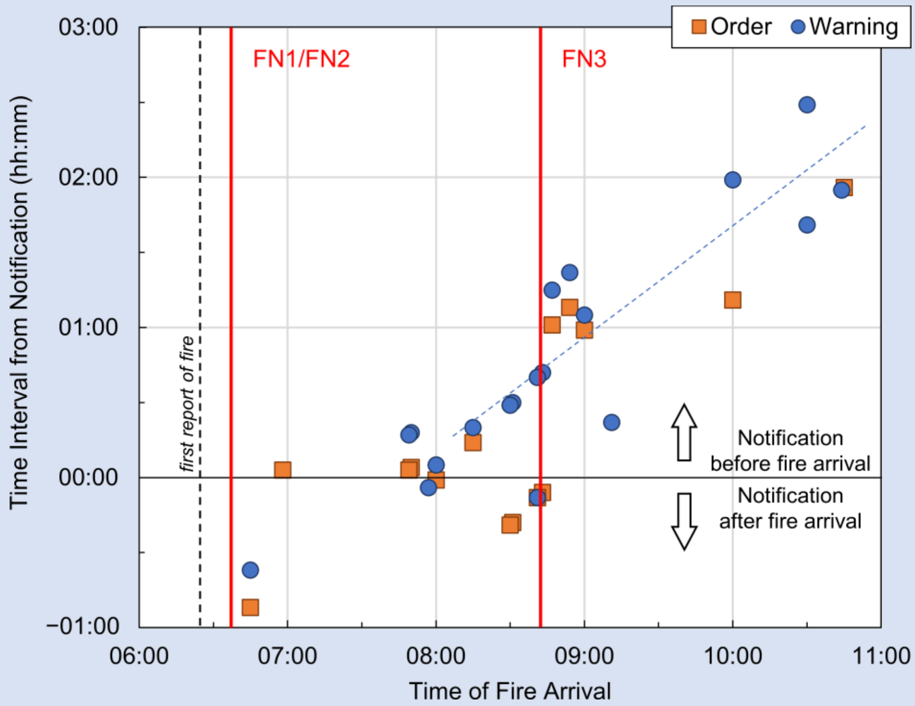



**Fig. 4.** Fire/notification/evacuation timeline scenarios as a function of evacuation status and distance between the community and fire origin.

The scenarios represent sequential temporal interactions among the fire environment, response/rescue attempts and community evacuation. After an ignition, time is always necessary to assess the fire spread and local conditions, make decisions on evacuation and response, inform the relevant agencies/AHJs and initiate the notification process. Even if all of these tasks are executed effectively and efficiently, there is still a non-zero minimum time between the fire ignition and the beginning of the public notification ($t_{order} + t_{IT} + t_{diss} > 0$). The area the fire covers in that period is represented by FN1. The number of residences, commercial properties, and civilians impacted will depend on what is in the area impacted by the fire during that initial time interval between ignition and the start of notification. While an ignition far away from a community may limit or eliminate the number of civilians involved in scenarios like FN1, the overall impact of the fire on the community may be larger as the fire spreads and grows.

**Camp Fire Example 11.** Time of fire arrival and first official evacuation notification, by evacuation zone.




The plot above, adapted from Ref. [6], illustrates the time gap between time of fire arrival and the time of official notification for each evacuation zone for the Camp Fire as it spread through Concow and Paradise. Early in the incident, before 08:45, evacuation notifications were sent after or concurrent with the arrival of the fire in each evacuation zone (FN1 and FN2). This is represented in the plot by data points below the *x*-axis. At 07:45, 80 minutes after the first report of the fire, evacuation notifications were being sent at the same time as fire arrived within the notified evacuation zones. The positive gap illustrated on the right side of the graph, after 08:45, shows how notifications were issued ahead of the fire as the incident continued to evolve, giving the civilians in these zones more time to evacuate before the arrival of fire (FN3).

#### 4.2.2.1. Fire/Notification Scenario FN1

*Fire near or at residence, no official notification → exposure/entrapment during egress*

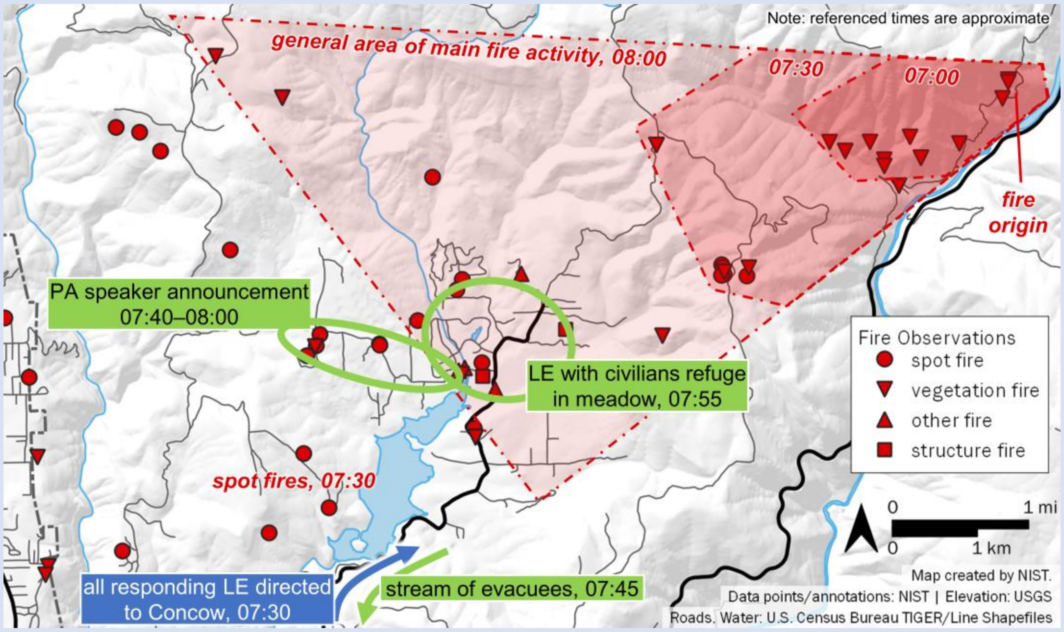
In FN1, the situational assessment of the fire by the IC and emergency officials is concurrent with fire impacts to a part of the community. In this scenario, civilians may see or be impacted by the fire before they receive an official notification or evacuation orders. These conditions can result in entrapments and burnovers during evacuation and limit the emergency response resources available to perform rescue assistance. Life-threatening fire conditions may require the formation of TRAs. If the fire origin is near the community, the area of community impacted can be small; however, the affected area can increase as the fire spreads and ignitions occur farther into the community (see Sec. 4.3).

#### 4.2.2.2. Fire/Notification Scenario FN2

*Simultaneous arrival of fire and official notification → exposure/entrapment during egress*

This is similar to FN1 with the addition of an official notification of the fire from emergency services who have been able to conduct at least a preliminary situational assessment and formulate an alert message. Notification can occur through various means and may include door-to-door messaging. The presence of first responders providing notifications can facilitate evacuation. However, the presence of first responders cannot be interpreted as an ability to reduce exposures through defensive actions. Again, high hazard conditions may require the formation of TRAs.

**Camp Fire Example 12.** Simultaneous arrival of fire and evacuation notification, leading to entrapment during evacuation in Concow.




The map above shows the area of Concow, a rural community located between the origin of the fire in Pulga and the town of Paradise. Red data points indicate individual fire observations before 08:00. The red shaded areas roughly indicate the area of main fire activity in 30-minute intervals after ignition. Note the significant number of spot fires ahead of the main fire activity.

The IC requested evacuation of Concow at 07:37, seven minutes after the first 911 calls were received reporting spot fires in the area. All responding law enforcement officers (LE) were directed to Concow to begin evacuations. Due to the location and the scattered spot fires ahead of the main fire front, the 911 calls were the first indication to the IC that the fire was within Concow. Firefighters on the ridge between Concow and Pulga observed the fire front spreading west at 07:30, indicated by the intermediate shaded polygon.

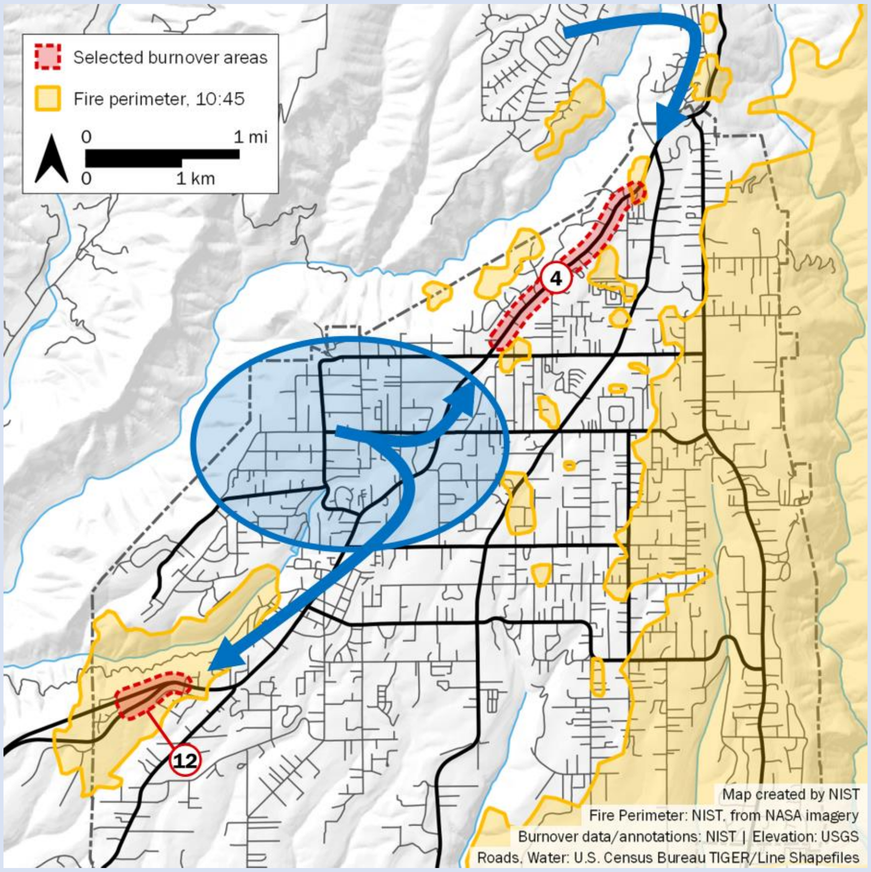
One of the first firefighters to access the Concow area conducted drive-by notifications of residents using the vehicle siren and public address speaker between 07:40 and 08:00. At the same time, law enforcement was directing civilians to seek shelter in the designated Wild Fire Safety Zone at the Camelot Meadow. Multiple spot fires grew rapidly and within minutes created impassable conditions, entrapping evacuating civilians and first responders at several locations and resulting in multiple burnover events and the formation of multiple TRAs (see Camp Fire Examples 15 and 19).

#### 4.2.2.3. Fire/Notification Scenario FN3

*No fire near/at residence, official notification, egress → exposed to fire on route to safety*

This scenario may occur when residents do not experience fire at their residence or other starting point of evacuation but get caught in one or more high fire exposure events (i.e., burnovers) during their evacuation to safety. As in FN1 and FN2, high hazard conditions may require the formation of TRAs.

**Camp Fire Example 13.** Evacuation impacted by fire along egress artery.




Civilians evacuating from western Paradise (area highlighted in blue) and from points north in Magalia who left before fire reached their part of the community were potentially caught in several burnovers that occurred on Skyway (*BO #4*, *BO #12*; indicated by the red shaded areas) [7]. The burnovers were a result of spot fires that ignited well ahead of the main fire. Heavy traffic from all areas of Paradise was utilizing Skyway as an evacuation route because other egress arteries to the east were closed due to the advancing fire. Traffic delays in combination with the rapid expansion of spot fires led to multiple burnovers and use of TRAs during evacuations. The map above shows the two burnover areas that affected Skyway between 08:30 and 14:00, and the fire perimeter observed via satellite at 10:45 (yellow shaded area) [7, 79].

#### 4.2.2.4. Fire/Notification Scenario FN4

*No fire near residence, official notification → early egress, or shelter in community wildfire safety zones without experiencing high exposures*

This is the desired evacuation scenario, where evacuation orders are issued and received with enough time to safely evacuate the civilian population before fire impacts the community or egress routes.

#### 4.2.2.5. Fire/Notification Scenario FN5

*No fire near residence, no official notification → early evacuation*

This scenario also represents a safe evacuation. This occurs when civilians are aware of a fire event, elect to evacuate before official orders are issued, and are able to get to a safe location without fire impacting their evacuation. If possible, this may be the best approach for susceptible subpopulations who need more time to evacuate. In some scenarios, there is potential for congestion and delays due to increased evacuation traffic from shadow evacuees, who are individuals who evacuate from locations outside of those specified in evacuation orders [80, 81].

### 4.2.3. Evacuation Scenarios

In certain fire incidents there may be no solution that avoids fire exposures to evacuees because the time to exposure is shorter than the time required for the entire population to reach a safety zone or evacuate (fire/notification scenarios FN1, FN2, and FN3). Understanding these scenarios can support the development of evacuation plans designed specifically to reduce high fire exposures to as many residents and first responders as possible.

Once a civilian decides to evacuate, additional decisions will be needed to select an egress route and destination, whether the destination is a wildfire safety zone or some location outside of the fire area. Depending on local egress routes and the starting point, egress from the community may require a longer travel distance or time than reaching a safety zone. There are several evacuation scenarios that an individual may encounter as a fire event develops:

E1. Shelter in place.

E2. Become entrapped during evacuation to safety zone.

E3. Evacuate to safety zone.

E4. Become entrapped during evacuation from the fire area.

E5. Safe egress from the community or to a safety zone.

The flowchart in Fig. 5 illustrates these five simplified evacuation outcomes. These evacuation scenarios are related to the fire/notification scenarios described above and are expanded on in the following subsections to provide context for the relationships among egress options, TRAs, and safety zones. To first order, risk of exposure in scenarios E2 and E4 is proportional to travel distance in the presence of fire, assuming potential exposure hazards are equal. This drives the need for a distributed community wildfire safety zone system to reduce the travel distance to safe areas.

Table 5 summarizes evacuation and sheltering options. Early evacuation (shaded green) is the only low hazard option—one that avoids exposure to the fire. Two options are shown for sheltering in buildings: residences and shelters. Both options are shaded gray to indicate the large range of potential risk based on local conditions. The next two columns describe evacuations in hazardous conditions. Evacuations that result in entrapments and burnovers are shaded red as the highest risk outcome, while evacuations where TRAs are formed are shaded orange indicating there is some safety benefit of TRAs. The last column describes the shelter-in-community option. This scenario is also shaded gray, since there is a range of possible fire exposure scenarios depending on the placement and access of wildfire safety zones.

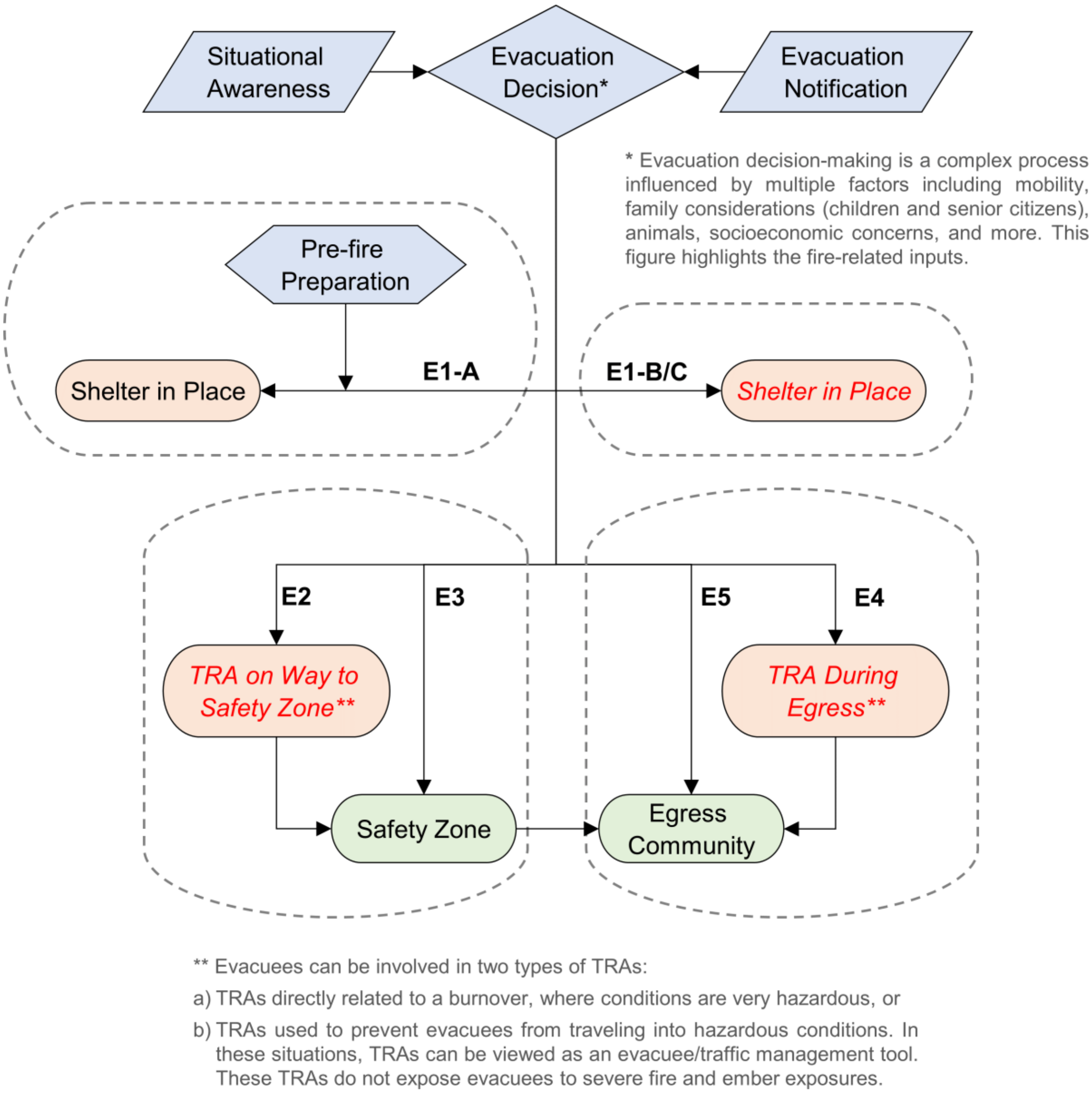



**Fig. 5.** Flow chart depicting generalized evacuation scenarios. Red text indicates hazard.

**Table 5.** Characteristics of evacuation and sheltering options.

| Evacuation/ sheltering option | Evacuate early | Shelter in place in residence | Shelter in community (SIC) | Evacuate in hazardous conditions/burnovers | Evacuate and shelter in TRA – not caught in burnover | Evacuate and shelter in designated safe building |
|---|---|---|---|---|---|---|
| **Descriptions** | Partial or full evacuation before fire reaches community | Residents shelter in their home | Residents shelter in a designated wildfire safety zone | Entrapped in a burnover during evacuation | Directed by first responders to take shelter in TRA | Residents shelter in designated wildfire shelter |
| **Life safety enhancements** | No exposure to fire | Limit travel in potentially hazardous conditions | Limited or no fire exposure in designated safety zone | A TRA may be formed *only* if local conditions permit | Reduced fire exposure | No fire or smoke exposure inside specially engineered building |
| **Life safety hazards** | Limited hazard associated with potential high-volume traffic; may experience smoke exposures | Can result in entrapment, injuries and/or death; may require rescue | Hazard with accessing local Safety Zone; hazard will increase with distance traveled, proximity of fire, and fuels and topography between residence and SIC location | Very hazardous; can result in injuries and/or fatalities | May experience fire and smoke exposures, although less severe than burnover conditions | Hazard while accessing local shelter; hazard will increase with distance away, proximity of fire, and fuels and topography between residence and shelter location |
| **Travel required** | By vehicle or mass transit | No travel required (if at home during incident) | By vehicle or on foot | By vehicle or mass transit | By vehicle or mass transit | By vehicle or mass transit |
| **Notes** | Road network must be able to accommodate the partial or full evacuation before hazardous conditions result in burnovers either in the community and/or in the egress corridors.<br><br>Early evacuation plans must be developed in parallel with trigger points for shelter in community.<br><br>This may be the desired option for mobility impaired residents and critical care and medical facilities unless a shelter in community option exists within reach and can be accessed with in-house mobility options. | Can evacuate after the fire intensity has subsided or not evacuate.<br><br>If property is prepared, resident is able and equipped, and exposure levels permit, defensive actions may save residence (although likely hazardous to residents). | | | First responders may relocate civilians between TRAs during the event to address safety and road capacity issues. | No standards or design guidance exist for the design, construction, and maintenance of such facilities specifically for WUI applications.<br><br>Such facilities will be expensive to design and maintain and may be beyond the reach of most small communities.<br><br>Retrofit of existing facilities will likely also be very costly. |

**Camp Fire Example 14.** Range of exposure levels experienced at TRAs.

a) Pearson Road TRA

b) Optimo TRA

The photographs above show images from two very different fire scenarios experienced in TRAs during the Camp Fire. On the left, the Pearson Road TRA was formed with high urgency in extreme fire exposure conditions burning over civilians evacuating in their vehicles. Exposures were so high that several vehicles ignited, and fire shelters were deployed inside a fire engine to block the radiation. Fortunately, an unbuilt, cleared residential lot was present to provide refuge for vehicles with support from a fire engine and dozer, which reduced the exposure levels enough to enable survival.

The Optimo TRA, pictured on the right, was formed with less urgency in response to traffic congestion and roadways blocked by fire. The location was at a paved parking area. With fuels set back at a greater distance, shelter inside commercial buildings, and support from fire engines, the exposure was less extreme than at the Pearson Road TRA.

#### 4.2.3.1. Scenario E1: Shelter in place

In this response scenario, the resident(s) seek shelter in their residence. Three distinct outcomes can result from this approach are discussed in this section. E1 scenarios can result in residents being exposed to very hazardous and life-threatening conditions. They should be carefully addressed during pre-fire evacuation planning.

*E1-A: Defend the structure/property*

The resident(s) made the decision to stay and defend their property well before the fire event and invested in extensive pre-fire planning. The structure has been hardened for fire and ember exposures and the parcel has defensible space that has been prepared and well-maintained. This approach requires a pre-fire assessment by a subject matter expert to determine whether the structure and parcel can be hardened to the necessary level so as to provide a safe environment for the resident. This may not be possible, depending on local conditions, and is the reason why a pre-fire assessment is necessary.[5] To enable their structure protection capabilities and enhance life safety, residents will likely need their own water supply, personal protective equipment (including firefighting garments and respiratory protection), and adequate physical and mental fitness for the task. Some of the hazards associated with the stay and defend approach are discussed in Section 2.2. This outcome assumes that the residents do not become entrapped. A scenario where a defended structure results in entrapment of residents is defined as scenario E1-C, described below.

*E1-B: Inadequate preparation*

A homeowner may elect to stay (FN5) or be forced to stay (FN1) in an unprepared property/structure for a number of reasons, including mobility impairment, lack of transportation, or concerns about property loss (including an uninsured property). A homeowner may also have a preconceived notion that their home will offer more protection than trying to evacuate during the fire. Staying in an unprepared residence can be very dangerous and may expose residents to life-threatening conditions when the property is exposed to fire and embers. Partial structure hardening may also provide a false sense of security. If fire reaches these types of properties, residents in these scenarios will likely require evacuation assistance. There may be a short time window for first responders to reach the residence before the fire arrives and limits access to the residence.

*E1-C: Entrapment*

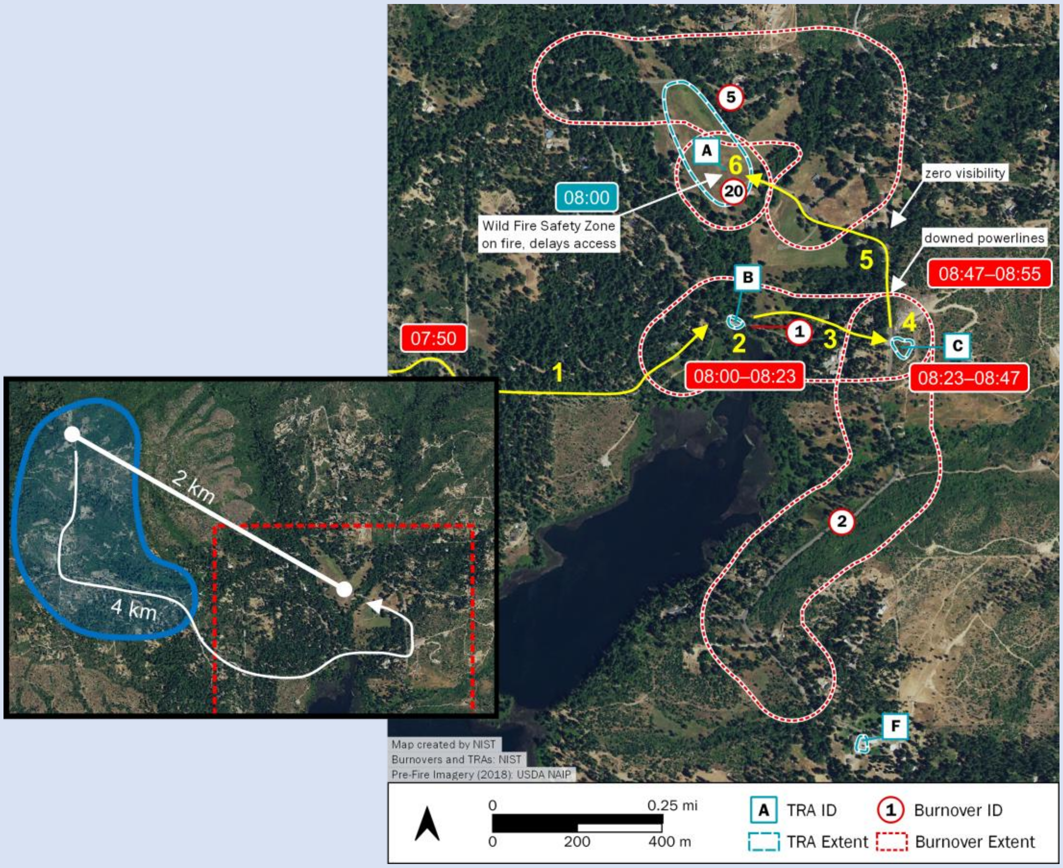
In this scenario, the resident(s) cannot evacuate because the structure, vehicle, parcel, or immediate surroundings are on fire. Residents will require rescues. High fire exposures may make timely access by law enforcement and firefighters difficult or impossible. Entrapment situations are not limited to the early stages of the event. While firefighting equipment is designed to tolerate higher exposures than unprotected vehicles, severe conditions will also restrict access by firefighters, limiting rapid response. Law enforcement equipment is not designed to tolerate the same thermal exposures as fire apparatus, and law enforcement personnel are typically not equipped with fire resistant clothing or PPE. Therefore, access into or through locations of high fire exposure may be more limited for other first responders than it is for firefighters.

#### 4.2.3.2. Scenario E2: Entrapped during evacuation to safety zone

In this scenario, the resident elected to seek shelter in a safety zone. However, local conditions deteriorated rapidly, and they became entrapped on the way. This scenario points to the need for multiple safety zones distributed throughout the community and the need to communicate the evacuation information to residents as quickly as possible so that they may complete evacuation before they are impacted by fire.

[5] Cases where residents should not stay include, but are not limited to, high density construction and residences near untreated wildland fuels. HMM can provide additional context for these scenarios; however, the assessment should still be performed by a subject matter expert.

**Camp Fire Example 15.** Entrapment en route to the safety zone at Camelot Meadow in Concow.




Civilians evacuating from the area circled in blue, west of the egress artery, were up to 2 km (1.2 mi) straight line distance and 4 km (2.5 mi) driving distance away from the pre-designated Wild Fire Safety Zone at Camelot Meadow (*TRA-A*, indicated with a blue square and outline). These civilians were caught in two burnovers (*BO #1* and *#2*, indicated with red circles and outlines) and took shelter in two TRAs (*B* and *C*) on their way to the meadow.

Two firefighters in a pickup truck were scouting out the fire and evacuating civilians in the west portion of Concow. Returning toward the exit **(1**, in yellow text**)**, they were blocked by fire and debris on Hoffman Road with 10 to 15 civilian vehicles following them (*BO #1*) **(2)**. The firefighters deployed fire shelters to shield civilians as they moved them to a TRA in the creek (*TRA-B*) while several vehicles were igniting. A dozer was able to access the TRA and clear the obstructed roadway **(3)**. However, the group was unable to reach the Camelot Meadow, and instead had to take refuge in a second TRA (*C*) at the intersection of Hoffman Road and Concow Road (*BO #2*) **(4)**. After 24 minutes, fire activity subsided enough that they could convoy **(5)** to the safety zone at the meadow to join the group already taking refuge there **(6)**.

The two burnovers that occurred before residents could reach the designated safety zone highlights the need for a distributed wildfire safety zone system that would reduce the travel distance between areas of relative safety.

### 4.2.3.3. Scenario E3: Safe evacuation to safety zone

In this scenario, the resident safely reaches a nearby safety zone. The safety zone may be close to their residence, but not necessarily in their direct evacuation path out of the community.

### 4.2.3.4. Scenario E4: Entrapment during evacuation from fire area

*E4-A: Evacuation from community*

This scenario can occur when a resident tries to egress directly from their home, workplace, or other location in the community, and is caught by fire during evacuation. Like the E2 scenario, the resident does not reach a safe area but instead gets caught in a burnover while in transit. The density and placement of safety zones, together with the accessibility of these zones from different parts of the surrounding community, will influence the prevalence of this scenario.

**Camp Fire Example 16.** Entrapment during evacuation from the fire area.


a) Bille Road


b) Pearson Road

The Camp Fire presents multiple examples of civilians becoming entrapped during their attempted evacuation from the fire. The two photos above show areas where vehicles were abandoned in the roadway when evacuees were overcome by fire during their escape from the initial fire impact in eastern Paradise. TRAs were formed to enhance life safety in both cases pictured, a) on Bille Road, and b) on Pearson Road.

*E4-B: Evacuation from safety zone*

This scenario differs from the previous situation in that the burnover exposures could readily be avoided by staying in the safety zone longer until conditions are safe for further evacuation.

### 4.2.3.5. Scenario E5: Safe evacuation from fire area

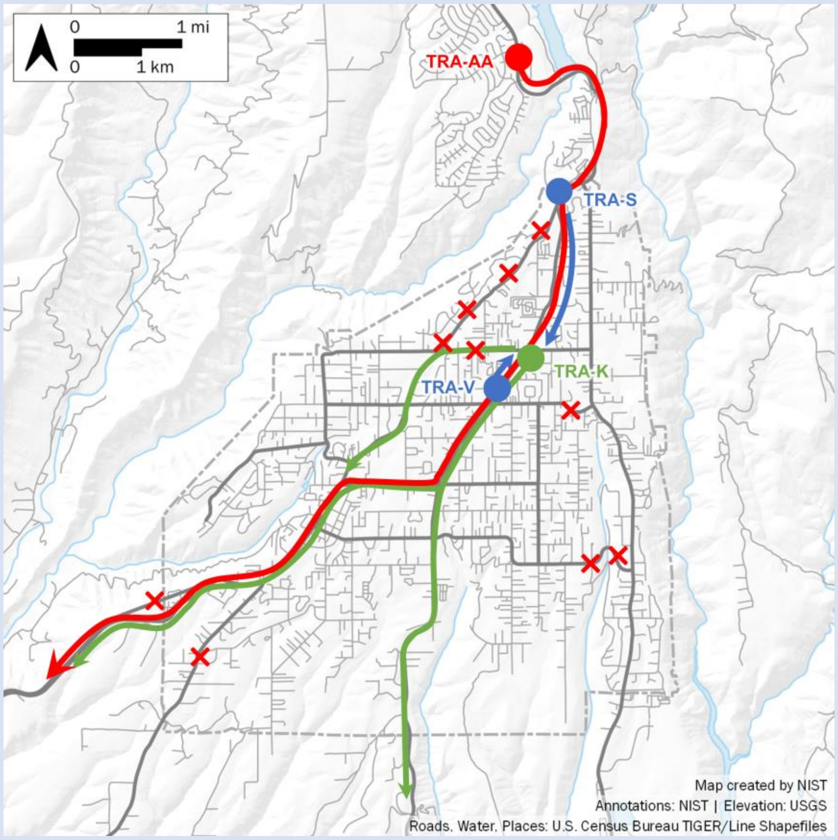
*E5-A: Evacuation from community*

This scenario is frequently associated with early warning and early evacuation, which can limit the exposure of residents to hazardous conditions. This preferred scenario is achievable in a number of fire ignition/fire spread and community evacuation scenarios.

*E5-B: Evacuation from safety zone*

This scenario is similar to the previous one. First responders at the safety zone may escort or direct residents out of the community when it is safe to do so. The enhanced situational awareness of first responders limits the potential of encountering dangerous conditions during further evacuation.

**Camp Fire Example 17.** Safe evacuation from Paradise after shelter in TRA.

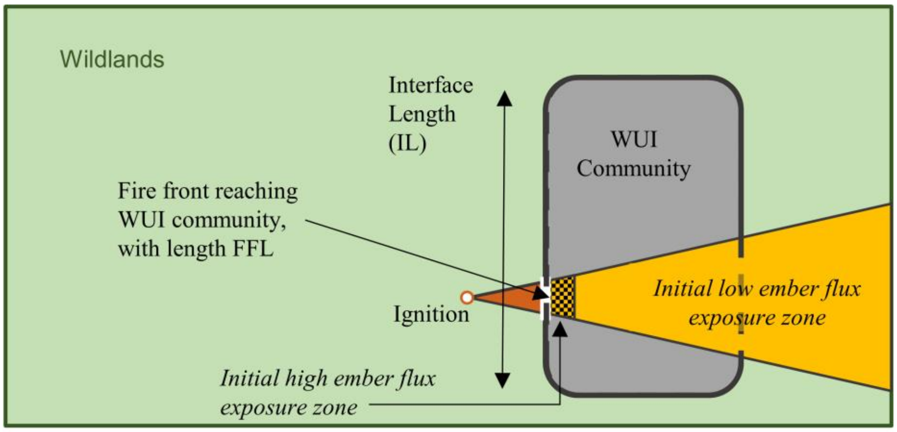



Several TRAs during the Camp Fire were maintained beyond the duration of the fire exposures in the immediate area. This was done so evacuees could wait safely until the egress routes were confirmed passable and additional transportation could be arranged for those without vehicles. The map above highlights two examples. Due to the numerous roadways blocked by fire, abandoned vehicles, or other obstructions (indicated by the red × marks), several hundred evacuees took refuge in the TRAs at the parking lots of the Paradise Plaza shopping center (*TRA-K*), CMA Church (*TRA-V*), and Optimo restaurant (*TRA-S*). After first responders were able to both coordinate a group of public transit buses to facilitate evacuation and identify a passable egress route, evacuees were escorted in convoys from the Optimo and CMA Church to consolidate at the Paradise Plaza. This occurred at about 16:30, indicated by the blue arrows on the map above. From there, a convoy was led out of the fire area to Chico. The first vehicles left at 17:00, seven hours after the TRA was first initiated. Several transit buses remained to collect later evacuees until 23:00. The evacuation routes taken from Paradise Plaza (*K*) are marked by the green pathways.

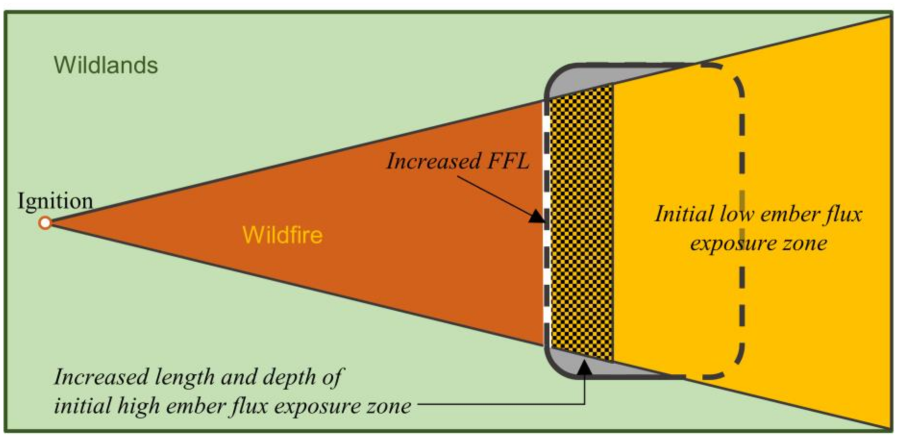
Later overnight, a similar convoy evacuation event occurred from the Rite Aid TRA (*AA*). Between 03:30 and 04:00 on November 9, after the fire front intensely burned through Magalia, dozens of people were escorted from Magalia to Chico on a route prescribed by first responders. This evacuation route is indicated by the red pathway in the map above.

### 4.3. Relationships Among Fire Ignition, Fire Growth, and Impact to Community

The extent of the fire front reaching a community will influence the initial area that needs to be evacuated. The conceptual diagrams in Fig. 6 illustrate idealized fire spread scenarios with ignition locations at two distances away from the edge of a WUI community. In both cases the fire is not contained before reaching the community. In the case where the ignition occurs near the community, Fig. 6a, the fire front length (FFL) represents only a small fraction of the community interface length (IL). The resulting initial impact on the community is relatively small, with FFL/IL<<1, and the extent of the high ember flux exposure zone downwind of the initial fire front also covers a small area of the WUI community.




a) Ignition near WUI community – shorter fire front impacting community




b) Ignition far from WUI community – longer fire front impacting community

**Fig. 6.** Idealized relationship between ignition location, a) near or b) far, from a WUI community. The fire front and ember exposures reaching the community are illustrated. The wind is directed from left to right. (Figure from Ref. [7]).

In the second case, illustrated in Fig. 6b, the wildland fire ignition occurs far from the community. The fire has enough fuel and distance to develop a fire front that represents a large fraction of the interface length of the community. In addition to the extended length of direct fire front assault, the high ember exposure zone represents a large fraction of the community and is illustrated as having a longer and deeper reach into the community. This deeper reach is related to the higher overall intensity of the fire front (assuming identical fuels, wind, and topography). The increased area of initial high ember flux exposure has the potential to overwhelm firefighting resources and enables the fire to rapidly establish itself throughout the community.

Looking at the relationship between the distance of the fire ignition from the community and community size, one can visualize that there is a "sweet spot" where the fire ignites far enough away to grow and impact the community with a full-length fire front (bottom scenario in Fig. 6), but close enough to reduce available evacuation time. This can be considered a worst-case evacuation scenario.

## 4.4. Temporal Illustration of Full Community Evacuation Scenarios

Figure 7 provides an illustration of the temporal relationship of fire and evacuation for five scenarios in which the entire community is evacuated. To illustrate the progression of time, columns indicate sequential, evenly spaced time intervals (a–i). Conceptually, this allows the comparison of relative evacuation times among scenarios.

In this illustrative set of community evacuation sequences, a baseline evacuation without any fire impacts is assumed to take four time intervals (see Scenario 4). This best-case scenario assumes that the community has an evacuation plan and that the plan has been rehearsed by first responders and communicated to residents. Although these assumptions are not critical to the scenarios illustrated in the figure, the baseline total evacuation time would likely be larger if these systems are not in place. Under each sequence, the four rows indicate:

1. the level of fire activity within the community, specified as low intensity (F-L) and high intensity (F-H). In this illustration, the period of low fire intensity is assigned one time interval (e), and high fire intensity is assigned two time intervals (f, g). These durations will differ in real WUI fire event, but are kept uniform in this example to enable comparisons between the five scenarios;
2. the status of evacuation warnings (W);
3. the status of evacuation orders (O);
4. whether evacuation is ongoing (E) or extended from the expected baseline evacuation duration (E-E) due to traffic and complications from the fire. Colors in the evacuation row indicate the potential fire hazard to evacuees: green is low, orange is moderate, and red is high.

Figure 7 illustrates the impact of fire on evacuation and the benefit of getting civilians out early. The first two scenarios, 1a and 1b, have similar outcomes and are the most hazardous for evacuees, since there is high potential to directly expose a significant fraction of the population to fire, smoke, and possible burnover conditions. The relevance of Scenarios 1a and 1b for communities in high WUI fire hazard areas is that there are fire spread/evacuation conditions under which there is insufficient time to fully evacuate the community without placing large fractions of civilians at risk. These dire scenarios highlight the need for a second tier of evacuation planning. Scenarios 2 and 3 expose progressively fewer civilians to hazardous conditions. The timeline represented in Scenario 4 enables all civilians to evacuate before the fire arrives and is the ideal evacuation outcome.

More information about each sequence is given in the sections below.

| Time interval | a | b | c | d | e* | f | g | h | i |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario 1a – ignition near community** | | | | | | | | | |
| Fire | | | | | F-L | F-H | F-H | F-L | F-L |
| Evacuation Warning | | | | | | | | | |
| Evacuation Order | | | | | O | O | O | O | O |
| Evacuation** | | | | | E | E | E | E-E | E-E |
| **Scenario 1b – fire approaching, evacuation orders only when fire reaches community** | | | | | | | | | |
| Fire | | | | | F-L | F-H | F-H | F-L | F-L |
| Evacuation Warning | | W | W | W | | | | | |
| Evacuation Order | | | | | O | O | O | O | O |
| Evacuation** | | | | | E | E | E | E-E | E-E |
| **Scenario 2 – fire approaching, earlier evacuation decisions** | | | | | | | | | |
| Fire | | | | | F-L | F-H | F-H | F-L | F-L |
| Evacuation Warning | | W | | | | | | | |
| Evacuation Order | | | O | O | O | O | O | O | O |
| Evacuation** | | | E | E | E | E | E-E | E-E | |
| **Scenario 3 – fire approaching, earliest evacuation decisions** | | | | | | | | | |
| Fire | | | | | F-L | F-H | F-H | F-L | F-L |
| Evacuation Warning | W | | | | | | | | |
| Evacuation Order | | O | O | O | O | O | O | O | O |
| Evacuation** | | E | E | E | E | E-E | | | |
| **Scenario 4 – fire approaching, early evacuation orders, time available for full community evacuation** | | | | | | | | | |
| Fire | | | | | F-L | F-H | F-H | F-L | F-L |
| Evacuation Warning | | | | | | | | | |
| Evacuation Order | O | O | O | O | O | O | O | O | O |
| Evacuation** | E | E | E | E | | | | | |

* Time interval of low fire intensity may be very short (approaching zero in many rapidly developing fire spread scenarios)
** Baseline evacuation without obstructions from fire, including planned contraflow and other traffic management

**Fig. 7.** Temporal representation of ignition, fire exposure, evacuation warning, evacuation order, and evacuation. The potential fire hazard to evacuees is indicated by color: green = low, orange = moderate, and red = high.

### 4.4.1. Scenarios 1a and 1b

Scenario 1 is characterized by dire situations with rapid impacts of fire on the community. In Scenario 1a, the fire starts very close to or within the community and rapidly grows to impact part of the community or the community as a whole. Community-wide evacuation orders are issued shortly after ignition. Once the fire arrives, there may be a period of low intensity (F-L) fire growth within the community that affect ongoing evacuation. Conditions deteriorate, and high-intensity fire conditions impact the evacuation (red E). Civilians can be trapped during evacuation if burnovers occur. Fire/smoke and possible burnovers during high fire exposure conditions (F-H) slow down evacuation, extending the duration of evacuations (E-E) past the peak fire activity. Evacuation after the fire peak is further slowed by fire-related obstructions such as downed utility lines and poles and abandoned and burned vehicles. There is significant potential for injuries and fatalities. This scenario can also occur when the fire reaches the community before evacuation orders have been issued, possibly because of spot fire ignitions far ahead of fire further away from the community resulting in new fires within the community.

Scenario 1b is similar to 1a, except that the fire starts at some distance from the community. The community is issued an evacuation warning (W) but is not ordered to evacuate until fire reaches the community. In this case, there may be time to adjust tactics, operations, or decision-making to take advantage of the warning time. If no adjustments are made, the net fire impact on evacuation is similar to Scenario 1a. Total evacuation time is longer than the baseline time requirements (i.e., Scenario 5) because civilians are impacted by fire, smoke, and potential road closures and burnovers.

### 4.4.2. Scenario 2

In Scenario 2, the fire starts far away from the community, as in Scenario 1b. In this case, however, the decision to evacuate the community is made earlier. Part of the evacuation occurs before impact from the fire. Contraflow and other traffic management tools can be used to expedite evacuation. A smaller percentage of the population may be impacted by smoke/fire if a significant fraction is able to evacuate before conditions deteriorate. However, civilians are still caught within the fire during evacuations. Total evacuation time is extended by the combination of fire and traffic, and evacuation continues during and after peak hazard conditions.

### 4.4.3. Scenario 3

In Scenario 3, the fire again starts far away from the community, but the evacuation orders are issued sooner than in Scenarios 1b and 2. In this case, an even larger fraction of the population is able to evacuate without being impacted by the fire. Only the last quarter of the normal evacuation window occurs within fire. The impacts of the fire extend the evacuation times of the final evacuees.

### 4.4.4. Scenario 4

As with Scenarios 1b, 2, and 3, the fire starts far from the community in Scenario 4. Early orders to evacuate provide time for the community to be fully evacuated before the fire arrives. It is likely that only a small fraction of all possible combinations of fire ignition location, fire spread rate, and community evacuation circumstances will result in this scenario.

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## 5. Proposed Approach

This section presents a framework methodology to assist communities and emergency officials in developing a comprehensive WUI fire response plan for evacuations that includes alternative life safety measures, such as shelter-in-community plans. The framework includes substantial pre-planning actions to mitigate the potential fire exposures civilians might encounter during evacuations. Mitigation includes fuel management along egress arteries and the designation and maintenance of wildfire safety zones throughout the community to be used in dire scenarios when there is insufficient time to fully evacuate. The approach presented in the following sections defines a set of fire–evacuation trigger zones based on WRSET and WASET, which are determined from anticipated fire spread rates and community evacuation times. Identifying these trigger zones or decision points before a fire incident can facilitate preparedness and training of the local community.

### 5.1. Mitigating Civilian Fire Exposures During Evacuation

Two strategies for mitigating fire exposure risk potential during evacuation are fuel management and a community system of wildfire safety zones. Their implementation supports evacuation planning by addressing scenarios where there is insufficient time to safely evacuate the entire community. In many cases, both strategies will likely be necessary, and they can work together to address specific community needs and leverage local community attributes (e.g., commercial parking lots, parks). Importantly, these two strategies are not substitutes for programs like "Ready, Set, Go!" and fire-evacuation scenarios (like Scenario E5) where there is sufficient time to safely evacuate.

One strategy for reducing the risk of fire exposures during evacuation is to mitigate the potential fire hazard presented to the evacuating public by managing fuels within the community and along egress arteries. A long-term commitment will be required to maintain the fuels within the community and to prevent buildup or accumulation of fuels along egress arteries. The goal is to prevent high fire exposure conditions that could potentially result in burnovers during evacuation. Collaboration with multiple landowners to carry out fuel treatments may be required. Treatments along egress arteries may need to reach well beyond the boundaries of the community to ensure a continuous corridor for evacuating civilians until they reach safe locations outside of the fire.

A second strategy is to create a distributed safety zone system within the community. The goal is to reduce risk by enabling civilians to get to lower-hazard locations with minimal/limited travel, thus reducing potential exposure opportunities. Travel time to these locations will be a function of road conditions, population density, and safety zone density. Note that this second approach calls for safety zones and not WUI fire shelters.[6] While the design and use of shelters that fully protect inhabitants from WUI fires may be a viable solution in the future, there are significant technical/science gaps to enable their design at this time. WUI fire shelters will also be significantly more expensive to construct and maintain and therefore may not be a readily implementable option for many existing WUI communities.

[6] A WUI fire shelter is not synonymous with an evacuation shelter.

## 5.2. Safety Areas – Wildfire Safety Zones and Community Sheltering Areas (Shelter in Community)

Community wildfire safety areas provide shelter from high fire exposures. These areas can be organized by the relative degree of protection they provide: TRAs, wildfire safety zones, and community fire shelters. Safety areas may be used for two reasons—to take immediate refuge from high exposure entrapments, and to manage traffic and prevent civilians from encountering high exposures. If a safety area is within reach, residents may divert there to take refuge until high exposure conditions along the evacuation route have improved sufficiently to continue toward a safe location.

The safety areas discussed in this section are intended to reduce thermal exposures (radiation and convection) to evacuees in order to prevent civilian injuries and the ignition of vehicles. Although a reduction of fire exposures is likely in these areas, evacuees can still expect to encounter significant smoke and ember exposures. Respiratory protection in the form of N95 or N99 masks can help by significantly reducing particulate exposures, but these devices will not remove the harmful gases in smoke. In addition to communication and preparedness, a comprehensive evacuation plan should also evaluate the smoke exposure that may be incurred in wildfire safety zones. Early community evacuation (when possible) is most likely a better option than the use of safety areas.

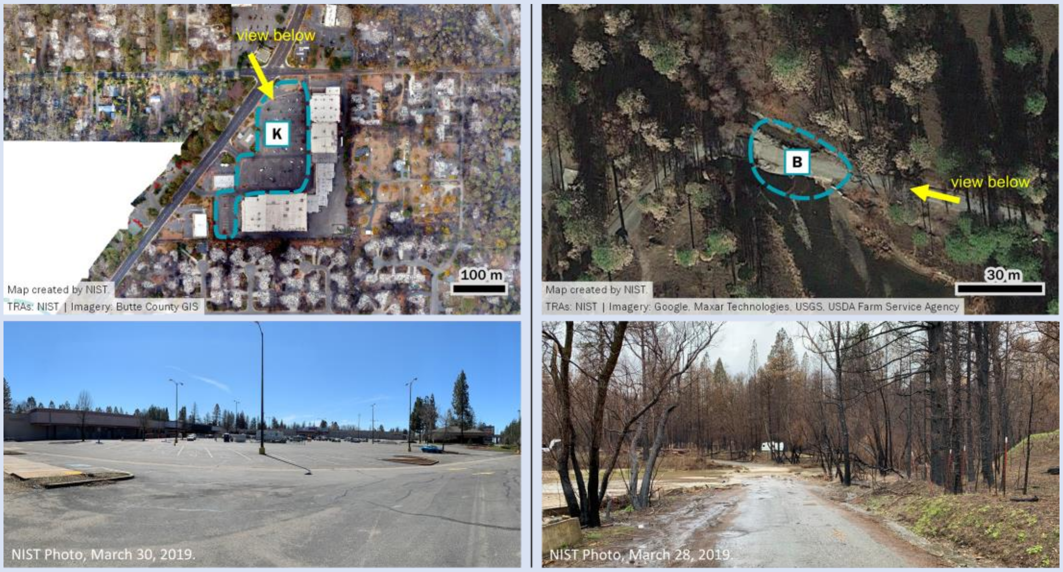
The development of community safety areas should be included in the overall evacuation plan. Their use will likely require first responder resources, which will remove firefighters from suppression tasks to focus on the shelter-in-community location(s). In the event of a fast-moving fire in which people are unable to evacuate in time, life safety is the priority.

### 5.2.1. Temporary Refuge Areas

There are fundamental differences among TRAs, wildfire safety zones, and community fire shelters. TRAs are locations that are used in crisis situations during the event as makeshift locations for emergency relief. They are not pre-designated areas and they may provide only limited protection.

TRAs can be divided into two subcategories based on their use in WUI fire events. First, a TRA may be established in response to a situation in which evacuating civilians are already trapped in a high exposure area and a readily accessible place with reduced fire exposures needs to be rapidly identified to shelter evacuees. Second, a TRA can be used to manage traffic and civilians in order to prevent civilians from encountering high exposures during evacuation. For example, a TRA can be implemented to keep evacuating civilians in a safe location (such as a large commercial parking lot) and block traffic from entering a hazardous road section. This is a critical traffic management tool that can be used by first responders during evacuation.

**Camp Fire Example 18.** TRA use during the Camp Fire.




a) b)

The NIST post-fire case study identified 31 separate TRAs that collectively provided refuge to more than 1200 civilians during the first 24 hours of the Camp Fire [6]. The TRA locations were binned into five categories: 14 parking lots (e.g., above right), 7 roadways, 6 structures, 3 natural areas (e.g., roadside creek, seen above left), and 1 maintained natural area (e.g., ballfield, maintained meadow).

The Paradise Plaza parking lot TRA in Paradise (a) and the Hoffman Road TRA at the creek crossing in Concow (b) are seen in the pre-fire aerial imagery and post-fire photos above.

TRAs were implemented by first responders for two reasons—to take immediate refuge from high exposure entrapments, and to manage traffic and prevent civilians from encountering high exposures. Within the first two hours of the fire's arrival in Paradise, multiple TRAs were formed in roadway intersections or similar areas of last resort. See Camp Fire Example 14.

After the initial fire front, hundreds of civilians were still evacuating when egress routes were blocked by fire and debris (abandoned and burned vehicles, downed trees and utility poles) and fire was still burning through the town. First responders established several large TRAs in parking lots of commercial shopping areas as places for people to wait until the roadways were safe to pass. See Camp Fire Example 17.

### 5.2.2. Wildfire Safety Zones

Wildfire safety zones are pre-designated locations characterized by open space with limited or no fuels present. They may provide additional protection relative to TRAs due to the reduced fuel and their pre-designated status. With pre-designated safety zones, residents can be aware of locations to seek reduced exposures within and around their community when hazardous fire and smoke conditions may impact their safe evacuation.

The presence of wildfire safety zones does not imply that their use will result in the lowest exposure hazards in all situations or that they should be treated as the default evacuation option. Safety zone definition has long been an important topic for wildland firefighters, although there are currently no U.S. standards for the design, sizing, density, or placement of community wildfire safety zones. Based on calculations of radiative exposures exclusively from vegetative fuels [82], a rule of thumb that can be implemented by firefighters in the field [83] is that a safe distance is four times the expected flame height. However, additional factors influence the exposure level, including convective heating, wind, slope, and protective clothing or shelters [84, 85]. Recent work by Campbell et al. [86] has incorporated adjustment factors for slope and wind conditions, implemented in a GIS tool for calculation and visualization of potential safety zones for wildland firefighters. More research is needed to further define adequate safety zones by incorporating fuels from the exposures from the built environment (e.g., residences, commercial buildings, and vehicles)

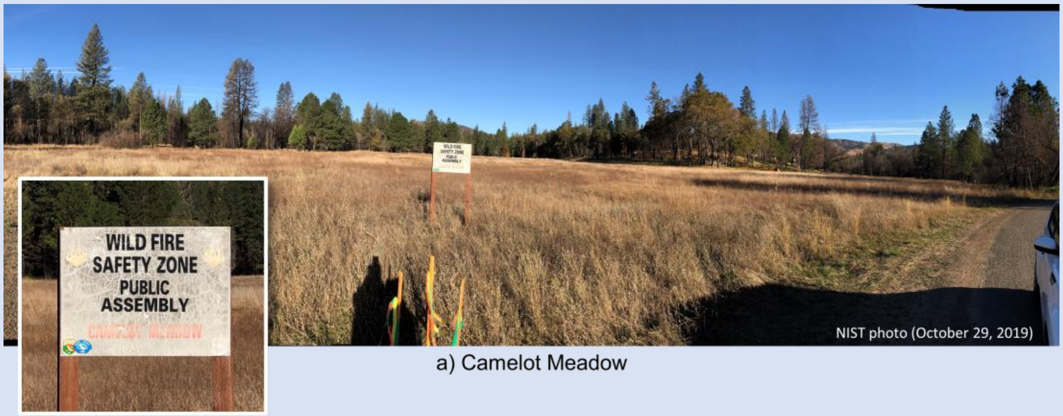
Wildfire safety zones might be reached by civilians on foot or in vehicles. Their design and sizing should reflect the needs of the local population and consider the specific characteristics of the community. The sizing of wildfire safety zones must consider the fraction of the community being served (the number of civilians and their vehicles) and potential fire exposures from surrounding fuels. Flashy vegetative fuels and thick forest can generate significant fire exposures. While relatively short in duration compared to a building fire, vegetative fire exposures must be factored into the creation of an exposure reduction buffer around the usable core of a wildfire safety zone.

There are significant benefits in establishing wildfire safety zones well before a fire as part of a comprehensive evacuation plan. Signage used to identify the wildfire safety zones and to direct civilians to them can help the community become more familiar with their locations and potential use. Civilians and mutual aid first responders will also benefit from reviewing the evacuation plans and maps with clearly demarcated wildfire safety zones.

Communities can use a variety of existing locations as potential wildfire safety zones. Wildfire safety zones should contain limited or no fuel and can be natural or manmade geographic features. Examples of areas that may be evaluated for potential use as wildfire safety zones include clearings, gravel areas and parking lots, bare earth lots, and well-maintained parks or other irrigated green areas. Areas to avoid using as wildfire safety zones include heavily wooded areas with understory fuels, areas near combustible structures (e.g., outdoor auxiliary features like gazebos), areas of flashy fuels (e.g., unburned tall dry grass), and high-density residential areas, which can ignite and result in structure-to-structure fire spread and very high exposures.

Commercial buildings can act as buffers for radiation, but ignition of the buildings and their contents is possible even if firefighters are present. The presence of firefighters to reduce or protect safety zones from surrounding exposures cannot be guaranteed in rapidly developing or large-scale incidents.

**Camp Fire Example 19.** Natural areas used as wildfire safety zones.




a) Camelot Meadow


b) Crain Memorial Park

The photos above show two examples of natural area safety zones on Concow; a) Camelot Meadow and b) Crain Memorial Park. Both locations were indicated in the existing pre-fire evacuation plans for the Concow area and had signage indicating their intended use as public assembly points during fire incidents.

The Camelot Meadow was minimally maintained as a 3.2 ha (8 ac) natural grass meadow; during the Camp Fire, the safety zone was temporarily unusable while the fire burned through it. Afterwards, an estimated 70 to 85 civilians took refuge in the burned meadow in addition to several first responders. The photo above shows the condition of the meadow one year after the fire.

Crain Memorial Park was another natural safety zone in Concow, characterized by a maintained field. It’s use during the Camp Fire was undetermined.

The placement of wildfire safety zones must be readily accessible to civilians in the area, and they must avoid high-hazard locations such as topographic features like chimneys and narrow canyons. If possible, high fuel load areas and dangerous topographic features should be avoided between the residences and the wildfire safety zone. This may be difficult to accomplish in intermix communities with high fuel loads and limited fire history. Special consideration should be given to the sheltering of civilians living in high fuel load areas in the perimeter of communities where limited time to egress may be available, and particularly when there is only a single egress route.

The proposed intent of wildfire safety zones is to reduce fire exposures to evacuating civilians in limited evacuation time scenarios and to get civilians to safety with the least amount of high fire exposures. This approach calls for a very distributed system of safety zones. In that context, having four safety zones of 2 ha (5 ac) each, distributed in high hazard intermix area, will likely provide greater accessibility than one single zone of 8 ha (20 ac). A distributed system provides more options and contingencies to both civilians and first responders and may reduce overall congestion by reducing travel distances and simplifying routes to the nearest safety zone.

While new communities will have options for the placement and sizing of wildfire safety zones, existing communities will need to leverage available opportunities that may allow rezoning or creation of suitable parks or other open spaces. Continued maintenance of wildfire safety zones, particularly those that utilize natural areas such as meadows, needs to be considered since fuel buildup can impact the usability of the zone.

### 5.2.3. Community Fire Shelters

There are no standards currently available for the construction and maintenance of commercial or residential buildings for use as fire shelters. Community fire shelters should be designed to withstand ember storms and direct fire impingement. Shelters will need to consider tenability, including conditioned and filtered ventilation, electricity, water, and meet accessibility requirements.

Commercial and residential buildings have both been used in past WUI events to shelter evacuating civilians. In one case, people were already located at the place of refuge (a casino) during the fire [12]. In two others, universities enacted their shelter-in-place response and students and faculty from across campus had to get to the designated building (gymnasium) to seek shelter [87, 88]. In these three cases, only people already on the general premises used these refuges, not the public at large. The Camp Fire provides a fourth example in which several buildings, including commercial and residential structures, were used as TRAs for the general public while being actively defended by firefighters [6]. Existing structures provide limited protection and should not be considered as standalone fire shelters. Depending on exposure levels, they may require active defensive measures to maintain their viability. Defensive actions can also be used to enhance the protection provided by TRAs and wildfire safety zones.

**Camp Fire Example 20.** Defensive actions at TRAs.


Just over half of the TRAs used during the Camp Fire (17/31) had the benefit of defensive actions to support the tenability of the location and the safety of the occupants and first responders. Defensive actions in four of the 17 cases were efforts directly related to life safety. One dramatic example is the use of a fire engine monitor nozzle to spray over an estimated 70 to 100 civilian vehicles assembled at the Bille Road TRA as fire burned around and over the evacuees.

In eight cases, the primary defensive actions were aimed at protecting infrastructure and commercial buildings that were used intermittently to shelter civilians. Five cases were characterized by exposure reduction in the area within or surrounding the TRA to reduce losses and enhance access to the TRA. In these situations, the civilians sheltering in the TRA were not in immediate danger. At the Optimo TRA, pictured above, there is record of at least three instances of firefighters suppressing the ignition of the commercial building adjacent to the TRA while the area was occupied by evacuees. The building was ultimately destroyed in the fire by another ignition after the TRA had been evacuated.

The remaining 14 TRAs without defensive actions highlight that, in many cases, there were not enough or the right type of resources to do so. This includes TRAs initiated by law enforcement or fire personnel without a fire engine, limited or unavailable water for suppression, and intensity of exposures that prevented safe action.

## 5.3. Developing a Coupled Fire-Evacuation System

To enable the development of a simplified and implementable evacuation plan for small and medium size intermix and isolated interface communities, an evacuation trigger zone concept defined by buffer zones around the community [61, 63, 64, 66, 68] is outlined in this section. These proposed zones can be used as a basis for notification and evacuation decision-making when coupled with fire spread information/estimates.

### 5.3.1. Trigger Zone Definitions

A three-zone system is presented here to support specific notification and evacuation thresholds. Zone widths are driven by the temporal relationships between evacuation requirements and anticipated/potential fire spread rates. Two minimum evacuation times, $t_{evac}$, are used to develop the zone widths:

- Minimum time needed for *Partial* Community Evacuation, $t_{evac,P}$
- Minimum time needed for *Complete* Community Evacuation, $t_{evac,C}$

Both $t_{evac,P}$ and $t_{evac,C}$ specifically assume no direct (e.g., flames, smoke) or indirect impacts (e.g., burned and downed trees or utility poles) of fire on evacuation but do include elapsed time from ignition to detection, detection to assessment, decision to evacuate and notification. The three proposed zones are named in a color-coded set—Purple, Red, and Green—arranged in expanding areas around the community as diagrammed in Fig. 8. Ignitions or fire spread into the different zones correspond to different courses of action and evacuation approaches.

While conceptually treated and shown as concentric areas in this discussion and figure, the true shape will depend on fire spread rates and are expected to have irregular shapes [63, 64, 66] influenced by wind, fuel types and loadings, and topography. Operational trigger buffers may differ from the calculated locations to facilitate identification using specific landmarks or geographic features [89].

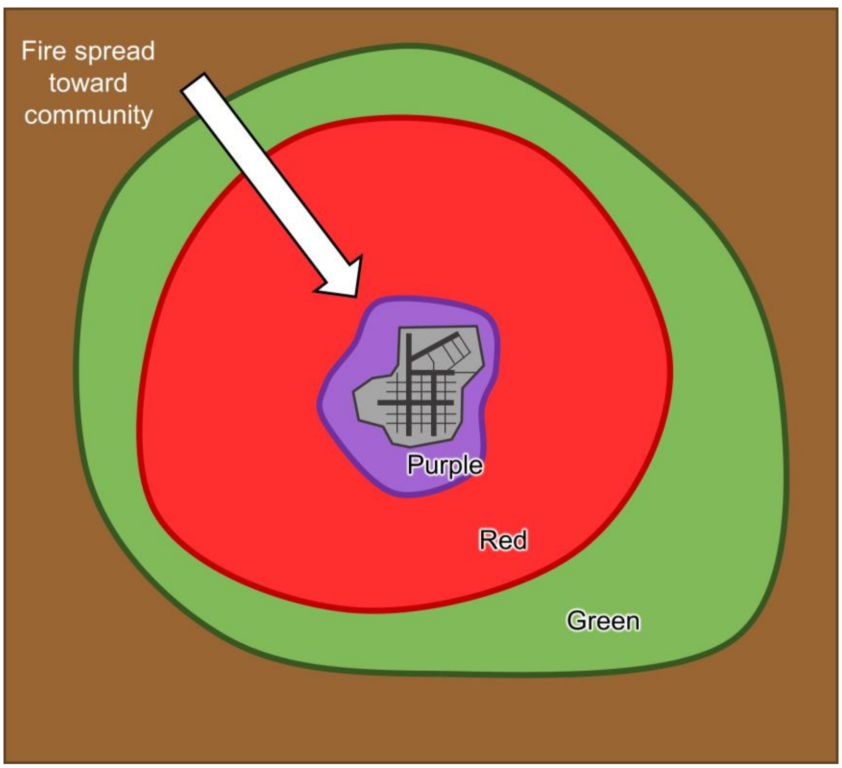



**Fig. 8.** Conceptual illustration of three ignition zones around a WUI intermix community. Zones may be asymmetrical because of fuels, fire history, topography, and prevailing winds. Fire spread directionality and intensity may not be uniform from all directions towards the community.

**Purple Ignition Zone:** The Purple Zone is the innermost zone. Ignitions within the Purple Zone are close to the community and can quickly generate hazardous conditions for localized portions of the community. Because of the proximity of the ignition to the community, there will be little time to safely evacuate before conditions in the impacted area become unsafe. Partial evacuation and/or shelter-in-community responses will likely be needed to reduce overall fire exposure hazards to the civilians immediately impacted. Based on community size, layout, fuels, fire history, topography, and prevailing winds, the Purple Zone may be small and localized or may even be non-existent.

**Red Ignition Zone:** The Red Zone represents the area in which a fire ignition spreading towards the community may not leave sufficient time to evacuate all parts of the community before the fire arrives. Shelter-in-community was discussed in Sec. 5.2 as an approach to address the life safety of civilians who cannot safely evacuate out of the community or the immediate hazard area. The Red Zone outer boundary, bordering the Green Zone, is defined by $t_{evac,C}$. The Red Zone is distinguished from the Purple Zone in that the ignitions occur farther from the community but still within the $t_{evac,C}$ temporal threshold. Ignitions in the Red Zone can generate a large fire front that exposes a large part of the community to significant fire effects.

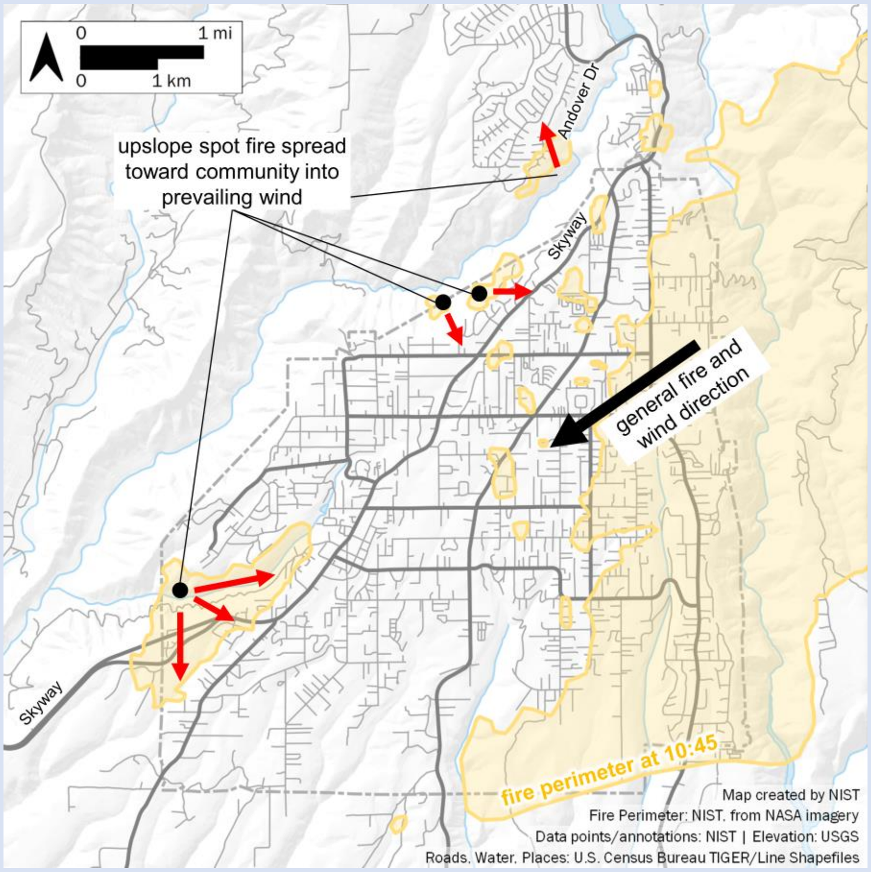
**Green Ignition Zone:** The Green Zone represents the region in which a fire is determined to pose a potential threat to the entire community and there is sufficient time to conduct a full community evacuation before the fire arrives. The inner border of the Green Zone, bordering the Red Zone, is defined by the minimum time required for a full community evacuation $t_{evac,C}$. An example corresponding to a similar scenario is shown in Fig. 6b. Topography, accessibility of ignition locations, and the anticipated chance of containment can also be used to establish the width of the zone to identify which fires should initiate an early evacuation. The outer edge to the Green Zone is based on fire behavior and fire spread rates. Local characteristics including fire history and the presence of watershed/fuel breaks and other topographic features could be used to establish the Green Zone outer boundary.

**Surrounding Region:** The surrounding region, illustrated by the brown area in Fig. 8, is defined as everything beyond the Green Zone. The area beyond the immediate community trigger zones can be viewed as monitoring of regional-scale fire activities. The proximity of a fire to the outer edge of the Green Zone, direction of fire spread, topography, and weather influences will be used to determine the issuance of evacuation warnings.

One approach to simplify the large number of possible ignition scenarios is to divide the zones into quadrants or sectors. Local knowledge, historical wind directions, topography, and fire history can be studied to understand expected directionality and create wind direction thresholds for the different quadrants. A review of all quadrants/sectors should be performed for three reasons:

1. Fire may occur during an unusual weather event,
2. Spot fire ignitions may result in fire “jumping over” the community and burning back from the other direction,
3. Locally unprecedented fire behavior exceeds historical fire spread and intensity.

**Camp Fire Example 21.** Spot fire ignitions on Skyway and Andover Drive in Magalia.




In the early stages of the Camp Fire, several spot fires ignited west of Paradise, several miles ahead and downwind of the main fire front. The ignition locations in canyons provided upslope fire spread pathways against the prevailing wind, directing fire back toward the community. Local winds may also have been affected by the canyon topography. These spot fires accelerated the timeline of fire impacts to the community, exposing evacuees on Skyway to fire in two places. The map above shows the fire perimeter as observed by satellite at 10:45 with the relevant spot fires and spread directions indicated.

Data of evacuation clearance times could be collected through evacuation exercises and supported by traffic modeling. While such data collection is non-trivial and may not represent a realistic worst-case scenario (such as evacuating at night in smoke without streetlights), or account for all human behavior, it may provide a realistic way to bound an absolute minimum evacuation time. With this evacuation time in hand, the remaining part of the ignition trigger zone development is determining the fire spread rate and direction coupled with the relationship between ignition location and size of the community. A fire resulting from an ignition far away may deviate slightly from its projected path and miss a small community several miles downwind. In contrast, a fire igniting closer to and spreading towards the community will require a significant redirection to miss the community. This concept is illustrated in Fig. 9, where fire spread direction is altered by 15 degrees to compare the two scenarios.

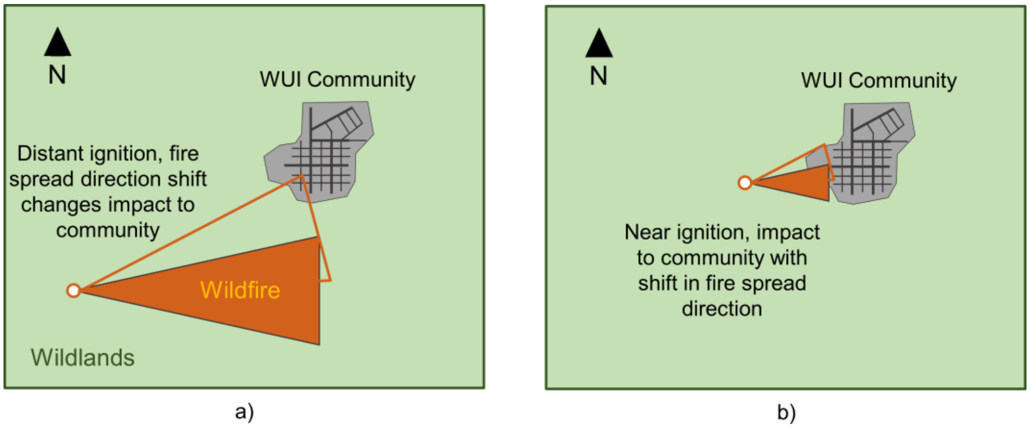
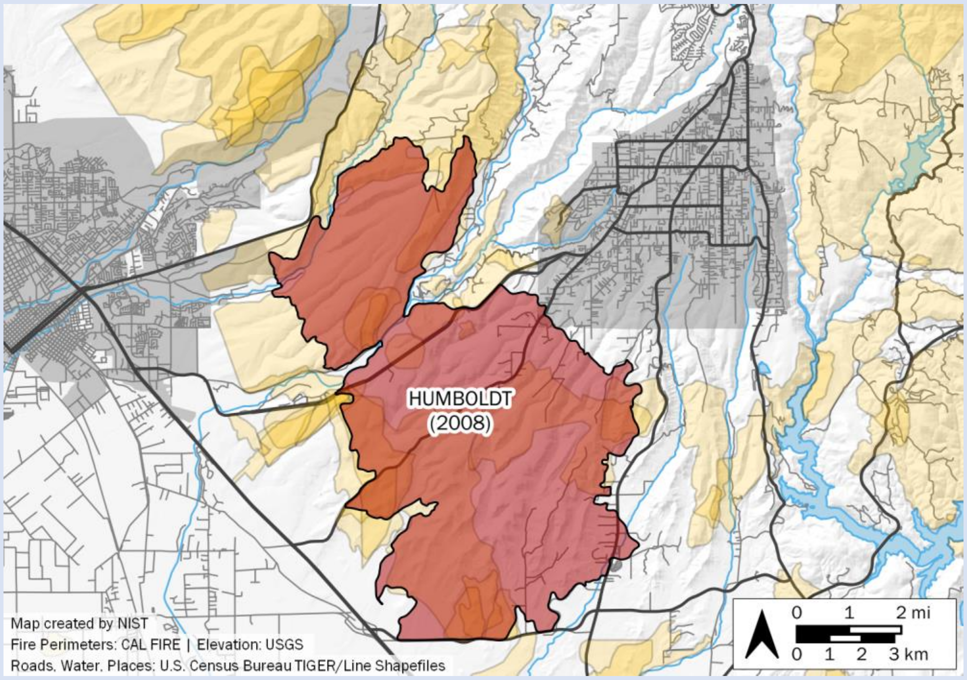



**Fig. 9.** Effect of fire spread deviation on community impact for ignitions near and far from a community. a) fire spread deviation of 15° will affect whether the community is impacted, b) similar deviation will not result in a no-impact scenario. Impacts of fuels and topography not shown.

Figure 9 illustrates how an ignition far from a community may result in scenarios where a community may be missed, and a "false evacuation" may take place. An additional consideration is that distant ignitions can generate larger fire fronts and more aggressive fire spread under the right conditions.

The two illustrated scenarios are idealized. Spot fire ignitions ahead of the fire may result in significant impacts to a community evacuation even if the spotting is several kilometers away from the community.

**Camp Fire Example 22.** Humboldt Fire (2008).




The map above shows the fire history, in yellow, from 1911 to 2018, before the Camp Fire. The Humboldt Fire is individually highlighted in red. On Wednesday, June 11, 2008, the Humboldt Fire ignited near the northwest area of the perimeter and spread rapidly to the south and east under strong north winds. A change in the wind direction on Friday threatened to push fire up the canyons deeper into the town. The fire destroyed 254 structures, including 74 homes in the southern reaches of Paradise. Nearly one-third of Paradise was evacuated during this incident, complicated by the fire impacts to three of the four egress routes.

### 5.3.2. Determining Ignition Zone Widths

Widths of the trigger zones, $d_{zone}$, are determined by estimates of fire spread distance covered during the time required for evacuations:

$$d_{zone} = FS_{max} \times t_{evac} \quad (4)$$

where $FS_{max}$ is the fire rate of spread and $t_{evac}$ is the time required for community evacuation (WRSET2). First, an assessment is made to determine the inner most part of the zone based on ignition location, expected effective fire spread rate, and community evacuation particulars. Then, an assessment of the outermost zone is developed. Because the potential for rapid fire spread exists during many severe wildfire and WUI events, attention should be placed on quantifying the expected $FS_{max}$.

Table 6 lists the distance from the inner boundary of the green zone and the boundary of an intermix community based on a range of fire spread rates $FS_{max}$ and different $t_{evac}$ durations. The calculations are the simple multiplication of Eq. (4); however, the values emphasize the potentially extensive distance/area of concern to accommodate evacuations. Table 6 shows that if a community requires two hours to evacuate (partially or fully, depending on the scenario) and the expected fire spread rate $FS_{max}$ is 4 mi/h (6.4 km/h), then the inner most green zone boundary should be set at 8 mi (12.8 km) from the boundary of the community. This scenario outlines a case where sufficient time is provided for a community to evacuate before the fire arrives. Considerations such as fuels along egress arteries, long range spotting, and other conditions that may impact different parts of the community evacuation still need to be addressed. The range of fire spread rates and evacuation times listed in the table are not unprecedented. Recent WUI fire events have been within these bounds. For example, the evacuation of Paradise during the Camp Fire took at least four hours, and the effective fire spread rate from ignition to the first spot fires in Paradise of 7 mi (12 km) in 1.5 hours, or 4.6 mi/h [7].

**Table 6.** Green Zone inner boundary distance, in miles, from edge of intermix community. (1 mi = 1.6 km)

| | $FS_{max}$ (mi/h) | | | |
|---|---|---|---|---|
| $t_{evac,C}$ or $t_{evac,P}$ (hours) | 1 | 2 | 4 | 6 |
| 0.5 | 0.5 | 1 | 2 | 3 |
| 1 | 1 | 2 | 4 | 6 |
| 2 | 2 | 4 | 8 | 12 |
| 4 | 4 | 8 | 16 | 24 |

Increasing the width of the trigger zones can be used to address uncertainty in fire spread rates and can be viewed as engineering safety factors. Additionally, the width of zones can be used to create temporal fire containment thresholds. Rapid fire spread under high winds or dry conditions can result in a fire covering more than a mile in 15 minutes. Quick containment will be dictated by time of day (impacting availability of aerial suppression), detection time, accessibility, staffing, and environmental conditions. If an ignition in the Green Zone cannot be contained (including spot fires), a full community evacuation should be considered when the fire reaches the boundary of the Green/Red Zone. There is a possibility that the fire may be contained in the Red Zone; however, the likelihood of that outcome should be weighed against the potential for long-range spotting and other conditions impacting containment. Spotting of the fire from the Green Zone into the Red Zone with limited chance of containment should also be considered.

The outer edge of the Red Zone intersects with the inner boundary of the Green Zone and marks the location where complete or partial evacuation may not be accomplished before the fire reaches the community. An ignition in the Red Zone that has potential to be contained presents a difficult situation with respect to response actions. If the fire cannot be contained, there will be insufficient time to safely evacuate the community. Consideration should be given to activation of evacuation procedures in all but select cases where the ease and speed of access may make containment highly probable. These cases should be explicitly defined, as even small reductions in the number of available first responder resources could result in fire impacting the community during evacuations.

The inner boundary of the Red Zone is dictated by the outer Purple Zone boundary. The Purple Zone can be used in locations where fires will have limited impact on the community as a whole and only partial evacuation or partial shelter-in-community may be necessary. These include scenarios where only a small fraction of the community is impacted owing to local conditions and layout of the community with respect to the fire spread. If such scenarios do not exist or cannot be reliably developed for a particular community, then a Purple Zone does not have to be used and the inner boundary of the Red Zone will abut the community boundary.

The evacuation timeline previously described in Sec. 4.2.1 can be used to facilitate the development of the evacuation plan using trigger points. The time estimates are cumulative.

1. Ignition/first observation, $t_d$
2. Situational assessment
3. Decision making
4. Order to evacuate
5. Communication of evacuation order, $t_{IT}$
6. Activation of notification systems, $t_{diss}$
7. Evacuation duration (including necessary time for evacuation of critical care facilities/schools/hospitals), $(t_{prep} + t_{trans})$

(Items 2–4: $t_{FDS}$; items 1–4: $t_{order}$; items 1–6: ITA; item 7: ET; items 1–7: ITS)

There is a minimum time from the observation/notification of an ignition to the activation (ITA) of public notification systems. This time can be viewed as an operational baseline; any evacuation time (ET) necessary for the public to reach safety must be added to the ITA time. The total time from ignition to the time a civilian reaches safety (ignition to safety, ITS, or WRSET) can be rewritten as the sum of ignition to activation (ITA) and the evacuation time (ET).

$$\text{ITS} = \text{WRSET} = \text{ITA} + \text{ET} \tag{5}$$

Equation (5) can be used to assess/characterize a scenario where the evacuation time involves civilians leaving the community or a scenario where civilians are directed to shelter in community. The goal is to have ITS less than the time from fire ignition until fire impacts egress arteries. While some time savings may be had with potential improvements of situational awareness and decision making (reducing ITA), the time required to evacuate the community will likely have the largest impact on developing the ignition zone thresholds.

## 5.4. Community Evacuation Options and Decisions

The risks of sheltering within the community should not be compared to the low exposure risks associated with an early evacuation, but rather to the realistic outcomes of a specific wildfire or WUI ignition and fire spread scenario where there is not sufficient time to safely evacuate part of or the entire community. Not all options will not be available for all fire scenarios. Direct comparisons among all options may not provide the necessary context for risk management.

### 5.4.1. Shelter in Community

Large communities with $t_{evac,C}$ times of several hours (e.g., 4 h) require significant lead time to accomplish a safe early evacuation. Combined with fast fire spread rates (e.g., 4 mi/h), this results in a significant Green Zone ignition radius (e.g., 16 mi) to fully evacuate. An alternative framing is that, for a community that needs four hours to fully evacuate, any ignition within

16 mi of the perimeter of the community should trigger a shelter-in-community response rather than a full evacuation if:

- egress arteries will not provide the desired life safety conditions to evacuating civilians,
- designated safety zones are in place, and
- the public is informed of the shelter-in-community response.

The shelter-in-community approach provides a risk management tool for scenarios where evacuation may expose civilians to high hazard conditions (i.e., burnovers). When conditions permit (time is available, egress corridors are accessible and remain open) evacuation may be the less hazardous approach. In other conditions, shelter-in-community or a combination of approaches may enhance life safety overall. Partial evacuation may also be considered, particularly for medical care facilities and other susceptible civilian populations.

### 5.4.2. Partial vs. Complete Community Evacuation

Communities can be evacuated in their entirety or partially. Partial evacuation can occur when only part of the community will be impacted by fire or when only part of the community can safely evacuate before fire conditions prevent continued safe evacuation. Figure 10 illustrates a first order assessment of fire impact to the community potentially permitting a partial evacuation.

There are benefits and limitations with both full and partial evacuation options. In both cases it is essential that clear and timely evacuation information is conveyed to the public. An advantage of a partial evacuation or phased evacuation targeting people who will experience hazardous conditions first is reduced traffic on the egress arteries resulting in more rapid evacuations and reduced gridlock. A full evacuation may be easier to communicate to all residents through mass notification systems like sirens; however, a simultaneous full community evacuation may result in significant traffic gridlock and ultimately slow down evacuation.

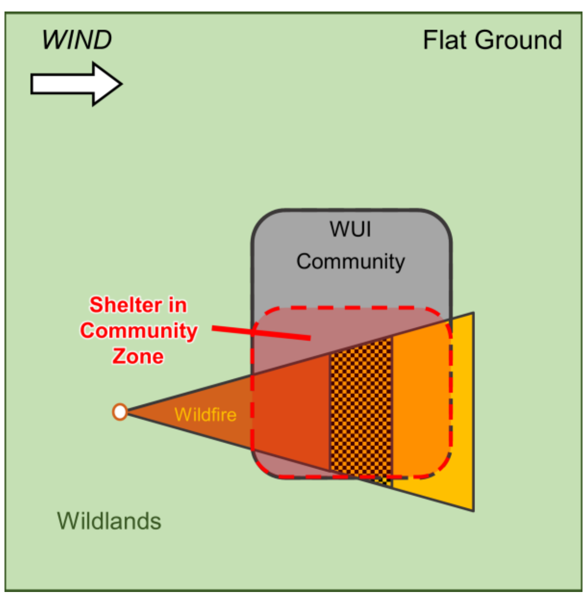


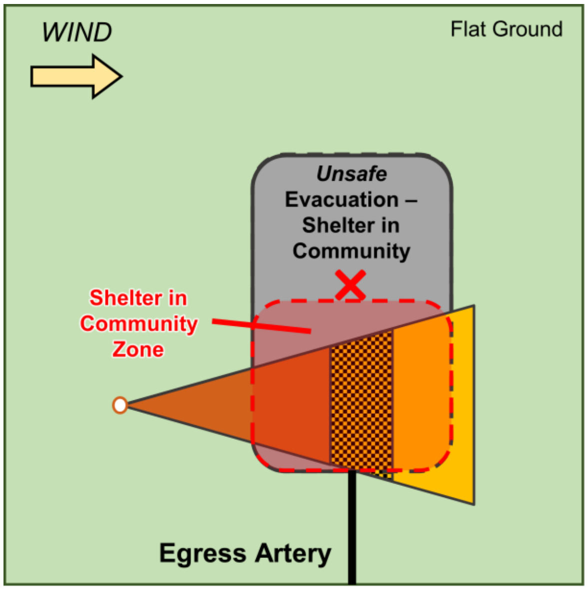

**Fig. 10.** First order assessment of initial impact of fire from nearby ignition resulting in partial evacuation.

If there is limited time to fully evacuate before the fire arrives and heavy fuel loadings are present along the egress arteries, there is a higher risk of civilians possibly becoming trapped by fire during evacuation. This is particularly important for intermix communities with limited fire history and heavy vegetative fuel loadings where high ember exposures can result in multiple ignitions within the community ahead of the main fire front, challenging suppression capacity and partial evacuations of the impacted areas.

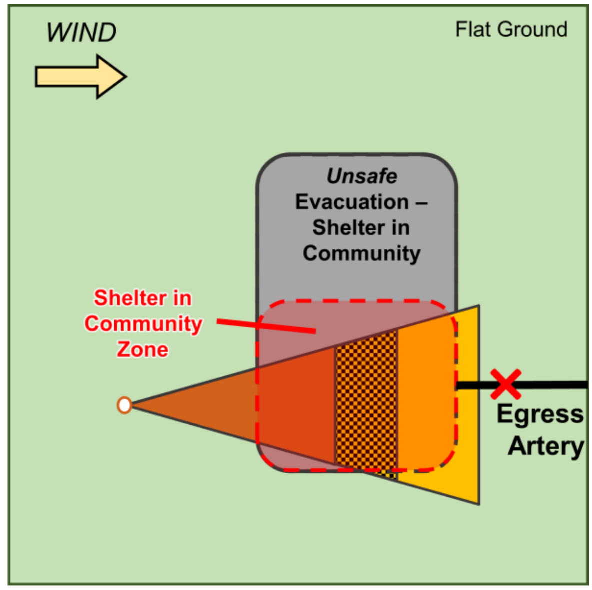
Figure 11 illustrates four second order assessment scenarios that can be developed/considered based on ignition locations, wind direction, effects of topography, and location and condition of evacuation arteries. The number of scenarios to be developed will grow significantly in number and complexity as the community is subdivided into more zones. The diagrams in Fig. 11 represent idealized situations of a two-zone WUI community. In all four cases, wildfire ignition occurs near the community (in the Red Zone), offering little time for evacuation in the areas immediately impacted by fire and embers. The areas of direct fire and ember exposures determine the zone where shelter in community may be implemented if safe evacuation cannot be achieved.

Figure 11a and b show how sheltering in the community may also be necessary for areas of the community that are not directly impacted by the fire if egress routes pass though the fire's projected path. Figure 11c shows a partial impact to the community, where areas that are not immediately impacted have access to a safe egress route and may evacuate without direct impacts from the fire. Figure 11d shows a similar configuration to that of Fig. 11c, with the inclusion of sloped terrain. In Fig. 11d, the slope may result in upslope fire spread that impacts egress routes on the upslope egress artery.

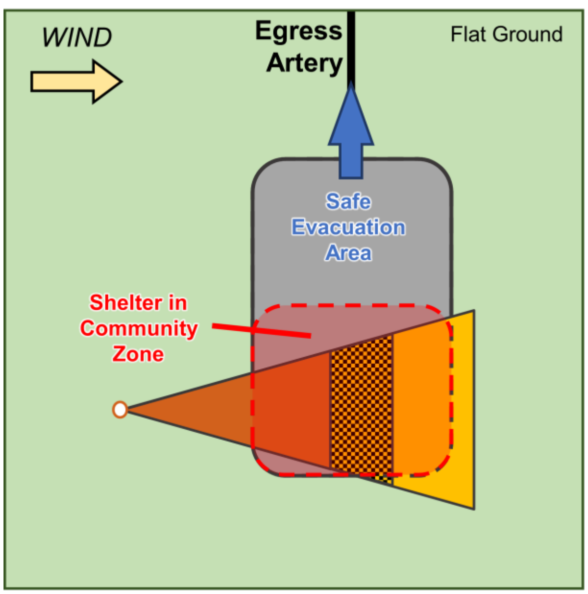
The complexities described above will also carry through to the implementation of the response. The reliability and time lags associated with situational assessment and changes in wind will further complicate real time response (see Sec. 6.3). Evacuation challenges can be partly mitigated by public involvement in the development of the evacuation plan, creating or engaging volunteer organizations to help with the evacuation (specifically, but not limited to, traffic management), extensive communication campaigns, and evacuation drills. The development of social engagement strategies for dissemination of evacuation and notification plans and public engagement of the community are beyond the scope of this report.



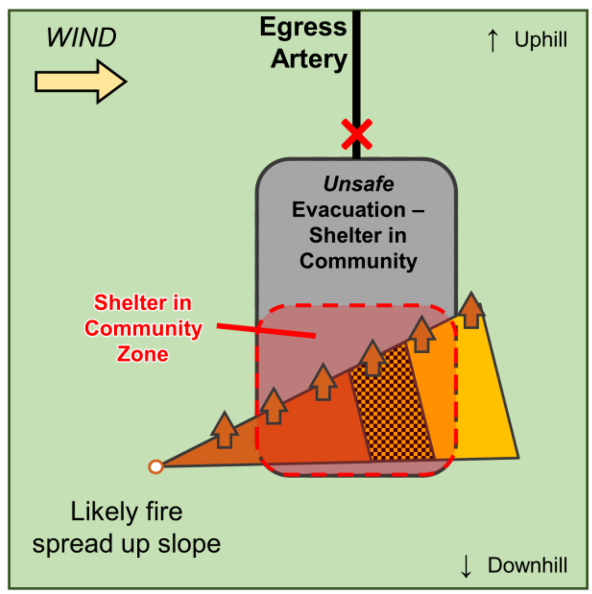

Second Order Assessment (Scenario 1) — Fire spread through community blocks the egress path for the non-impacted area.




Second Order Assessment (Scenario 2) — Similar to Scenario 1 with potential for egress artery to be further compromised outside of community.




Second Order Assessment (Scenario 3) — Non-impacted area of community has clear egress pathway. Individuals without enough time to evacuate from the fire impacted area will need to shelter in community.




Second Order Assessment (Scenario 4) — The enhanced fire spread up the slope may increase fire spread and compromise the initially non-impacted area and the egress artery.

**Fig. 11.** Four second order WUI community assessments accounting for wildfire ignition and egress artery locations and topography.

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# 6. Implementation

Implementation of the proposed approach is presented as three phases in the following sections: assessment, planning, and execution. During the assessment phase, communities should collect any existing evacuation plans, as well as various fire- and evacuation-related community and demographic data, to evaluate the needs and capabilities of the community to respond to a WUI fire. These results will be incorporated into the evacuation plan in the planning phase. Based on the capacity of the community to evacuate and the potential fire behavior, trigger buffers and decision points can be pre-planned for a range of scenarios. Once a plan is developed, the execution phase includes continual advance planning and maintenance, in addition to any incident response.

## 6.1. Assessment

The primary purpose of the assessment phase is to collect the community attribute data necessary for the planning, development, or revision of a community notification and evacuation plan. A WUI Community Hazard Framework is specifically built for that purpose [90]. It is likely that much of the information identified in the WUI Community Hazard Framework is already included in various community and local government documents; however, collecting all the necessary data in a centralized digital location will facilitate a more comprehensive and effective development of notification and evacuation plans. Any existing notification and evacuation plans, along with the supporting material used for their development, should also be identified.

This data collection will enable an assessment of conditions and attributes within the community and its surroundings. Demographic data and information regarding senior citizen and medical care facilities will enable the identification of susceptible populations. Data on vegetative and built environment fuel densities will provide context of possible fire behavior, particularly when viewed together with fire history, topography, and weather statistics on high wind events.

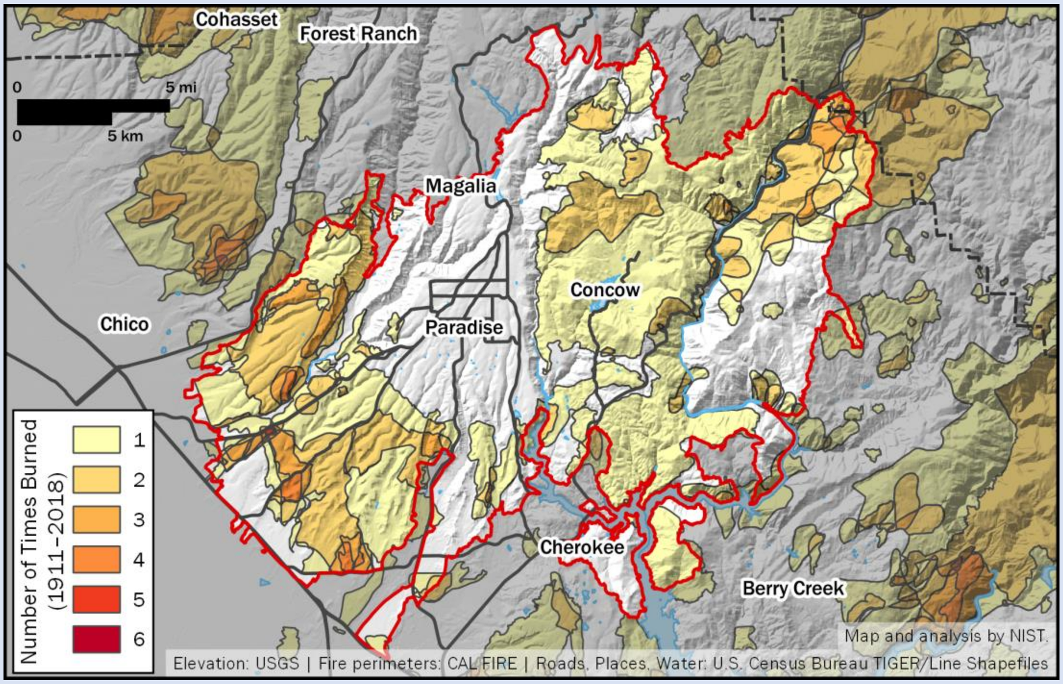
**Camp Fire Example 23.** Paradise fire history.

The map figure below shows the fire perimeters of the recorded wildfires in northern Butte County from 1911 to 2018, shaded to indicate the number of times each area burned. The red outline indicates the extent of the Camp Fire. Forty-two percent of the Camp Fire footprint had not burned in the last 100 years, including the area in and immediately around Paradise.

Lack of historical fire does not, by default, translate to low fire hazard. The absence of fire activity in the intermix community contributed to significant fuels build up. The fuels built up together with the severe lack of precipitation and strong winds all contributed to the severe fire behavior that caused the loss of life and structure destruction.

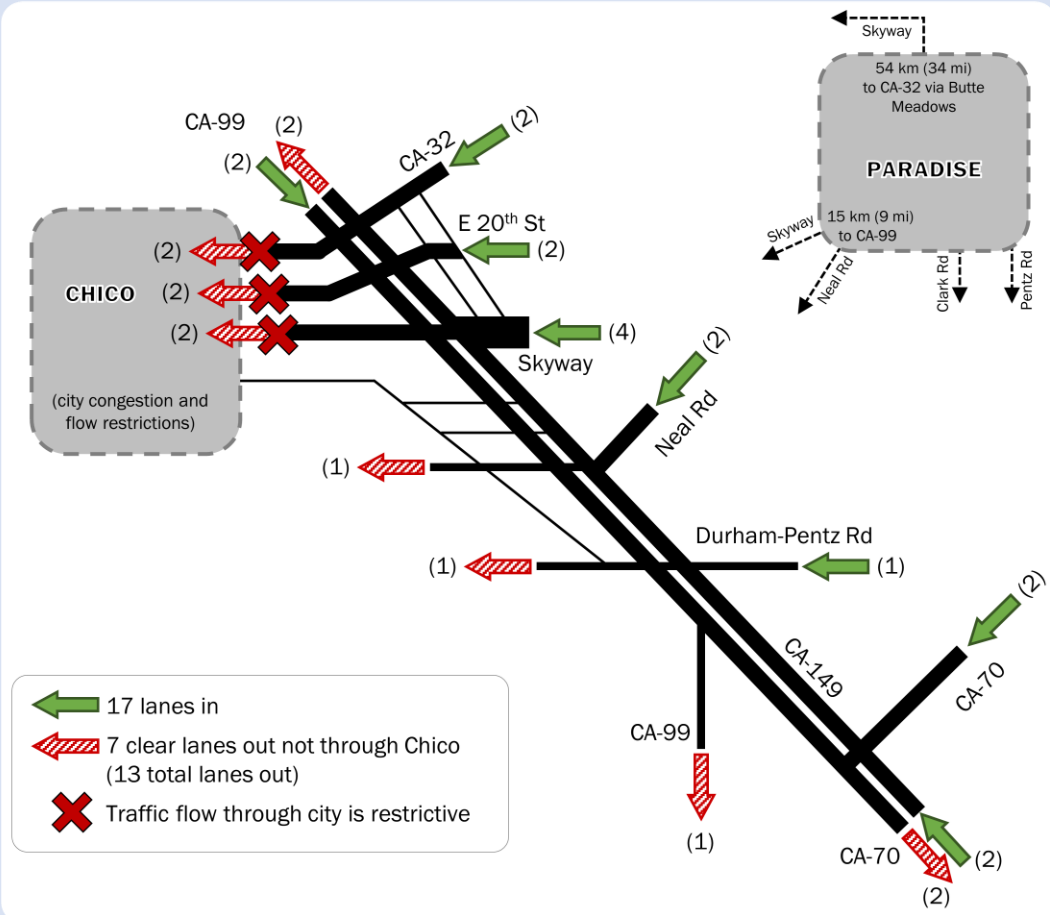
Historically, fires in Concow had been contained upwind of Paradise before ever crossing the West Branch Feather River canyon (approximately 240 m deep, 800 m rim to rim). During the Camp Fire, the combination of wind and drought caused the fire to be uncontainable in Concow. Paradise was impacted by both an ember assault that caused 30 of spot fires (see Camp Fire Example 7) and a very intense and extensive fire front.

The absence of historical fire should not be viewed as a benefit or absence of hazard, but rather assessed in the overall context of fuels, topography, and local weather (wind and drought). Communities that have not regularly experienced fire and have extensive vegetative fuels accumulation may therefore be prone to severe WUI fire events. Past fire history alone cannot solely be used to predict the severity of future events. *(continues on next page)*




Details of the road network, fuel, topography, and fire history can provide context for evacuation hazards and can be used to identify potential burnover locations. Data collection on possible wildfire safety zones and access to these zones will also be critical in the development of the community evacuation plan. Destination locations for evacuees should be identified and road capacity and potential fire hazards should be documented for the entire travel corridor from the community. Gridlocks and road restrictions can occur many miles away from the evacuating community and can result in traffic getting backed up all the way to the community.

**Camp Fire Example 24.** Impact of traffic gridlock beyond the immediate community.




The schematic above diagrams the road network around Paradise and the number of lanes available for evacuation traffic flow in and out of the network during the Camp Fire. The nearest sizable communities, and the locations that residents were familiar with, included the cities of Chico and Oroville located on CA Highways 99 and 70. The four southern evacuation routes from Paradise all merge with CA-99 or CA-70. Due to existing traffic in the neighboring communities, the restrictive flow through urban areas, and the extent of feasible implementation of contraflow, the net result was the reduction of 17 incoming lanes into 7 available outgoing lanes. The widespread merging and traffic restrictions experienced outside of the fire area resulted in backups that reached from Chico all the way back into Paradise, impacting the ability of evacuees to get out of the fire area and compromising the life safety of evacuees.

Large-scale evacuations are often taxing on roadway networks and infrastructure. Evacuation plans need to account for evacuee travel and need to address potential bottlenecks and restrictions even if these occur many miles from the community being evacuated.

Information on the status and hardening of critical infrastructure should also be collected. This includes any structure hardening and fuel treatments around critical infrastructure like water pumping stations, telecommunication towers, and electrical distribution equipment. The purpose of collecting this information is to identify infrastructure hardening needs and to understand the potential failure of these critical systems. Hardening of key infrastructure systems is part of developing a reliable notification and evacuation plan.

Information on the time needed to evacuate the community should be collected from any previous evacuations. If limited data exists on community evacuation, an evacuation drill may provide critical information for the development of the community evacuation plan. Evacuation of part of the community will provide useful information on minimum evacuation times; however, it may not necessarily identify critical traffic flow/congestion issues that may only manifest at higher traffic flows. The primary purpose of the evacuation drill is to determine minimum ignition to safety (ITS) timelines without any direct or indirect impacts from fire. Such a drill will also provide a training opportunity for first responders to implement traffic management tools like contraflow and to coordinate with relevant partner agencies. Community participation in the development of the evacuation plan will also provide practice and training for residents. The determination of ignition to notification activation (ITA) time can be determined in one or more separate first responder exercises.

Information on first responder staffing, availability and timing/arrival and capacity of mutual aid resources should also be collected. This information can then be reviewed in the context of egress and ingress arteries. Discussion with the community and regional fire agencies will help identity which fires and under what conditions fires may get out of control. This assessment will be enhanced by knowledge of regional fire history, vegetive fuel distributions, and historical weather data.

## 6.2. Planning

Community- and regional-specific data collected during the Assessment phase will influence the design and implementation of the plan. This section provides a high-level overview of the workflow for development of community notification and evacuation plans. In the U.S., evacuation decisions during a fire incident are typically made by the IC and executed or enforced by a number of different agencies. Therefore, it is critical to develop the plans with and integrate and inform all AHJs impacted *before* an event. The presented methodology is developed for small and medium size intermix, and isolated interface, communities (conceptually on the order of 30 000 residents or fewer).

### 6.2.1. Developing the Community Notification and Evacuation Plan

The notification plan should work hand in hand with the decisions and expectations set forth by the evacuation plan and vice versa. The means of notifying large fractions of the community should be identified and consider population density, demographics, and infrastructure. Notification plans should consider opt-out, rather than opt-in, notification systems to increase participation rates. Specific consideration should be given to the notification of critical care facilities and groups that may need additional assistance. Infrastructure hardening throughout and surrounding the community may be necessary to ensure a reliable and resilient notification system, particularly if power is cut off (intentionally or accidentally). Developing contingencies accounting for loss of power, internet, and phone services and the potential evacuation of the Emergency Operations Center or people in other emergency management roles will result in a more resilient notification plan.

Community evacuations can be summarized in the following two questions:

- Under what conditions (what fire and when) should an evacuation be initiated?
- Who should be evacuated and where should they evacuate to?

To address the above two questions the development of the evacuation plan is divided into three primary steps.

1. Identify the Green/Red Zone threshold indicating scenarios with insufficient time to evacuate.
2. Develop evacuation scenarios for fire ignitions within the Red Zone.
3. Identify the Purple Zone adjacent to the community where ignitions may have localized effects on only a portion of the community.

### 6.2.1.1. Step 1 – Identify the Green/Red Zone threshold

Data collected in the assessment stage is used to identify the threshold for the Red/Green Zones. The ITS data is used together with estimated fire spread rates ($FS_{max}$) for the expected worst-case conditions to identify the boundary of the Green and Red Zones. By establishing this boundary there is a spatial threshold around the community that defines the early evacuation and full community evacuation scenarios. Any fire outside of this boundary that is heading towards the community will trigger a community-wide evacuation. The radius of the Green Zone, as discussed previously in Sec. 5.3.1, can be increased to address uncertainties in evacuation time and fire spread rate and can be viewed as an engineering safety factor. For reference, a zone depth of 1 mi, for a fire that travels at 4 mi/h provides only 15 minutes of “additional” evacuation time before the fire impacts the edge of the community. It is for this reason that a reliable community evacuation time (ITS) needs to be determined in the assessment stage.

The exact location of the ignition in the development of the Green Zone fire scenarios is less important than the combination of maximum fire spread rate and direction of fire spread. Topographic features and climatology of strong winds can help identify general scenarios. As mentioned in Sec. 5.3.1, dividing the Green Zone into sectors may help with the design process.

The probability of ignition and the likelihood of containment do not factor in the development of the Green Zone. The first step in the development of the Green Zone is to determine the inner boundary—the distance from a community that will allow enough time for a full evacuation. To make the zone useful, criteria need to be further developed to identify which ignition in the Green Zone will warrant the full community evacuation.

Wind, topography, and fuels are the primary drivers that influence fire spread. Since topography does not change and vegetative fuel buildup is a long-term process, the primary variables that need to be characterized are fuel moisture, wind, and firefighting response. Note that fire spread rate is not directly included since it was prescribed for the establishment of the Green Zone/Red Zone boundary. Local fire history and weather records can be used to establish thresholds for fuel moisture and wind speed parameters. With respect to fire department response, two considerations are the availability of first responders and accessibility of the ignition location. Availability of first responders should be considered in the context of an ongoing regional fire storm which may reduce the response capacity below typical performance levels.

The established fuel moisture, wind, and firefighting response characteristics can be used to help triage ignitions in the Green Zone. Slower moving fires occurring during lower winds or wetter fuel conditions will take longer to reach the community and may be successfully controlled by aerial resources; however, these fires should not be dismissed and need to be monitored carefully (see Sec. 6.3 on execution).

*Additional Fire Considerations*

There are several specific cases where additional alternative or supplementary ignition zones might be developed. The first is the development of scenarios for lower fire spread rates, again using the above approach. Such scenarios may provide context for non-catastrophic events. Fires, however, can generate their own wind and gain momentum so in many ways one of the most important components to consider for non-extreme events is the effectiveness of suppression.

Another is the extent of the fire front when the fire reaches the community. There are many factors that drive the extent and intensity of the fire front as a function of time. The fire front that impacted the town of Paradise in the 2018 Camp Fire was over 1 km (1.5 mi) in length, 11 km (7 mi) from the origin.

Reliably predicting fire spread is challenging; however, there could be certain cases where topographic features and other natural breaks may be used to refine or create “exclusion zones” with the Green Zone. Fires in these exclusion zones should not pose a threat to the community, although they should be carefully monitored. The development of potential exclusion zones should carefully consider extreme fire behavior and long-range spotting that can take place over several miles.

Refinements of fire “restarting” after a large fuel break are beyond the scope of the initial zone development and introduce complexities and unknowns and that may increase risk by inadvertently underpredicting detailed fire behavior that may negatively influence evacuation decisions.

*Additional Evacuation Considerations*

Consideration should be given to the evacuation of critical care facilities to avoid the need for simultaneous use of resources for evacuation of multiple critical care facilities. Evacuation plans should include accommodation of patients on a full community evacuation. Additional preplanning should address evacuation assistance with the mobility impaired population.

Communities should consider the use of trained community volunteers for traffic management and assess the potential for leveraging existing infrastructure (e.g., buses/trains) for mass evacuations. Coordination with neighboring jurisdictions can help to avoid gridlock in surrounding communities from impacting the evacuation from the community in the path of the fire.

#### 6.2.1.2. Step 2 – Develop evacuation scenarios for ignitions in the Red Zone

While evacuations ideally will take place without impacts from fire, there are scenarios where the coupling between fire ignition/spread and time to evacuate the community will generate potentially hazardous conditions. A fire that ignites in the Red Zone will pose an evacuation challenge if it spreads towards the community and cannot be contained. For ignitions at the outer limit of the Red Zone (at the interface with the Green Zone), evacuation may be completed without fire impacts if the assumed maximum fire spread rate is estimated correctly. Ignitions that occur closer to the community will pose an ever-increasing evacuation risk. The goal of Step 2 is to identify and characterize scenarios where there is insufficient time to safely evacuate, and develop evacuation solutions, or alternatives, to manage these higher exposures and to reduce the overall fire exposures to civilians.

To develop lower risk solutions, the data and characteristics of egress arteries and the availability of possible wildfire safety zones will need to be assessed. Egress arteries will need to be evaluated for capacity, accessibility, and potential for burnovers (i.e., fuels and fuel setbacks). Similarly, existing locations for the establishment of wildfire safety zones should be assessed for size, exposures, evacuee capacity, surrounding civilian population, and accessibility.

The option of clearing and maintaining fuel reductions along egress arteries should be reviewed together with the option of implementing a system of distributed wildfire safety zones. The analysis of egress arteries and the implementation of a distributed wildfire safety zone system can be used to develop the shelter-in-community response and to assess the feasibility of partial evacuation options. Fuel treatments to enhance access to safety zones and the implementation of community and parcel hardening programs like HMM [40] should also be considered.

#### 6.2.1.3. Step 3 – Identify the Purple Zone

This is an optional step that addresses a specific scenario in which fire impacts a small fraction of the community. Evacuation planners can use sectors in the Red Zone to further develop likely community exposure scenarios (including size of wildfire front and relationships to egress arteries) to determine if any Purple Zones can be developed which will lead to the zoning of the community in order to accomplish partial community evacuations (or partial sheltering in community). Fire ignitions in Purple Zones are reserved for fire ignitions near or within the community where local conditions will contain the fire to only part of the community. Specific consideration should be given to spot fire ignitions within the community and the availability of resources to control the initial fire and any spot fires. Fires that ignite within the Purple Zones may still require large (complete community) evacuations if they develop into community conflagrations or occur during a fire storm when multiple regional fires coincide with a high wind event and first responder resources are extended on multiple incidents.

### 6.2.2. Accounting for Uncertainties and Including Safety Factors

The above outlined three step process allows a community to establish preliminary boundaries for the ignition zone boundaries as a function of ITA, ITS, and maximum expected fire spread rate. Developing trigger conditions that reflect realistic worst-case scenarios requires high quality inputs for ITA, ITS and $FS_{max}$. The first two values can be supported through a combination of exercises. The fire spread rate and direction are the most challenging to predict. Regional fire history in similar fuels and topography can be used to bound limits of fire spread rates. In some cases, fire spread direction may be relatively straightforward to predict based on topography and prevailing winds. However, the conditions during the actual event will ultimately drive the fire and determine if the community gets impacted. There is significant value in preparing beforehand, understanding the spatiotemporal relationships between fire ignition/fire spread and decision-making, and developing evacuation options that reduce fire exposure risks to civilians and first responders.

The fast fire spread rates that can occur during high wind wildland/WUI fire events, together with the necessary time to evacuate communities, will determine the trigger zones. These ignition zones will likely span areas that are many miles away from the community boundaries. Care should be taken so that $FS_{max}$ is not underestimated and to provide realistic estimates for the time required for community evacuation, accounting for scenarios such as a nighttime evacuation or other adverse conditions that could extend evacuation times. Ongoing roadway construction or other temporary closures of egress arteries should be addressed in the development of the evacuation plans, either directly or in the form of a safety factor in the ITS value. This is particularly true for small to medium size communities with limited egress routes. For example, if a community only has six egress lanes and construction has closed two of the six, the impact of that reduction will be very significant. The evacuation plan should contain provisions for revisions and adjustments based on changing egress route conditions.

Community engagement and public education are critical components of a successful notification and evacuation system. Such efforts:

- Communicate the impact and cost of evacuations and inform the public of the risks.
- Communicate the scenarios and options/limitations so the public understands what they should do and how they will get the necessary information.
    - This will inform the public on how little time may be available in certain scenarios and the value of being prepared (programs like “Ready, Set, Go!”).
    - Create mechanisms to inform seasonal or temporary residents (including visitors) of the notification/evacuation plans.
- Help conduct evacuation exercises.
- Garner public acceptance and support for:
    - the implementation of fuel treatments along egress arteries, including on private property, if necessary,
    - infrastructure hardening,
    - installation/ improvements to mass notification systems,
    - creating/establishing wildfire safety zones, and
    - participation in volunteer programs to manage evacuation traffic.
- Encourage planning for early evacuation of critical care facilities and other residents requiring assistance.

## 6.3. Execution

The implementation and execution of the evacuation plan can be divided into three temporal categories; during pre-planning and normal operations, just before and during high hazard conditions (e.g., during Red Flag Warnings or days with critical fire weather), and during a wildfire/WUI fire.

### 6.3.1. Pre-Planning and Normal Operations

Activities occurring well before the fire season or high hazard conditions include:

- Maintenance of egress arteries and wildfire safety zones
- Maintenance and upgrades to first responder communication, public notification, and traffic management equipment
- Establishment of communications channels for the dissemination of fire/notification and evacuation information[7]
- Training of first responders, including publics works, law enforcement, and volunteers on principles of WUI fire safety
- PPE for law enforcement, public works and volunteers
- Updating the evacuation plan, specifically ITS and, by extension, the Red/Green Zone boundary based on any evacuation route alterations (maintenance/closures)
- Monitoring fire activities in the surrounding region and keeping awareness of scenarios of reduced first responder staffing that may impact early fire containment in non-high hazard conditions.

### 6.3.2. High Hazard Conditions

High hazard conditions outlined in the evacuation plan will likely include Red Flag Warnings, high wind events, regional fire storms, or other emergencies or disasters that may deplete or reduce local first responder resources. If high hazard conditions are forecast, AHJs should inform the community of pending conditions and use the opportunity to communicate evacuation scenarios and restate where evacuation data will be available. Communication with surrounding jurisdictions located within the Green and Red Zones will be critical for rapid and effective situation assessment in the event a fire ignites within or spreads into the zones.

Active fires outside the Green Zone that have the potential to spread into the zone should be closely monitored for direction and rate of spread.

Communication of changing conditions to the public is critical. AJHs should inform the public using established communication channels and keep information current.

### 6.3.3. During a Fire

A fire burning within the identified ignition zones will activate the emergency management response. The evacuation and notification plan developed by first responders and community officials, pre-event training, hardening of egress arteries, and implementation of wildfire safety zones will provide input to facilitate and support community evacuation decision-making. The evacuation plan, even if it is not followed exactly, because of different actual fire spread rates or other deviations from the assumed/planned conditions, will serve as a foundation for real-time

[7] These channels should be clearly conveyed to the public before high hazard events and the proposed channels should be used and remain current during an event. This will limit/avoid conflicting information during rapidly changing conditions. Multiple unused channels may cause confusion and may not be effective if staffing limitation will prevent them from being kept current during a severe wildland/WUI event.

decision making. Experience from training exercises, pre-fire preparations, and communication with participating agencies will enable effective dissemination of information, resulting in reduced exposure hazards to civilians and first responders. Continual assessment of conditions to change/adapt evacuation thresholds, and the use of the evacuation triangle (Fig. 1), will provide spatiotemporal context for evacuation decisions.

The following factors will impact the evacuation decisions made by the incident commander:

### Fire in the Green, Red, or Purple Zone

In the event of an ignition near the community, important parameters include the location, accessibility, time of day, availability of resources, weather, and direction and rate of spread of the fire (towards the community or not).

### Fire Containment

Rapid fire spread under high wind and dry fuel conditions can result in a fire covering more than one mile in 15 minutes. Early containment will be dictated by time of day (influencing the availability of aerial suppression), accessibility, staffing, fuels, topography, and local weather. If an ignition in the Green Zone cannot be contained (including spot fires) when it reaches the Green /Red Zone boundary, then a full evacuation should be considered. There is a possibility that the fire may be contained in the Red Zone; however, this should be weighed against long-range spotting and the previously described conditions impacting containment. If available, historical data on fire containment under similar conditions may provide supporting information, although changes in fuels (i.e., fuel loading or moisture content) may result in more aggressive fire behavior that what has been experienced historically.

### Situational Assessment and Evacuation Decisions

As the event develops, field observations (from fire department, law enforcement, and dispatch [emergency 911 calls]) and other data streams, should be used to enhance situational assessment and determine the current fire spread rate. Information will be communicated to partner agencies and the public using the established channels as evacuation decisions are adapted to the current situation. Increasing fire spread rates may require a shift in the Green/Red Boundary and call for an evacuation when the fire is further away from the community than initially planned for.

## 7. Recommendations

The concepts presented in this report can be used by AHJs and WUI communities as needed. There are three technical recommendations aimed at informing future research that will help enhance the development of community notification and evacuation plans.

ESCAPE R1. Understand the relationship between fire spread and duration of wind events. This may impact evacuation projections in the future.

ESCAPE R2. Understand the relationship between wind events and effectiveness of initial containment.

ESCAPE R3. Develop methodology for assessing the performance of wildland fire spread models using pre-fire predictions and post-fire fire spread data.

One further recommendation to facilitate evacuations, agnostic to any particular evacuation plan, is explicitly listed here particularly because of its potential beneficial impact and relative ease of implementation.

ESCAPE R4. Social tools like remote work during high fire hazard weather events may reduce road congestion and enhance evacuation if residents are already located at a common point with family (i.e., home) and preparation time to onset of evacuation is reduced.

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## 8. Summary

Wildland fires can impact communities quickly, posing a serious threat to life safety of residents, evacuees, and first responders, as evidenced from numerous events within the past decade. WUI fire events have led to rapid large-scale evacuations and have resulted in destroyed communities and loss of life. The need for WUI community evacuations can become apparent minutes to hours before a community is impacted by fire. The rapid onset, range of scenarios, and complexity of WUI fire incidents and evacuations calls for dedicated pre-planning of the emergency response and contingencies.

This report offers an overview of existing practices and concepts related to community evacuation and alternatives including stay and defend and shelter in place. Evacuation beyond the fire area will always be the safest; staying within the fire area, by choice or by circumstance, can be dangerous or deadly. However, recent events show that there may not always be time to fully evacuate the community before fire impacts it. This possibility is particularly important to consider during pre-planning. In addition to scenarios where there is sufficient time for evacuation, solutions should be sought for dire scenarios in which the fire impacts the community faster than the time it will take to safely evacuate.

Community evacuations present numerous challenges, from the large number of potential fire scenarios and variability of fire behavior to the stochastic events as an incident unfolds, including spot fire ignitions, egress obstructions, and human behavior. Advances in computing power are improving the capability to run complex evacuation modeling simulations to support evacuation planning. A discussion of the many components needed to reliably predict evacuations highlights the challenges associated with managing uncertainties and the large number of scenarios to be considered. Limitations on the state-of-the-art fire and evacuation models means that their outputs must be carefully interpreted within the broad scope of possible evacuation events. The overall complexities and associated uncertainties of these models call for a simplified general approach with a heavy emphasis on flexible and adaptive pre-planning.

Various evacuation complications and considerations are presented in this report for multiple spatial/temporal scenarios based on findings and examples from actual WUI events, particularly the recent Camp Fire in Butte County, CA in 2018. The lessons learned from the Camp Fire have been used to highlight potential challenges that should be considered in the context of each individual community and to outline various intermix community evacuation scenarios. Several scenarios are characterized by insufficient time to safely evacuate the community before the fire impacts evacuation, compromising life safety of evacuating civilians and responding emergency personnel. The potential for such dire situations means that communities must have several options available to enhance life safety when evacuation is not possible.

Just as important is the ability of communities to identify these scenarios as they occur. To address this, a methodology to link fire spread and community evacuation actions using a set of evacuation trigger zones is presented. Adapting the community evacuation response to the evolving situation based on trigger zones can mitigate civilian fire exposure risk. A key need in pre-planning is to identify critical temporal/spatial thresholds in the evacuation continuum where complete community evacuation will not be possible before the community egress arteries are negatively impacted by fire. The proposed methodology was developed specifically to help small and medium size WUI communities define these zones and pre-plan for different evacuation scenarios. The report offers a path forward for the assessment of existing communities for evacuation and notification planning, along with considerations for developing the evacuation plan. Also included is a discussion on executing the evacuation plan, including monitoring of actual fires and the use of real time data to adjust the planned evacuation and notification actions as necessary.

The report provides authorities having jurisdiction (AHJs) of small and intermediate-sized intermix communities with context of WUI fire events that will enable them to better evaluate different hazard reduction and risk management strategies in order to enhance the life safety of residents and first responders. This is particularly important for communities that may not have the resources or expertise to conduct or evaluate a more complex evacuation analysis. While additional research is needed to optimize the concepts discussed here, the presented information can inform communities and help develop and improve community sheltering and evacuation planning.

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## Appendix A. California Large-Loss Fire Statistics

Data compiled from the California Department of Forestry and Fire Protection (CAL FIRE) for fires in the State Responsibility Area[8] of California between 2017 and 2022, listed in Table A-1, show that a small number of fires contributed the majority of structure losses. Only 1 % of all fires resulted in structure loss. High-loss fires, defined as incidents with 100 or more damaged or destroyed structures, accounted for 18 % of fires with losses, but 95 % of structure losses over the six-year period.

**Table A-1.** Recent WUI fire structure loss statistics in California (CAL FIRE State Responsibility Area).

| Year | Number of fires | Number of fires with losses | Total losses[a] | Number of large-loss[b] fires | Total losses[a] from large-loss fires | Percentage of large-loss fires[c] | Percentage of losses from large-loss fires/total losses |
|---|---|---|---|---|---|---|---|
| 2017 | 3470 | 41 | 12061 | 12 | 11565 | 29% (12/41) | 96% (11565/12061) |
| 2018 | 3504 | 36 | 24227 | 4 | 23731 | 11% (4/36) | 98% (23731/24227) |
| 2019 | 3086 | 19 | 802 | 2 | 549 | 11% (2/19) | 68% (549/802) |
| 2020 | 3501 | 45 | 10621 | 11 | 10005 | 24% (11/45) | 94% (10005/10621) |
| 2021 | 3054 | 35 | 3535 | 5 | 3036 | 14% (5/35) | 86% (3036/3535) |
| 2022 | — | 28 | 876 | 3 | 544 | 11% (3/28) | 62% (544/876) |
| **Total** | **16615** | **204** | **52122** | **37** | **49430** | **18% (37/204)** | **95% (49430/52122)** |

*Note*: Total number of fires was not yet available for 2022.
[a] total losses = damaged + destroyed structures
[b] large-loss fires defined as total losses ≥100
[c] number of large-loss fires divided by number of fires with losses

[8] Areas of the state of California where CAL FIRE is responsible for fire suppression and prevention, rather than local or federal agencies.