FINAL REPORT

Title: An Assessment of Research Needs
Related to Wildland Firefighter Safety

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List of Abbreviations/Acronyms

FiSL MED – Fire Sciences Lab Merged Entrapment Database
GACC – Geographic Area Coordination Center
JFSP – Joint Fire Science Program
NWCG – National Wildfire Coordinating Group
US – United States

Keywords

Burnover, entrapment investigation, entrapment data, fire behavior, fire environment, firefighter fatalities

Abstract

Wildland firefighters in the United States (US) are exposed to a variety of hazards while performing their jobs in America's wildlands. Although the threats posed by vehicle accidents, aircraft mishaps and heart attacks claim the most lives (Figure 1), situations where firefighters are caught in a life-threatening, fire behavior-related event (i.e. an entrapment) constitute a considerable danger because each instance can affect many individuals. In an attempt to identify the scope of our understanding of the causes of firefighter entrapments a review of the pertinent literature and a compilation and synthesis of existing data was undertaken. The literature review and the creation of a firefighter entrapment database (https://www.wfas.net/entrap/) led to the identification of five key findings: (1) previous investigations of firefighter entrapment incidents have similar summaries and recommendations, (2) the entrapment investigation process and existing data reporting/storage systems are flawed, (3) there is likely a substantial under-reporting of entrapment incidents, (4) the annual number of entrapment-related fatalities are decreasing but the number of entrapment incidents are not and (5) information from previous entrapments can be used to predict/project future entrapment hazard and risk. A summary of research needs is also presented.

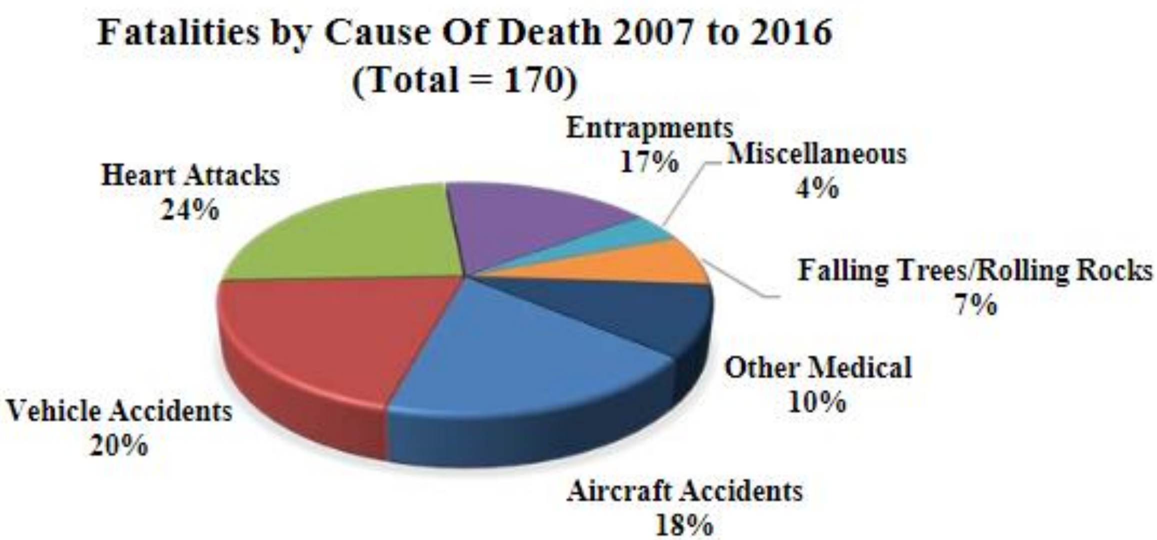

Figure 1. US wildland firefighter fatalities by cause, 1990 to 2016. Originally published as Figure 1 in NWCG (2017).

Objectives

The Joint Fire Science Program's (JFSP) Governing Board recognizes the need for further research on topics related to firefighter safety and has requested an assessment of the current state-of-knowledge and potential role of the JFSP in sponsoring research into entrapment avoidance, escape routes and safety zones. Given the expertise and background of the project team members, an analysis of the various environmental factors that affect firefighter safety in relation to firefighter entrapments was undertaken. Our objectives were to: (1) establish a focused research team consisting of 2 lead scientists and 2 post-doctoral researchers to facilitate project execution, (2) conduct a comprehensive subject matter review, (3) compile and synthesize the available information to infer trends and evaluate potential research opportunities, (4) assess knowledge gaps and summarize expressed needs of fire managers and (5) produce recommendations on possible avenues of future research. The primary product of the assessment is a Review article (Page *et al. In review*), thus readers should refer to that article for specific details regarding the project findings.

Background

Since the introduction and adoption of a centralized suppression-oriented wildland firefighting paradigm in the US, wildland firefighters have been employed to protect and manage various natural and human resources. Both wildland fire scientists and firefighters have long noted the numerous challenges involved with such an undertaking due to the complexities of wildland fire as a physical process (Finney *et al.* 2015) and the social and behavioral aspects of individuals and organizations (Putnam 1996). Unfortunately, the combination of well-meaning and action-oriented attitudes with dynamic and volatile fire environments has resulted in hundreds of entrapment-related firefighter deaths (Mangan 2007; NWCG 2017). Despite these fatalities, some of which have garnered substantial public attention (e.g. Yarnell Hill), investment in fundamental research that directly focuses on how firefighters assess and reassess fire behavior, escape routes and safety zones to avoid entrapments has been limited.

In an effort to better understand the current state-of-knowledge associated with firefighter entrapments in the US a review and synthesis was completed. The review covered the extant body of scientific, technical, investigative and instructional subject matter, and included a survey of several prominent entrapment reporting systems. In combination, the literature review and the most comprehensive firefighter entrapment database compiled to date were used to identify several key findings.

Literature review

During the review we consulted a variety of published work that dealt directly or indirectly with firefighter entrapments in the US. Specifically, we reviewed:

- > 100 firefighter entrapment investigation reports,
- > 50 peer-reviewed papers,
- ~ 40 agency-produced technical reports,
- ~ 30 articles from the so-called grey literature (i.e. conference proceedings, non-refereed articles, etc.), and
- ~ 10 personal opinion articles.

References to the pertinent literature can be found in the bibliographies published at the end of this report as well as in Page *et al.* (*In Review*).

Entrapment definition

During the literature review we recognized that there currently exists some confusion in the wildland fire community about the differences/similarities between the terms ‘entrapment’ and ‘burnover’. Therefore, before continuing we sought to clarify the terminology in order better facilitate project execution by producing an encyclopedic entry (see Page and Freeborn *In press*). Page and Freeborn (*In press*) state that an entrapment includes situations where a fire behavior-related event poses an immediate threat to peoples’ lives because (1) a fire moves through and overtakes individuals (i.e. a burnover) or (2) the individuals escape by will or luck (i.e. a near-miss or close call). Thus, a burnover is a specific type of entrapment where the threat to peoples’ lives becomes actualized. Due to the likely significant under-reporting bias associated with near-misses (see *Finding 3*), our review focuses on entrapments where there was a burnover.

Human factors

Data and knowledge of the environmental factors that affect fire behavior can only move our understanding of how and why entrapments occur so far. A significant portion of our understanding of entrapment potential lies in the human factors. The human dimensions of wildland firefighting represent a broad range of topics and disciplines, including psychology, sociology, leadership and fire safety (Putnam 1995). Larson *et al.* (2007) present a diverse assortment of approximately 270 sources of information related to human factors that are relevant to wildland firefighting organizations and culture. While the effect of human decision-making on wildland firefighter entrapments is clear (see Putnam 1995), a detailed accounting of these effects is beyond the scope of the current project.

The current federal wildland fire policy stipulates that land management plans and fire management plans incorporate the best available science supplied by an active, interagency fire research program (Fire Executive Council 2009). Whilst fire management plans are written to reflect firefighter and public safety as the first priority, it is less apparent whether incident commanders and firefighters consult the best available science and information delivery systems when developing strategies and operational tactics. Human factors play a role in determining how firefighters incorporate and implement new research findings into operational decision-making. For example, Alexander *et al.* (2016) noted a gap in the understanding of how firefighters utilize various fire behavior prediction tools to assess escape routes and fire travel times. Although it is currently unclear if and how wildland firefighters incorporate new research findings into their standard operating procedures, an analysis of fire research outcomes by fire managers suggested that a lack of manager awareness was a barrier to successful application of science (Hunter 2016). Work from other disciplines also indicates that perceived usefulness, ease of use and the need to acquire additional skills are common barriers to successful integration (Farzandipur *et al.* 2016). Additional research is needed to fully identify the factors associated with successful dissemination of new research into the field.

Firefighter Entrapment Database

Objective 3 – Compile and synthesize available information

Data sources

Data from several US-based reporting and storage systems for entrapment-related wildland firefighter fatalities and injuries were compiled. The data sources comprise the five surveillance systems noted by Butler *et al.* (2017), which include databases maintained by the US Fire Administration, the National Fire Protection Association, the US Bureau of Labor Statistics, the National Institute for Occupational Safety and Health and the Risk Management Committee of the National Wildfire Coordinating Group (NWCG). Additional formal and informal storage systems reviewed included the Wildland Fire Lessons Learned Center Incident Review Database (Available at https://www.wildfirelessons.net/irdb [accessed 8 February 2019]) and the Always Remember! website (Available at https://wlfalwaysremember.org/ [accessed 8 February 2019]).

Database creation, storage and access

All existing data that could be acquired along with supplemental verbal and written responses from fire managers about specific incidents were merged into a database of firefighter entrapments, referred to as the Fire Sciences Lab Merged Entrapment Database (FiSL MED). The database has been made available online (see https://www.wfas.net/entrap/) (Figure 2) and includes information on the location, date and approximate time (GMT), number of personnel involved, the number of fatalities and location quality for entrapments with a burnover that have occurred within the Continental US since 1979 (Figure 3). Location quality is currently classified into 4 categories; Estimated – an estimated location based on the description provided in the entrapment investigation, Fire start location – the location of the origin of the fire with the entrapment, Good – actual entrapment location, and Unavailable – no known location information. The year 1979 marks the beginning of the availability of high quality gridded weather data (i.e. Abatzoglou 2013) and also coincides with the availability of other dynamic fire environment data such as fuel type information derived from Landsat imagery (e.g. Kourtz

1977). As of March 2019 the database contains 342 known entrapment incidents, of which 193 (56%) have accurate spatial locations, with the remaining entrapments currently limited to the reported location of the fire origin associated with the entrapment (32%), estimated based on written descriptions (8%) and those entrapments with no known location information (4%).

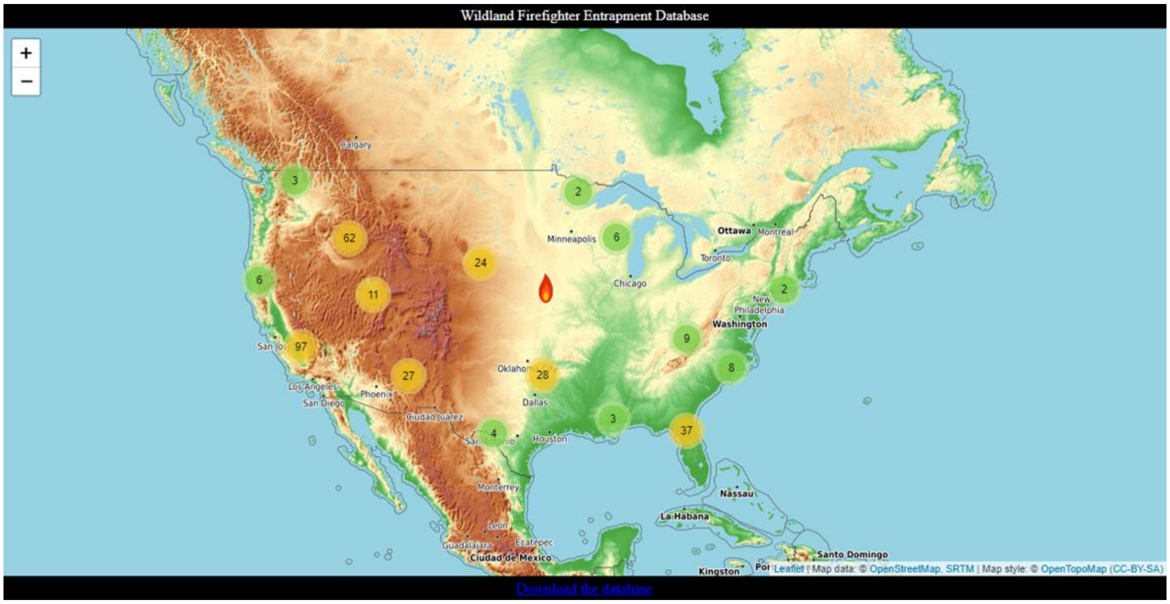

Figure 2. Screen shot of the online version of the Fire Sciences Lab Merged Entrapment Database, see https://www.wfas.net/entrap/.

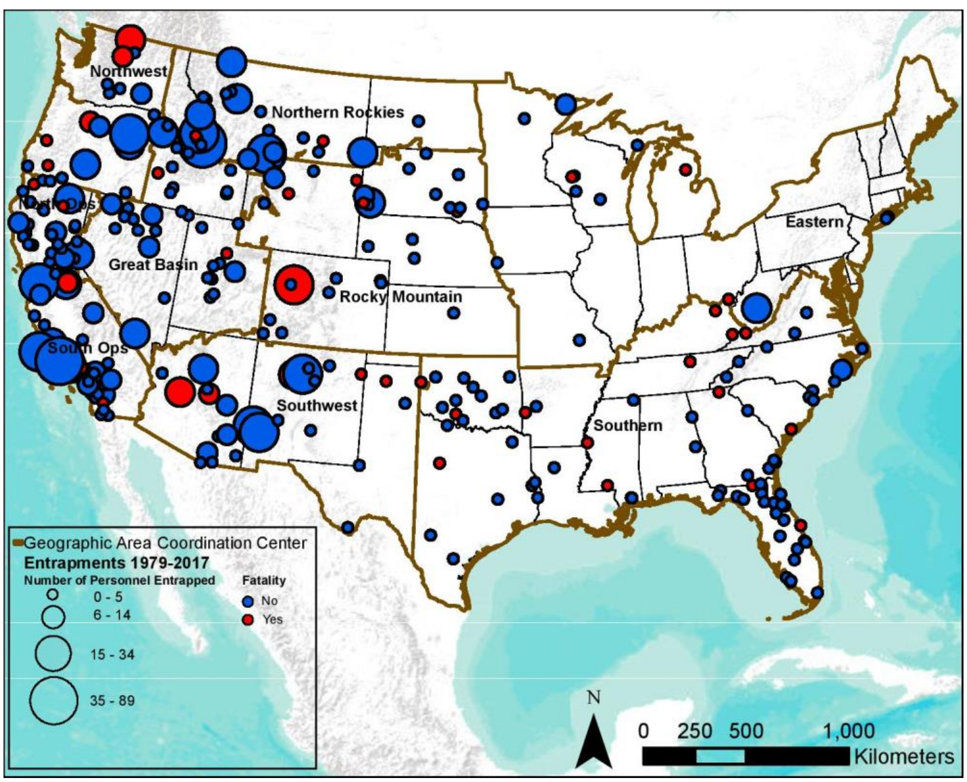

Figure 3. US wildland firefighter entrapments where there was a burnover, 1979-2017.

Key Findings

Objectives 2, 3 and 4 – Undertake comprehensive review, synthesize findings and assess knowledge gaps

Finding 1: Previous investigations of firefighter entrapment incidents have similar summaries and recommendations

With few exceptions, major systemic reviews have been initiated following either single fires or groups of fires that had entrapment-related fatalities (e.g. Moore *et al.* 1957; Bjornsen *et al.* 1967, Wilson 1977; NWCG 1980). Many of these reviews have formed the basis of training aids, guidelines and safety protocols (Table 1). Despite the fact that these training aides and guidelines summarize findings from dozens of fires where hundreds of firefighters were killed over a period of more than 60 years they contain much of the same content (Figure 4).

The similarities among the safety guidelines, protocols and entrapment investigation recommendations have been noted by others. Specifically, a task force established following a series of fatality fires in the late 1970s (NWCG 1980) recognized the repeating patterns in fatality investigation reports related to both the fire environment and the subsequent investigation recommendations. They noted that part of the problem was associated with "…incomplete implementation of previous studies' recommendations." More recently, others (e.g. Gabbert 2019) have continued to recognize that the recommendations contained within investigation reports are rarely unique and are often duplicates of previous findings.

Finding 2: The entrapment investigation process and existing data reporting/storage systems are flawed

Today, the typical document produced following entrapments on federally managed land is similar to a Facilitated Learning Analysis (USDA Forest Service 2016). These documents tend to have a long narrative format with little summary information. The lack of basic information (e.g. latitude and longitude, description of entrapment site) in these documents and the format in which they are presented (e.g. long paragraphs) makes it difficult to gather and objectively assess important factual information.

While many of the US agency-specific investigation guides do reinforce the importance of documenting the natural features at an entrapment site (Mangan 1995), it seems that in reality many of the details either fail to be measured/described or included in the final report. Page and Butler (*In press*) note that after reviewing over 200 entrapment investigation reports only a minority (~75) contained suitable information on both the fire environment (fuels, weather and topography) in/around the entrapment site and the size of the refuge area (i.e. physical dimensions) to adequately assess the influence of these factors on entrapment survivability. The failure to permanently record this important information represents a huge loss to current and future wildland firefighters.

Table 1. Common US wildland firefighter safety protocols, guidelines and their origins.

Guideline	Brief description	Source
Accident Check List for Forest Fire Fighters	A list of approximately 48 items under 11 categories submitted by the California Region of the US Forest Service to improve firefighter safety.	US Forest Service California Region (1954)
Standard Fire Orders	Ten standard orders to follow while engaged in wildland fire operations. Based on an analysis of 16 fires between 1937 and 1956 where 79 firefighters perished.	McArdle (1957)
Watch Out Situations (Standards for Survival)	Eighteen environmental and operational situations that warrant caution when engaged in wildland fire-related activities. The original list of 13 situations were developed sometime between 1967 and 1975.	Origin unclear, see Ziegler (2008)
Downhill Checklist	Specific requirements that must be in place prior to building fireline downhill. Based on an analysis of 3 fires where firefighters died while constructing downhill fireline.	Bjornsen *et al.* (1967)
Common Denominators of Fire Behavior on Tragedy Fires	Five common characteristics among 67 fires that had fatalities between 1926 and 1976.	Wilson (1977)
Common Denominators of Fire Behavior on Fatal and Near-fatal Fires	Four common characteristics among 67 fatal and 31 near-fatal fires between 1926 and 1976.	Wilson (1977)
Eight Firefighting Commandments	A list of 8 items to obey while engaged in fire suppression operations. Formulated based on the acronym WATCH OUT.	NWCG (1980)
Thirteen Prescribed Fire Situations that Shout Watch Out	A list of 13 items that warrant caution during prescribed fire operations.	Maupin (1981)
LCES	A system for operational safety, which emphasizes Lookout(s), Communication(s), Escape Routes and Safety Zone(s).	Gleason (1991)
Look Up, Look Down, Look Around	List of environmental indicators that may be indicative of the potential for extreme fire behavior.	NWCG (1992, 2018)
Fire Environment Size-up Model (Risk Management Process)	A 4 step model developed from the results of a survey of experienced wildland firefighters that can be used as a decision support system.	Cook (1995)
21st Century Common Denominators for Wildland Firefighter Fatalities	A list of the four major causes of firefighter fatalities between 1990 and 2006.	Mangan (2007)
Common Denominators on Tragedy Fires – Updated for a new Human Fire Environment	Eight human factors common to fires where there was a fatality. Developed with a focus on fatality fires that have occurred in the 21st century.	Holmstrom (2016)
Common Tactical Hazards	Ten items related to firefighting tactics that may affect firefighter safety.	NWCG (2018)

Figure 4. Visual representation of word and phrase frequency in the form of a word cloud based on the wildland firefighter guidelines and safety protocols listed in Table 1. Larger words occurred more frequently in the guidelines and those words with the same color occurred in similar proportions.

The current reporting and storage systems for data related to wildland firefighter entrapments also have several issues. Either by law or practice many of the systems store data related to the same incident, which is both inefficient and potentially confusing. As noted by Butler *et al.* (2017), some systems are required to track firefighter fatalities due to various legal statutes, while others may not include fatalities associated with some specific tasks and duties. Having multiple reporting systems with different inclusion criteria makes it difficult to assess the quality and completeness of the various datasets.

Two wildland fire-specific systems stand out as having the potential to fill the role as the primary repository for housing data related to entrapment injuries and fatalities, namely the NWCG Safety Grams and the Wildland Fire Lessons Learned Center Incident Review Database. In their current form each system has unique advantages and disadvantages that requires the use of both to gather and compile adequate temporal, spatial and physical information associated with each incident. For example, the NWCG Safety Grams do not provide specific details regarding the time, exact location or environmental conditions associated with the reported incidents. Conversely, the Incident Review Database does have links to reports that contain details associated with entrapment incidents, but older incidents tend to have little/no documentation and as noted above, much of the documentation is of poor quality and does not provide adequate factual information about the entrapment.

As of the writing of this report there is no one dataset that can be consulted which contains adequate information on the spatial location, time, and other specific information for wildland firefighter entrapments in the US. The FiSL MED represents an attempt to initiate such a database but a long-term plan to update and maintain the database is needed.

Finding 3: There is likely a substantial under-reporting of entrapment incidents

Firefighter entrapments include situations where fire moves through or overtakes personnel (i.e. a burnover) and where personnel avoid being overtaken by fire due to will or luck. In our assessment we focused the data collection and synthesis efforts on entrapments where there was a burnover. This was due to the likely significant under-reporting bias related to entrapments considered to be near misses or close calls. Strohmeyer *et al.* (2018) note that a stigma among firefighters tends to result in a resistance to label events as entrapments in order to avoid the attention and scrutiny that may follow. Additionally, prior to the late 1980s the existing firefighter entrapment databases seem to have a priority for storing information related to fatal firefighter entrapment incidents, rather than non-fatal burnovers and near-misses. Thus, there is likely a significant under-reporting bias for firefighter burnovers and near-misses prior to the late 1980s.

Although near-misses or close calls usually don't result in significant injuries, they still represent situations that can provide valuable insights into the conditions that result in rapid changes in fire behavior and how those changes affect firefighter safety. Much of the basic fire environment information relevant to entrapments that result in a burnover is also relevant to near-misses, with the primary difference being the lack of a specific entrapment location. In order to utilize the data associated with these incidents it is recommended that firefighters and fire managers report and investigate these incidents the same way they do incidents that resulted in a burnover. Extra details regarding the escape routes utilized would provide additional useful information.

Finding 4: The number of entrapment-related fatalities are decreasing but the number of entrapment incidents are not

To date the majority of reports summarizing firefighter entrapments in the US have only presented data related to the number of fatalities through time. All of these summaries have been at least partially based on the data compiled by the NWCG and stored by the National Interagency Fire Center. A compilation of this data is presented based upon the annual number of entrapment-related fatalities between 1926 and 2017 (Figure 5) and associated entrapment rates using the number of fires and area burned between 1992 and 2015 (Figure 6).

Similar to the findings provided in other published sources, there has been a downward trend in the annual number of entrapment-related fatalities since 1926 (Figure 5). Despite several peaks associated with high fatality events, the annual number of entrapment-related fatalities has been dropping by approximately 0.4 (6%) fatalities per decade, although the trend is only marginally significant (P-value = 0.157).

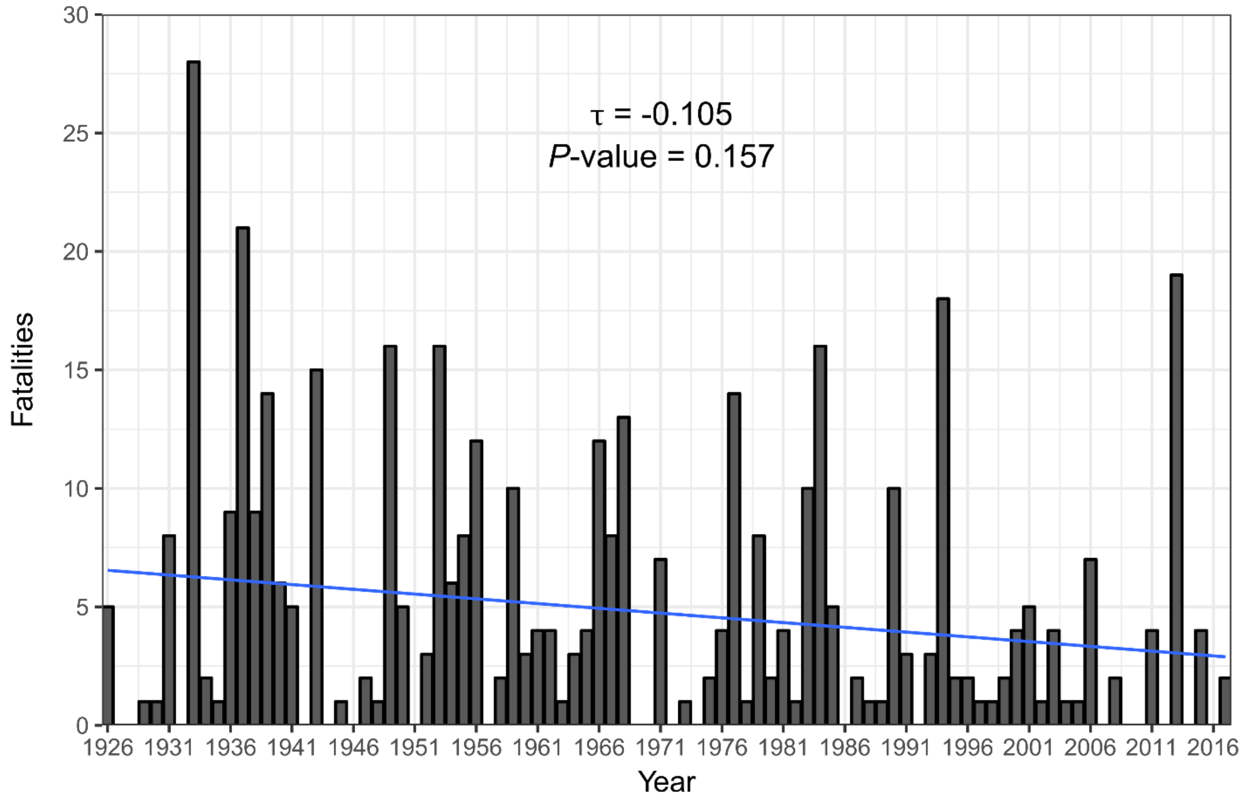

Figure 5. Entrapment-related wildland firefighter fatalities in the Continental US, 1926 to 2017. The nonparametric Mann-Kendall test (Mann 1945; Kendall 1975) was used to identify the presence of significant monotonic trends. The value τ represents the Kendall rank correlation coefficient, i.e. the strength of the relationship, with the corresponding probability that the trend does not exist (*P*-value). Data were compiled from National Interagency Fire Center (2018).

When the annual number of entrapment-related fatalities are viewed in relation to the annual number of fires and area burned additional trends can be inferred. Unfortunately, due to the lack of high quality data on US fire activity for all fire sizes prior to 1992 (Short 2015) the current analysis is limited to years with the best data, 1992 to 2015 (Figure 6; Short 2017). The analysis indicated that the highest fatality rate by area burned occurred in 2013 (~0.6 per 100 000 ac (40 469 ha) burned) due to the 19 fatalities on the Yarnell Hill Fire (YHFI Report 2013), with the lowest average rates found in the late 1990s and early 2000s. Since 1992 the average number of fatalities per 100 000 ac (40 469 ha) burned has decreased by approximately 0.01 (9%) per decade, which is marginally significant. However, the fatality rates based on the yearly number of fires shows little change with an average of about 0.5 fatalities per 10 000 fires or 1 fatality every 20 000 fires (Figure 6*a*). There has been a general decrease in the annual number of wildland fires in the US over the same time period, which accounts for the fatality rate remaining unchanged even though the total number of fatalities has been decreasing.

Those entrapments that occurred between 1987 and 2017 (i.e. 285) represent the period that encompasses the most overlap between existing entrapment databases. The data during this time period reveal that the total number of entrapment incidents, i.e. those with and without fatalities, have not been significantly declining during this period (Figure 7). However, there does seem to be a declining trend in the average number of personnel entrapped per incident, decreasing at a rate of approximately 0.8 people per decade, although the relationship was not statistically significant (Figure 7*b*). Although the absence of statistically significant upward trends in fatalities and entrapments is encouraging, the results of the trend analysis should not dissuade further understanding of the circumstances that lead to these rare and highly consequential events.

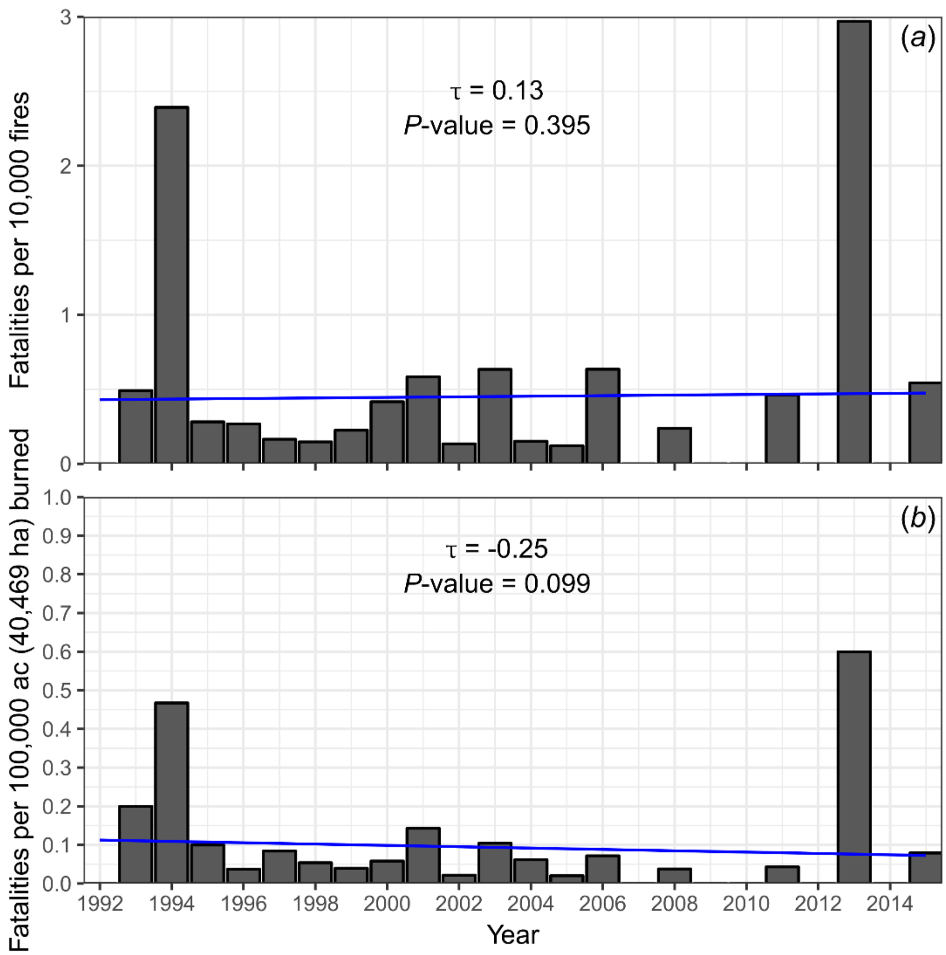

Figure 6. Entrapment-related wildland firefighter fatality rates in the Continental US from 1992 to 2015 by (*a*) the number of fatalities per 10 000 fires and (*b*) the number of fatalities per 100 000 ac (40 469 ha) burned. The nonparametric Mann-Kendall test (Mann 1945; Kendall 1975) was used to identify the presence of significant monotonic trends. The value τ represents the Kendall rank correlation coefficient, i.e. the strength of the relationship, with the corresponding probability that the trend does not exist (*P*-value). Data were compiled based on number of fires and area burned from Short (2017) and fatalities per year provided by the National Interagency Fire Center (2018).

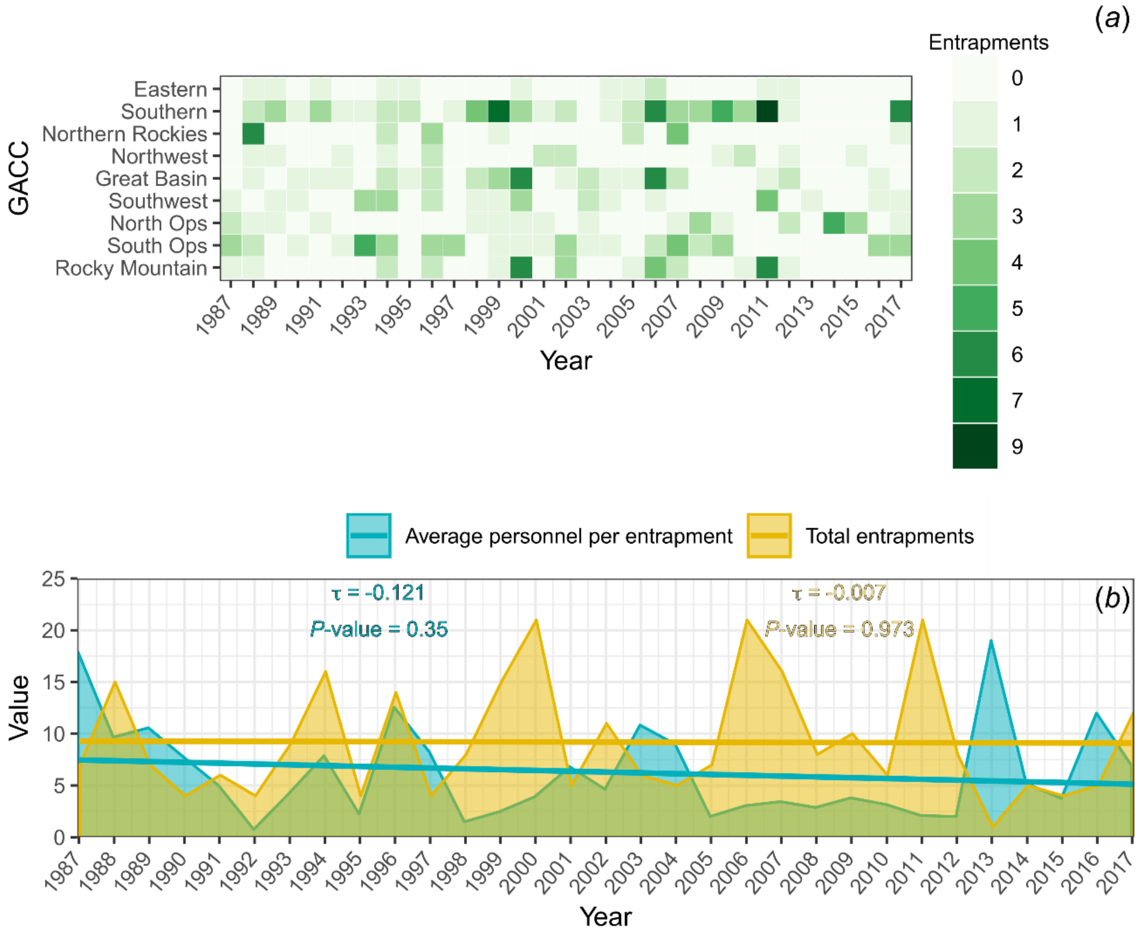

Figure 7. Trends in all firefighter entrapments (i.e. with and without a fatality) where there was a burnover in the Continental US between 1987 and 2017 by; (*a*) Geographic Area Coordination Center (GACC) and (*b*) the total number of entrapment incidents and the average number of personnel per entrapment incident. Note that North Ops and South Ops in (*a*) represents Northern and Southern California, respectively. The nonparametric Mann-Kendall test (Mann 1945; Kendall 1975) was used to identify the presence of significant monotonic trends. The value τ represents the Kendall rank correlation coefficient, i.e. the strength of the relationship, with the corresponding probability that the trend does not exist (*P*-value). The boundaries of the GACCs are shown in Figure 3.

Finding 5: Factual information from previous entrapments can be used to predict/project future entrapment hazard and risk

In addition to consulting the firefighter safety protocols and guidelines (Table 1), we suggest that firefighters could benefit from access to maps that identify the environmental conditions common to previous entrapments. Characterizing the environmental conditions at the location and time of an entrapment allows the development of relationships that can be used to predict entrapment potential across space and through time (Figure 8). For example, spatially-explicit data on both static (i.e. fuels and topography) and dynamic variables (i.e. fire weather) during previous entrapments could be used with statistical models to produce maps that depict the locations and times when entrapment potential is high. Figure 9 illustrates an example application using two methods of modelling entrapment potential for an area around a firefighter fatality that occurred during the Thomas Fire on December 14, 2017 in Southern California (California Department of Forestry & Fire Protection 2017).

According to the first method based on several fuel and topographic characteristics described by Page and Butler (2018), the Thomas Fire entrapment occurred within one of the most dangerous watersheds (Boulder Creek-Sespe Creek) for firefighters in Southern California, with only 3% of other similar watersheds being ranked as more dangerous (Figure 9*a*). Likewise, according to the second method based on an analysis using rare-event logistic regression (Imai *et al.* 2008) with the compiled entrapment data and predictor variables of fire weather and slope steepness, much of the area in and around the entrapment location had high potential for an entrapment (Figure 9*b*). Similar methods and outputs may eventually be useful sources of information for wildland firefighters as they refine situational awareness before and during fire suppression operations.

In addition to near real time applications, models capable of mapping entrapment potential based on environmental conditions could be used to reconstruct or forecast long-term changes across the landscape or over time. For example, a daily gridded climatology and a dynamic fuels map could be overlaid with a digital elevation model (DEM) to quantify the expansion or contraction of entrapment potential both seasonally and over the course of several decades. Entrapment potential could then be used to quantify spatial and temporal trends in firefighter exposure, and area-wide summaries of entrapment potential could possibly be used as an alternative to the number of fires or burned area as a means of normalizing fatality and entrapment rates. Regardless of the application, it is important to reiterate that the goal of any such model would be to identify the environmental conditions most similar to those found at the locations and times of previous entrapments. At the cost of reducing the sample size, creating separate models using subsets of the full entrapment database could reveal regional and/or temporal variations in the environmental conditions surrounding the entrapments. Moreover, it must be recognized that combinations of environmental conditions that support rapid accelerations towards extreme fire behavior will not be identified as "dangerous" if an entrapment was never recorded under those conditions. Shifts in firefighting strategies and tactics into fire environments capable of supporting extreme fire behavior but where an entrapment was never recorded will challenge this empirical modelling approach.

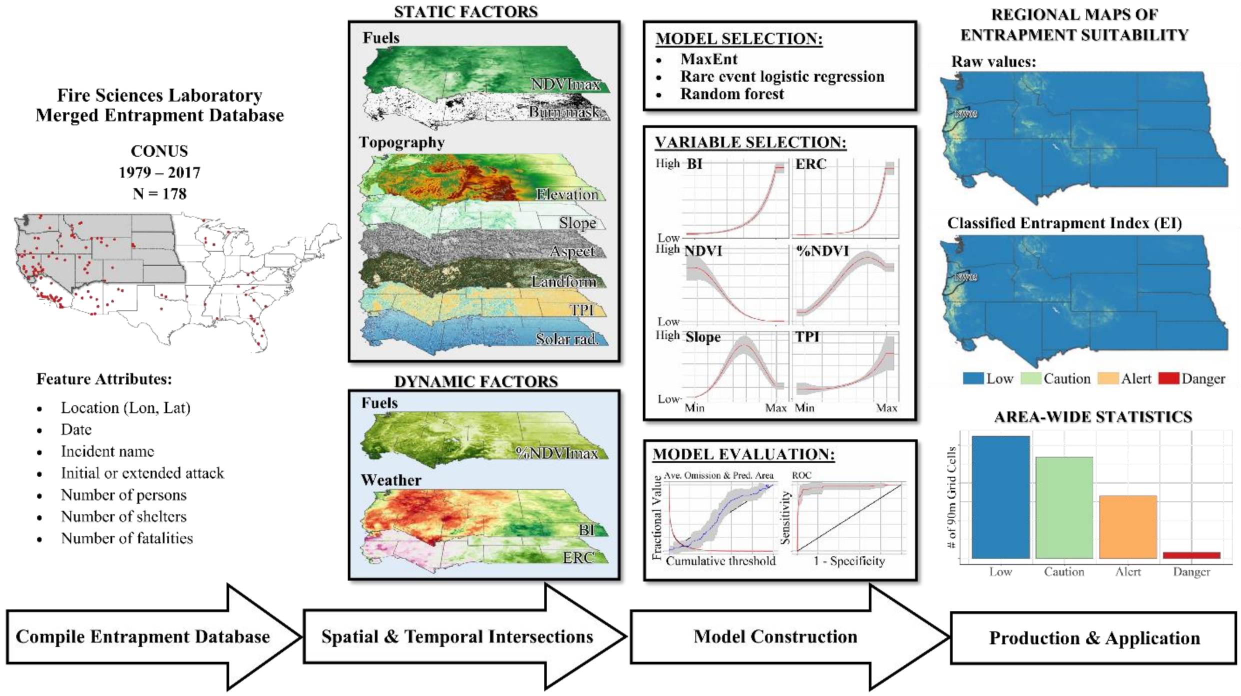

Figure 8. Schematic representation of an example process to assess and predict firefighter entrapment potential across space and through time. Important environmental data gathered at previous entrapment locations is coupled with statistical models to derive relationships that can be used to predict future entrapment potential.

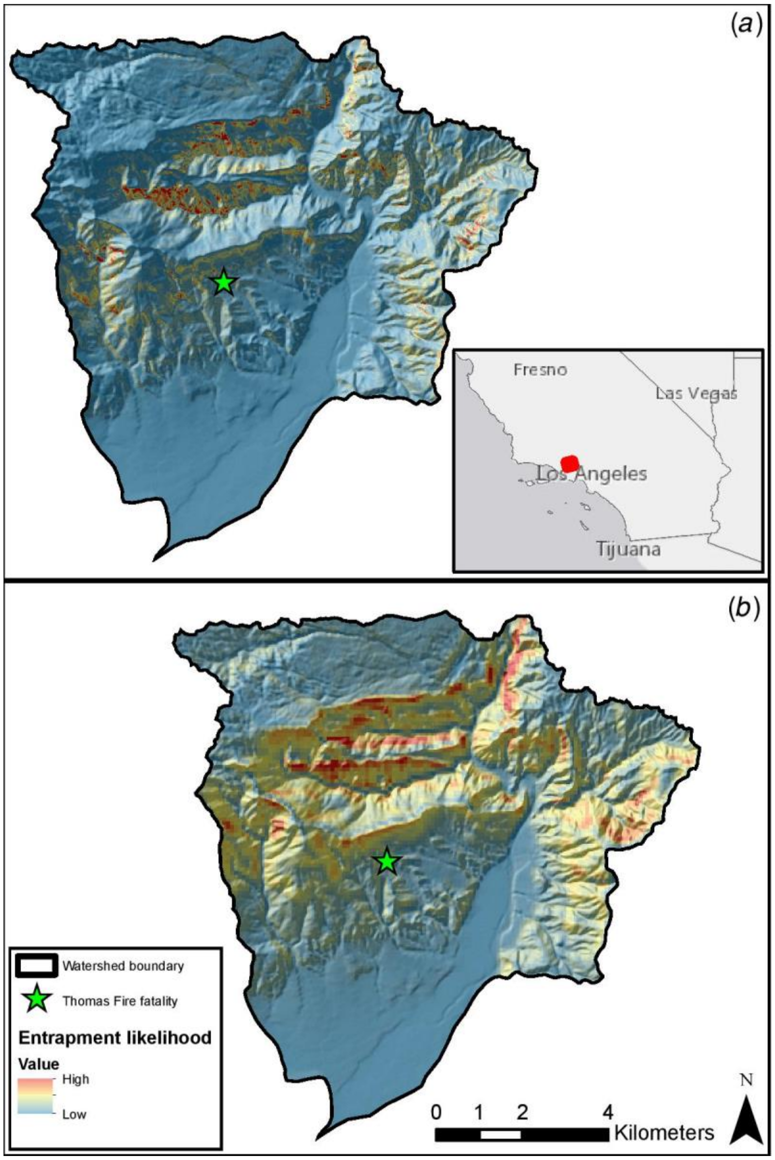

Figure 9. Two methods for predicting the likelihood of an entrapment on December 14, 2017 near the location of the Thomas Fire fatality within the boundaries of the Boulder Creek-Sespe Creek watershed in Southern California. Predictions are based on; (*a*) the maximum entropy methods for several fuel and topographic factors as described by Page and Butler (2018) and (*b*) logistic regression using fire weather (Energy Release Component and Burning Index) and slope steepness from the merged fire occurrence and entrapment database.

Research Needs

Objective 5 – Recommendations

The subject of wildland firefighter safety is complex with aspects of the physical and biological sciences as well as psychology (individuals) and sociology (cultures). Achieving significant progress towards developing solutions that will improve firefighter safety requires a coordinated multi-year, multi-project approach. Implementing such a complex program of work necessitates the identification of specific research objectives that are complimentary and build on each other through time. Given the current state of wildland fire science and management, defining those objectives will be difficult as it is currently unclear what the desired end-state or outcomes are of the various stakeholders, i.e. firefighters, fire managers, land managers and the public. It is reasonable to suspect that all stakeholders would want to minimize the dangers posed to wildland firefighters and eliminate firefighter deaths and injuries, but it is not clear what tradeoffs are associated with the inevitable shift in risk to other values that would need to occur in order to make that a reality.

This project provided an initial scientific assessment of the problem of wildland firefighter safety through the lens of firefighter entrapments. Therefore, this work should be considered only a part of a larger discussion of future research priorities associated with firefighter safety. The assessment discussed by Page *et al.* (*In review*) concluded that firefighter entrapments continue to occur in part due to the inability of firefighters to anticipate rapid increases in fire behavior that are caused by changes in the fire environment that happen over small spatial and temporal scales. To address this issue we developed a list of several items that should be investigated to enhance both fundamental knowledge and the tools used to disseminate that knowledge to improve wildland firefighter situational awareness.

Inadequate knowledge

With regards to the prediction of extreme fire behavior, we echo the research needs presented by Werth *et al.* (2011, 2016), which include a better understanding of plume dynamics and its effects on spotting, improvements in measuring and representing complex fuel structure, more observations of windflow in complex terrain to improve or create better wind models, an understanding of how ambient winds and topography affect fire interactions and additional research to quantify the effects of atmospheric stability on fire behavior. We also acknowledge the recommendations by Butler (2015) who suggested that additional research is needed to address; (1) how convective energy affects safety zone size, (2) how clothing affects the likelihood of burn injury, (3) better information on travel rates over complex terrain, (4) methods to integrate escape route travel times into safety zone assessments, (5) a better understanding of the effectiveness of bodies of water as safety zones, (6) knowledge as to how firefighters can determine if an area is survivable and (7) methods firefighters can use to apply safety zone standards.

Additional knowledge gaps that were found to be important in this review were:

- A better identification of the environmental factors that lead to rapid increases in fire behavior including important interactions and their relative influences.
- The development of fire behavior models capable of anticipating the times and locations where rapid increases in spread rate and intensity are possible.
- Methods for improving crew situational awareness regarding changes in weather, fire location and the best available escape routes.
- And, improved NWP models and weather forecasts that provide high resolution, spatially-explicit information on the timing and influence of thunderstorms and other high-wind events on near-surface wind speed and direction. Ideally, forecasts should have lead times of at least 12-16 h so that incident plans could be altered before the start of an operational period.

Inadequate tools

Several issues regarding the inadequacy of the current set of tools for anticipating or identifying the conditions that affect entrapment potential were identified based on an analysis of needs related to four of the standard firefighting orders that directly relate to the environmental and fire behavior factors commonly associated with entrapments (Table 2). A complete catalog of these tools including their purpose, spatial and temporal resolutions, and operating platforms can be found in Page *et al.* (*In Review*).

Generally, the assessment in Table 2 suggests that in addition to better information on how firefighters utilize or do not utilize fire behavior prediction tools, including preferences on capabilities, format and organization, future tools should:

- Provide updated fire environment information, including fire position, at hourly or sub-hourly intervals (i.e. near real-time) so that firefighters can better anticipate the changes that lead to extreme fire behavior (Wall *et al.* 2018).
- And, have the ability to merge the updated information with firefighter/equipment locations in relation to safety zones and escape routes, in order to develop a comprehensive system similar to the one proposed by Gabbert (2013), i.e. the “Holy Grail of Firefighter Safety”.

Table 2. Some of the current tools and their limitations related to 4 of the standard firefighting orders.

1. Keep informed on fire weather conditions and forecasts.	
Current tools	A whole suite of websites and mobile applications currently provide information on the various weather, fire danger, and climate variables that are important for assessing fire behavior potential (see Page *et al. In review*).
Limitations	Few have the ability to provide a comprehensive set of weather-related information at the spatial and temporal scales most relevant to wildland firefighters.
2. Know what your fire is doing at all times.	
Current tools	Various platforms can provide information on fire position based on satellite detections (https://firms.modaps.eosdis.nasa.gov/map/#z:3;c:0.0,0.0;d:2019-04-03..2019-04-04), infrared interpretation (https://www.nifc.gov/NIICD/infrared/phoenix_capabilities.html), and locally near real-time with drones or infrared cameras in aircraft.
Limitations	Very few of these technologies can provide near real-time information on fire position. Those that can are usually limited by aircraft restrictions and the ability to conveniently transfer and display the data to firefighters.
3. Base all actions on current and expected behavior of the fire.	
Current tools	Numerous fire behavior prediction tools are available to predict fire behavior. Some have also been distilled into tabular, graphical or mobile application formats (see Page *et al. In Review*).
Limitations	Many fire behavior models cannot currently run faster than real-time and rapidly incorporate updated fire environment information in a field setting.
4. Identify escape routes and safety zones and make them known.	
Current tools	Some guidelines currently exist to aid in the identification of escape routes and safety zones (NWCG 2018). A new mobile web application (https://wise.wildfireanalyst.com/) can provide site specific information on safety zone size.
Limitations	There are not currently any tools available that can provide real-time, site specific information on escape route effectiveness in a field setting.

Improved data collection and storage

In order to continue improving our knowledge of the factors that affect firefighter entrapments and produce better quality tools, a centralized data repository that contains updated information on the details associated with past incidents is needed. Although several storage systems already exist, each of these have significant shortcomings.

We have presented a database recently compiled by the authors that provides many of the details that have been excluded from previous storage systems. It is hoped that a similar database could be maintained and updated in a central location so that other researchers could access the data. Besides the information technology required to support such a system, we have identified additional data collection and quality issues that are needed to fully capture the details of each entrapment incident. Specifically, an unacceptably high proportion of investigative type documents and reports of firefighter entrapments either fail to include or fail to adequately summarize the relevant environmental factors associated with each incident. In order to facilitate data collection and storage we recommend that future entrapment investigations explicitly include summaries containing information on all of the relevant fire environment factors in a non-narrative format (Table 3).

Table 3. Recommended minimum data collection and reporting standards for the relevant fire environment variables associated with firefighter entrapments that involve a burnover or are considered a near-miss. It is suggested that the measurements be made at or immediately adjacent to the burnover location. The measurement location for a near-miss may not be obvious, so best judgement is recommended.

Factor	Comments
Fuels	
Fuel type	Fuel type should be reported based on the 6 broad categories described by Scott and Burgan (2005). If live fuels are involved, provide a brief description of the species and any unique characteristics (e.g. dead material in crown or fuel age).
Fuel height	Estimated height of vegetation that was burning in or immediately adjacent to the entrapment area.
Dead fuel moisture	Estimated or measured moisture content of dead surface fuels, preferably reported as % of oven-dry weight. Include estimates for all applicable size classes (i.e. fine fuels or larger).
Live fuel moisture	Estimated or measured live fuel moisture content, preferably reported as % of oven-dry weight.
How fuel variables were assessed	Description of methods used to estimate or measure the reported fuel characteristics.
Weather	
Temperature	Estimated or recorded air temperature at/near entrapment site prior to the burnover. The value should reflect the air temperature that is not influenced by the fire and should be reported at a time that is as close to the entrapment time as feasible.
Relative humidity	Estimated or recorded relative humidity at/near entrapment site prior to the burnover. The value should reflect the relative humidity that is not influenced by the fire and should be reported at a time that is as close to the entrapment time as feasible.
Wind speed	Temporally averaged wind speed that was recorded or estimated at/near entrapment site prior to burnover. Include averaging period (i.e. 5 or 10 min) and applicable reference height and exposure (e.g. in-stand eye-level or 6 m open). Measurement should be free of influence from the fire. See Andrews (2012) for an in-depth discussion. Note any changes in wind speed during the preceding 1 to 2 hours before the entrapment.
Wind direction	Temporally averaged wind direction that was recorded or estimated at/near entrapment site prior to burnover. Include averaging period (i.e. 5 or 10 min) and applicable reference height and exposure (i.e. eye-level or 6 m). Measurement should be free of influence from the fire. See Andrews (2012) for an in-depth discussion. Note any changes in wind direction during the preceding 1 to 2 hours before the entrapment.
Measurement source/quality	Description of methods used to estimate or measure the weather characteristics, including models or websites used and weather station location and name.
Topography	

Slope steepness	Slope steepness at the entrapment site and measurement method. Consider reporting slope steepness measured upwind from the entrapment site if it is significantly different.
Terrain description	Provide brief description of the dominate terrain characteristics around the entrapment location, including descriptions of terrain shape (e.g. canyons).
Refuge area	
Location	Provide latitude and longitude of entrapment location(s) as reported by a Global Positioning System.
Physical dimensions	Include a sketch or diagram of the entrapment area that contains locations of personnel and equipment as well as distances from terrain and vegetation features.
Separation distance between firefighters and flame zone	Distance between firefighters and flame zone during the burnover.
Escape route(s)	
Travel route(s) of firefighters	Travel route followed by firefighters from work area to entrapment area. Preferably shown on a map or as a GPS track with photos of trail quality.
Fire behavior	
Rate of spread	Observed or estimated spread rate of fire before and during the entrapment. Note any significant temporal variation in the 1-2 h before entrapment.
Flame length / height	Observed or estimated flame characteristics before and during the entrapment. Note any significant temporal variation in the 1-2 h before entrapment.
General fire behavior	General notes on fire behavior including fire type (surface versus crown fire), spotting activity and any significant temporal variations leading up to the entrapment. Provide photos and video footage of fire behavior with time stamps whenever possible.
How estimates were obtained	Details associated with how fire behavior estimates were either measured or modelled. If fire behavior was measured, include appropriate details.
Other	
Approximate date and time of burnover	Date and time that the entrapment occurred, including time zone.
Safety Zones	Locations of any planned safety zones, particularly in relation to the escape route utilized.
Fire size	Estimated fire size at the time of entrapment.
Equipment involved	Description of any equipment involved and their location within the entrapment area. Include details associated with the use of the equipment as a shield or accessories such as fire curtains.
Photographic evidence	Photographs and video footage of the entrapment location. Consider the use of high resolution ground or aerial-based laser ranging (LIDAR) equipment to capture 3-D point clouds of entrapment location and surrounding area; see Loudermilk *et al.* (2009) for examples.

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Appendix B: List of Products

Online firefighter entrapment database (1979-2018)

See https://www.wfas.net/entrap/.

Articles in peer-reviewed journals

Jolly WM, Freeborn PH, Page WG, Butler BW. A wildfire early warning system to reduce wildland firefighter and community risk during extreme wildfire events. (manuscript in preparation)

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Other published materials

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