CSIRO PUBLISHING

International Journal of Wildland Fire **2019**, *28*, 551–569
https://doi.org/10.1071/WF19022

Review

A review of US wildland firefighter entrapments: trends, important environmental factors and research needs

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Abstract. Wildland firefighters in the United States are exposed to a variety of hazards while performing their jobs. Although vehicle accidents and aircraft mishaps claim the most lives, situations where firefighters are caught in a life-threatening, fire behaviour-related event (i.e. an entrapment) constitute a considerable danger because each instance can affect many individuals. In an attempt to advance our understanding of the causes of firefighter entrapments, a review of the pertinent literature and a synthesis of existing data were undertaken. Examination of the historical literature indicated that entrapment potential peaks when fire behaviour rapidly deviates from an assumed trajectory, becomes extreme and compromises the use of escape routes, safety zones or both. Additionally, despite the numerous safety guidelines that have been developed as a result of analysing past entrapments, we found issues with the way factual information from these incidents is reported, recorded and stored that make quantitative investigations difficult. To address this, a fire entrapment database was assembled that revealed when details about the location and time of entrapments are included in analyses, it becomes possible to ascertain trends in space and time and assess the relative influence of various environmental variables on the likelihood of an entrapment. Several research needs were also identified, which highlight the necessity for improvements in both fundamental knowledge and the tools used to disseminate that knowledge.

Additional keywords: burnover, entrapment data, entrapment investigation, fire behaviour, fire environment, firefighter fatalities.

Received 16 February 2019, accepted 21 May 2019, published online 25 June 2019

Introduction

Wildland firefighters in the United States (US) are employed primarily by federal, state and tribal land-management agencies to provide a safe and effective response to unplanned wildland fire ignitions (USDI, USDA 2014). Firefighters are typically arranged into crews and teams based on the type of specialised training they receive, including handcrews, engines, helitack and smokejumpers, and can be deployed both locally and nationally across 10 geographic areas through a dispatch system operated by the National Interagency Coordination Center (available at https://www.nifc.gov/nicc/ (accessed 23 April 2019)). Although current US fire policy allows a flexible response to wildland fires, the majority of fires are fully suppressed despite positive feedbacks between future wildfire risk and suppression response – often referred to as the wildfire paradox (Silva *et al.* 2010; Calkin *et al.* 2014, 2015). These positive feedbacks place increased demand on firefighters to respond to and engage with an ever-increasing number of large wildfires (Calkin *et al.* 2005; Nagy *et al.* 2018).

The link between firefighter safety and an understanding of fire behaviour has been conveyed by several firefighters and fire researchers. For example, Barrows (1951) described the need for a working knowledge of fire behaviour so that firefighters can anticipate changes and thereby reduce risk. Moore *et al.* (1957) recommended the development of fire behaviour experts in order to better identify indicators of change that precede unusual or unexpected fire behaviour. Likewise, Bjornsen *et al.* (1967) argued for a special emphasis on research to understand the causes of blow-up or erratic fire behaviour. These early analyses recognised the threat to firefighter safety posed by unexpected changes in fire behaviour based on the identification of common characteristics among fires that had a fatality. Learning from past firefighter fatalities is a goal of the wildland fire community (e.g. TriData Corporation 1998) and has been employed on numerous occasions to improve firefighter safety, primarily through the development of guidelines or checklists (Ziegler 2007; Alexander and Thorburn 2015).

When firefighters are affected by a life-threatening, fire behaviour-related event, an entrapment has occurred (National Wildfire Coordinating Group 2014; Page and Freeborn 2019). These events mark specific points in time and space that are both unique and rare. The rarity of entrapments is likely related to the fact that during fires with mild fire behaviour (i.e. low rates of spread), firefighters usually have sufficient time to react to unanticipated changes and adjust their position, tactics or strategy. Typically, only during the infrequent alignment of fire environment conditions that promote high rates of spread (i.e. extreme fire behaviour) and large fire growth (Strauss *et al.* 1989; Andrews *et al.* 2003) do firefighters lack the time required to adapt or escape, potentially owing to a combination of the unexpected nature of the increase in fire behaviour (Moore *et al.* 1957; Bjornsen *et al.* 1967; Bishop 2007) and the inability to quickly utilise escape routes (Beighley 1995; Fryer *et al.* 2013). Therefore, detailed analysis of the circumstances and factors that influence the likelihood of an entrapment will presumably reveal important information about the conditions under which extreme fire behaviour develops as well as insights into how firefighters can anticipate their occurrence. Recent reviews by Werth *et al.* (2011, 2016) provide details about the individual elements of the fire environment that contribute to extreme fire behaviour.

Here, we review the literature on the subject of firefighter safety with a focus on the research and data related to US wildland firefighter entrapments. We follow the entrapment definition described by Page and Freeborn (2019) and focus the discussion and analysis on entrapments where there was a burnover that may or may not have involved a fatality. Although there has been significant and increasing emphasis on how human factors are linked to firefighter safety, the present review mainly contains reference to the literature that discusses how various environmental factors affect the likelihood of an entrapment. The specific topics discussed include:

1. A summary of the findings from important historical reviews associated with past firefighter entrapments that produced several key safety guidelines and protocols,
2. A discussion of previously identified environmental characteristics commonly associated with firefighter entrapments,
3. A critique of the entrapment investigation process, including how the relevant findings and data are reported and stored,
4. Current spatial and temporal trends of entrapment incidents based on a newly compiled firefighter entrapment database, with a brief analysis of some important environmental factors that affect entrapment potential and how to use that information to predict or project future entrapment hazard, and
5. A summary of research needs to improve knowledge, tool development and data collection and storage procedures.

The ultimate goal of the review is to provide a synthesis of the relevant US-focused literature in order to identify the research needed to fill critical gaps in data collection, data storage and accessibility, technological capacity and fire behaviour knowledge to improve firefighter safety.

Literature review

Important historical reviews

With few exceptions, major systemic reviews have been initiated following either single fires or groups of fires that had a high number of firefighter fatalities. Some of these reviews produced recommendations that have led to changes in operations and training (Moore *et al.* 1957; Bjornsen *et al.* 1967) and policy (USDA, USDI 1995) as well as culture (TriData Corporation 1996, 1997, 1998). Additionally, many of the analyses have formed the basis of several training aids, guidelines and safety protocols (Table 1), which generally have similar word content (Fig. 1). An appreciation of these historical reviews and their impact on wildland firefighter safety provides both context to the current discussion and an understanding of their limitations. Note that the descriptions of the historical reviews in the following paragraphs only reference a subset of the guidelines and protocols listed in Table 1. For more detailed information, readers are encouraged to consult the source reference for each guideline and protocol listed.

In 1957, the US Forest Service released a report (i.e. Moore *et al.* 1957) detailing recommendations to reduce the likelihood of wildland firefighter fatalities based on an analysis of 16 entrapment incidents that occurred between 1937 and 1956. The fires analysed included some well-known incidents, including the Blackwater (Brown 1937), Mann Gulch (Rothermel 1993), Rattlesnake (Cliff *et al.* 1953) and Inaja fires (USDA Forest Service 1957). Moore *et al.* (1957) noted that among the fatality fires, the 'blow-up' or erratic fire behaviour observed before the entrapment was unexpected by those entrapped and occurred in flashy fuels when the fire danger was critical. Within this context, flashy fuels are considered to be the fine (i.e. diameter <6 mm), highly combustible fuels that readily ignite when dry (National Wildfire Coordinating Group 2014). Their analysis also identified 11 contributing factors that were similar among the fires, which were summarised into the 10 standard firefighting orders (McArdle 1957). The fire orders were adopted by the US Forest Service and have since become an integral part of wildland firefighter training and standard operating procedures. The format and specific content of the fire orders have changed slightly over time but they are currently organised into three groups based on their importance: a fire behaviour group, a fireline safety group and an organisational control group (Ziegler 2007).

Following the 12 firefighter fatalities in 1966 on the Loop Fire in southern California (Countryman *et al.* 1968), another set of recommendations to improve firefighter safety was provided by Bjornsen *et al.* (1967). A list of 13 principal factors common among eight major fatality fires was compiled, which had substantial similarities to the list provided by Moore *et al.* (1957). Bjornsen *et al.* (1967) suggested that the majority of fatalities were related to an unexpected increase in fire behaviour associated with flashy fuels, critical fire danger and specific topographic configurations called 'chimneys'. Unique among the items in the list developed by Bjornsen *et al.* (1967) was the recognition of the dangers associated with downhill line construction. Five recommendations on how to correctly locate and construct downhill fireline were provided based on an analysis of three of the fatality fires (Inaja, Silver Creek and Loop Fires), which are still in use today (National Wildfire Coordinating Group 2018).

Another analysis of fires between 1926 and 1976 where 222 perished was used to develop five common denominators on fatality fires and four common denominators on fatal and near-fatal fires (Wilson 1977). The denominators of fire behaviour on fatal and near-fatal fires indicate that the most dangerous conditions occur: (1) on small fires or quiet areas of large fires; (2) in light fuels; (3) when there is an unexpected shift in wind speed and direction; and (4) when fire runs uphill.

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 ~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 was developed sometime between 1967 and 1975	Origin unclear, see Ziegler (2008)
Downhill Checklist	Specific requirements that must be in place before building fireline downhill. Based on an analysis of three fires that occurred between 1956 and 1966 where firefighters died while constructing fireline downhill	Bjornsen *et al.* (1967)
Common Denominators of Fire Behaviour on Tragedy Fires	Five common characteristics among 67 fires that had fatalities between 1926 and 1976	Wilson (1977)
Common Denominators of Fire Behaviour on Fatal and Near-fatal Fires	Four common characteristics among 67 fatal and 31 near-fatal fires that occurred between 1926 and 1976	Wilson (1977)
Eight Firefighting Commandments	A list of eight items to obey while engaged in fire suppression operations. Formulated based on the acronym WATCH OUT	National Wildfire Coordinating Group (1980)
Thirteen Prescribed Fire Situations that Shout Watch Out	A list of 13 items that warrant caution during prescribed fire operation	Maupin (1981)
LCES	A system for operational safety, which emphasises Lookout(s), Communication(s), Escape Routes and Safety Zone(s)	Gleason (1991)
Look Up, Look Down, Look Around	List of environmental factors that may be indicative of the potential for extreme fire behaviour	National Wildfire Coordinating Group (1992, 2018)
Fire Environment Size-up Model (Risk Management Process)	A four-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	National Wildfire Coordinating Group (2018)

These common denominators are frequently discussed in firefighter training and are included in field guides that are meant for personnel who engage in fireline duties (e.g. National Wildfire Coordinating Group 2018). Similarly, Mangan (2007) proposed four new common denominators based on his analysis of firefighter fatalities between 1990 and 2006, which include several non-entrapment-related factors associated with aircraft and vehicle accidents as well as personal fitness.

Again, following a series of fatality fires in the late 1970s, the National Wildfire Coordinating Group established a task force to identify potential commonalities (National Wildfire Coordinating Group 1980). The task force recognised the repeating pattern of similarities among fatality fires and noted that part of the problem was associated with '…incomplete implementation of previous studies' recommendations'. They suggested that closely monitoring local weather and transmitting that information to line personnel should reduce uncertainty and the risk of entrapment. One interesting finding was the explicit recognition that wildland firefighting should not involve the exposure of firefighters to life-threatening situations.

Despite the widespread use of guidelines produced by distilling the commonalties among past fatality fires, there has been some critical discussion in regards to the way in which they have been presented (Steele and Krebs 2000; Braun *et al.* 2001; Brauneis 2002) and their current relevance (Holmstrom 2016). Some firefighters and fire researchers have suggested that simplifying much of the information presented in these guidelines could refocus attention onto what personal experience has shown to be the most important elements. For example, Gleason (1991) proposed adopting a system for operational safety that focused on four key elements, namely Lookout(s), Communication(s), Escape Routes and Safety Zone(s) (i.e. LCES). Additionally, Alexander and Thorburn (2015) suggested the addition of an 'A' for Anchor point(s), leading to the acronym LACES in order to reinforce the importance of an anchor point(s) on minimising the possibility of an entrapment. Furthermore, Putnam (2002) proposed a new set of 10 standard fire orders based on personal experience and a psychological analysis that emphasised situational awareness, taking action, re-evaluation, knowing when to disengage and accountability.

Fig. 1. Visual representation of word and phrase frequency in the form of a word cloud based on the text that makes up the wildland firefighter guidelines and safety protocols listed in Table 1 (excluding the guideline titles). Larger words occurred more frequently and those words with the same colour occurred in similar proportions. The *wordcloud* package in *R* (R Core Team 2015; Fellows 2018) was used to construct the word cloud after removing common words such as 'the' and 'we'.

Common environmental characteristics

The examination of the historical reviews revealed that those elements of the fire environment that can change quickly across space or through time and lead to rapid increases in fire behaviour, sometimes referred to as 'blow-up' (Arnold and Buck 1954) or 'eruptive' (Viegas 2006) fire behaviour, are particularly important to firefighter safety. Although each entrapment incident has unique elements, they usually share some common environmental characteristics, including light flashy fuels in brush or grass fuel types, changes in wind speed and/or direction and steep slopes in complex topography (Fig. 2; Wilson 1977; Bishop 2007). A significant amount of research has described either the direct importance of these elements on firefighter safety or their indirect effects on fire behaviour. A brief summary of findings from mainly US-based research is described below.

Fuel types composed primarily of vertically oriented small-diameter fine fuels (i.e. light fuels) such as grass or brush are known to be highly flammable and susceptible to rapid increases in spread rate and intensity (Countryman 1974; Saura-Mas *et al.* 2010; Simpson *et al.* 2016). Both empirical evidence (Cheney *et al.* 1993; Cheney and Gould 1995) and mathematical models (Rothermel 1972; Viegas 2006) indicate that rapid increases in spread rate and intensity are possible in light fuels owing to their high surface area-to-volume ratios and fuelbed porosity (e.g. Countryman and Philpot 1970), which decreases drying time

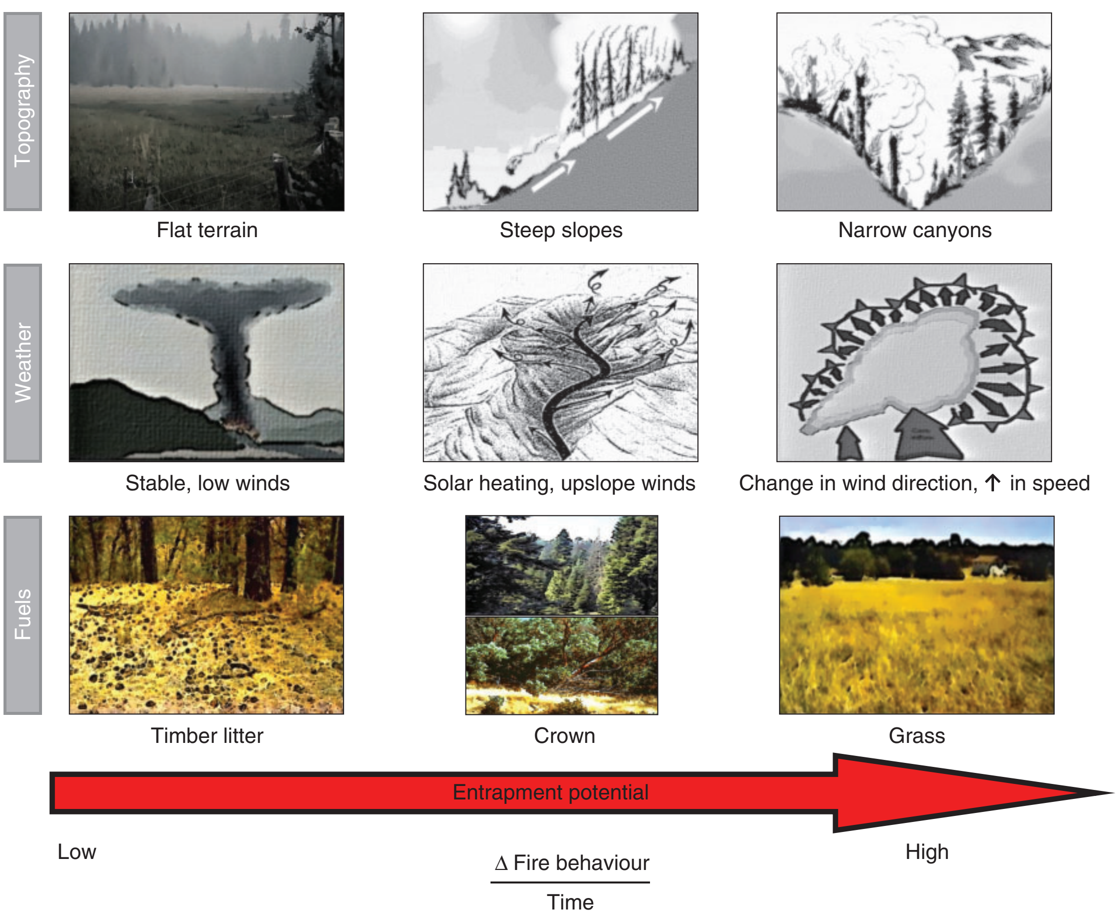

Fig. 2. Example characteristics of the fire environment (top to bottom) that promotes rapid changes in fire behaviour (left to right).

and increases the rate of burning relative to larger-diameter 'heavy' fuels (Byram 1959). Additionally, changes in fuel type that occur over space can, owing to the effects of local climate and topography, vary over small spatial scales and lead to rapid changes in fire behaviour. For example, variations in aspect within complex terrain can affect whether a fire burns in a timber rather than grass fuel type (Holland and Steyn 1975). Such a change in fuel type, from understorey timber litter to grass, could potentially result in a rapid and potentially unexpected increase in rate of spread (Bishop 2007).

Increases in wind speed and changes in wind direction produced by cold fronts, convective thunderstorms and foehn winds have also been shown to affect firefighter safety (Schroeder and Buck 1970; Cheney *et al.* 2001; Lahaye *et al.* 2018*a*, 2018*b*). This is due to the effects of wind speed on fire behaviour (Rothermel 1972; Catchpole *et al.* 1998), where depending on fuel type, rates of spread can increase quite dramatically with corresponding increases in wind speed (Sullivan 2009; Andrews *et al.* 2013). Additionally, a sudden increase in head fire width associated with a wind direction change can lead to a rapid increase in fire spread rate and intensity in the area downwind of the fire front, also known as the 'dead-man zone' (Cheney and Gould 1995; Cheney *et al.* 2001). The potential consequences of a rapid increase in wind speed and change in wind direction have recently been demonstrated by the death of 19 firefighters during the 2013 fire season on the Yarnell Hill Fire in Arizona, USA (Yarnell Hill Fire Investigation Report 2013). Outflow winds from a nearby thunderstorm rapidly changed the direction and speed of the fire, which produced a fire run that overtook the firefighters with rates of spread between 270 and 320 m min^{-1} and flame lengths of 18–24 m (Alexander *et al.* 2016). Unfortunately, most numerical weather prediction (NWP) models and the forecasts partially based on them generally have low skill, in terms of point forecasts, for wind speed and direction changes associated with convectively driven thunderstorms (Done *et al.* 2004; Page *et al.* 2018), except when lead times are within 1–2 h (Johnson *et al.* 2014). However, bias-corrected and optimised NWP models used in ensembles generally have good skill in forecasting the approach and passage of cold fronts (Ma *et al.* 2010; Sinclair *et al.* 2012; Young and Hewson 2012), but forecast skill may be region- and storm-dependent owing to several factors (Schultz 2005; Shafer and Steenburgh 2008). Likewise, some foehn wind events can generally be anticipated several hours to days in advance (e.g. Nauslar *et al.* 2018), but this forecast skill also probably varies regionally.

In areas of complex topography, factors such as spotting or slope reversals (Bishop 2007) also increase the danger to firefighters owing to the effects of slope steepness on fire behaviour (e.g. Van Wagner 1977; Butler *et al.* 2007) and an increased possibility of surprise as these phenomena can be difficult to predict. Steep slopes that are prone to flame attachment (i.e. slope steepness >24°) are particularly dangerous to firefighters (Sharples *et al.* 2010; Lahaye *et al.* 2018*c*; Page and Butler 2018) owing to the rapid increase in spread rate caused by enhanced convective and radiant heating to unburned fuels (Rothermel 1985; Gallacher *et al.* 2018). Additionally, if firefighters are surprised by specific fire runs on steep slopes, the potential for successful escape is further hampered by slower travel rates (Baxter *et al.* 2004; Campbell *et al.* 2017, 2019) and the requirement for larger safety zones (Butler 2014*a*). These topographic factors lead to an increase in both the likelihood of an entrapment and the probability of a fatality during an entrapment (Viegas and Simeoni 2011; Page and Butler 2017, 2018). There are several examples of past extreme fire behaviour events that resulted in fatalities that were at least partially attributed to rapid increases in fire behaviour associated with steep slopes, including the Mann Gulch (Rothermel 1993), Battlement Creek (Wilson *et al.* 1976) and South Canyon (Butler *et al.* 1998) fires.

Entrapment reporting

Investigation process

Much like other organisations involved in high-risk industries that are prone to the loss of life, such as medicine (Leape 1994) and air transportation (Haunschild and Sullivan 2002), US wildland fire management agencies have an obligation to investigate the sequence of events and surrounding circumstances that contributed to the occurrence of an accidental injury or fatality. Most wildland fire management agencies have specific criteria for determining whether an entrapment requires an investigation and what the purpose and scope of the investigation should be, which are usually detailed in various legal statues and agency directives (e.g. Bureau of Land Management 2003; Whitlock and Wolf 2005; Beitia *et al.* 2013). Although descriptions of each organisation-specific process are beyond the scope of the current discussion, the general processes do have substantial similarities.

Once the agency with jurisdiction decides that an official investigation is appropriate, an investigation team composed of a designated leader along with several technical specialists, one of which is usually a fire behaviour specialist, is formed. After the team has convened, the investigation process begins by gathering and compiling evidence, such as witness statements, physical evidence and a chronology of events. The team is then tasked with producing a report that details the evidence gathered as well as the various causal and contributing factors, followed by a series of recommendations that '…are reasonable courses of action, based on the identified causal factors that have the best potential for preventing or reducing the risk of similar accidents' (Whitlock and Wolf 2005, p. 59). As noted by the National Wildfire Coordinating Group (1980) and others (e.g. Gabbert 2019), rarely are the recommendations produced by these reports unique as they often are similar to those from previous investigations.

Report archiving and access

Several US-based systems currently store and disseminate information on wildland fire-related injuries and fatalities. Butler *et al.* (2017) reviewed five different surveillance systems that are used to report wildland firefighter fatalities, which include systems maintained by the US Fire Administration, the National Fire Protection Association, the US Bureau of Labour Statistics, National Institute for Occupational Safety and Health and the National Wildfire Coordinating Group. Butler *et al.* (2017) found that there was substantial overlap among the systems, with each having a slightly different focus based on criteria formally required by law and how each system deals with unique subsets of wildland firefighter tasks and duties (e.g. aviation). Despite the differences between systems, they tended to report similar annual summary statistics.

One of the most widely used databases to report injuries and fatalities is maintained by the Risk Management Committee of the National Wildfire Coordinating Group. As opposed to the other reporting systems, this database is maintained exclusively for wildland firefighters engaged in direct support of wildland fire activities regardless of agency and includes not only incidents associated with fatalities but also other incidents that involved potentially life-threatening accidents. Publications called Safety Grams (available at https://www.nwcg.gov/committees/risk-management-committee-rmc-safety-grams (accessed 23 April 2019)) are released yearly, which describe basic information about each life-threatening incident that occurred during the previous year, including the approximate location, number of individuals involved and the type of incident. Within the database, entrapment incidents are usually labelled as 'entrapments' or 'burnovers'.

Additional formal and informal systems are used to store information related to wildland firefighter fatalities and injuries in the US. The Wildland Fire Lessons Learned Center Incident Review Database (available at https://www.wildfirelessons.net/irdb (accessed 23 April 2019)) is a central repository that is continuously updated with publications that describe the circumstances related to incidents with injuries, fatalities or near-misses. The database also includes documents with information related to non-wildfire-related events such as prescribed-fire escapes and chainsaw operations. Entrapments within the database can be specifically queried by selecting the 'entrapment' and 'burn injury' incident types. Another system that tracks wildland firefighter fatalities is the Always Remember! website (available at https://wlfalwaysremember.org/ (accessed 23 April 2019)). The website is maintained by a group of volunteers who organise, collect and store information related to incidents that involved a wildland fire-related fatality, such as the name and date of incident, the incident location and a summary of the circumstances that led to the fatality. Entrapments can be identified by selecting 'burnovers' in the incident list.

Current limitations

Current reporting systems have several issues that inhibit efficient data utilisation. Either by law or practice, many of the systems store data related to the same incident, resulting in duplication, which is both inefficient and potentially confusing. As noted by Butler *et al.* (2017), some systems are required to track firefighter fatalities owing to various legal statutes, whereas 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 datasets.

There are two wildland fire-specific systems that have the potential to fill the role as the primary repository for housing data related to entrapment injuries and fatalities, namely the National Wildfire Coordinating Group Safety Grams and the Wildland Fire Lessons Learned Center Incident Review Database. In their current form, each system has unique advantages and disadvantages that require the use of both to gather and compile adequate temporal, spatial and physical information associated with each incident. For example, the 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 are less likely to have an official report, which results in a potential under-reporting bias. Furthermore, although many of the US agency-specific investigation guides do reinforce the importance of documenting the natural features at an entrapment site, it seems that in reality many of the details, such as the physical location of the entrapment site and the specific environmental conditions, either fail to be included in the final report or are included in such a manner as to greatly increase the difficulty of extracting the data. 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 and 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.

Entrapment analysis

Fatality trends

The majority of reports summarising firefighter entrapments in the US have only presented data related to the number of fatalities through time. Specifically, summaries of the fatalities associated with firefighter entrapments have been published for the periods 1910–96 (National Wildfire Coordinating Group 1997), 1926–2012 (Cook 2013), 1976–99 (Munson and Mangan 2000), 1990–98 (Mangan 1999), 1990–2006 (Mangan 2007) and 2007–16 (National Wildfire Coordinating Group 2017*a*). All of these summaries have been at least partially based on the data compiled by the National Wildfire Coordinating Group and stored by the National Interagency Fire Center (2018) (Fig. 3).

Similar to the findings provided in all other published sources, there has been a downward trend in the annual number of entrapment-related firefighter fatalities in the US since 1926 (Fig. 3). Despite several peaks associated with high-fatality years, the annual number of fatalities has been dropping at a rate of ~0.4 (6%) per decade, although the trend is not quite significant (*P* value 0.157). Cook (2013) showed that the number of fatalities caused by entrapments dropped from a high of 6.2 per year between 1926 and 1956, when organised fire suppression began to mature, to 1.6 per year between 2004 and 2012. Similarly, the National Wildfire Coordinating Group (2017*a*) has documented decreases in entrapment-related fatalities from 4.3 per year between 1990 and 1998 to 2.8 per year between 2007 and 2016.

The annual number of entrapment-related fatalities indicates substantial variability from year to year (standard deviation 5.7, coefficient of variation 121%) even though the annual number of incidents remained fairly constant throughout the period (1926–2017) at approximately two per year (Fig. 3). The recurrence interval, or the average time between years that exceed a specific number of entrapment-related fatalities,

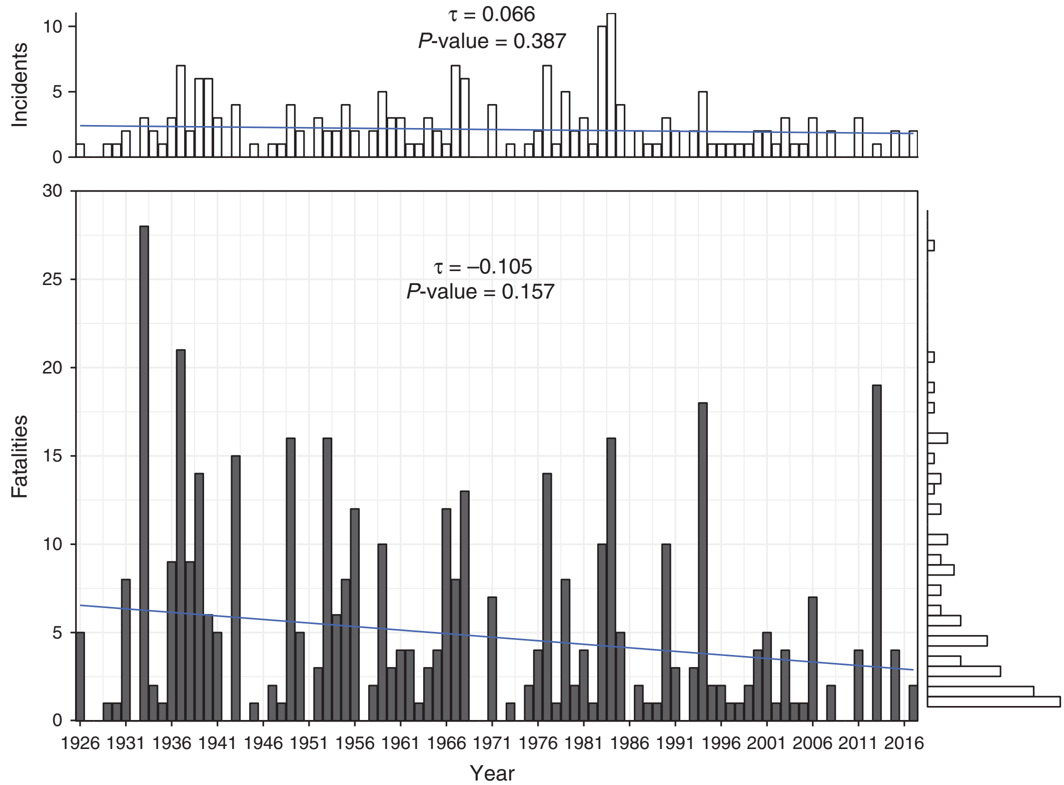

Fig. 3. Entrapment-related wildland firefighter fatalities in the continental US, 1926 to 2017. The corresponding number of incidents (top panel) and the distribution of annual fatalities (right panel) are also shown. The non-parametric Mann–Kendall test (Mann 1945; Kendall 1975) was used to identify 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).

suggests that high fatality years (i.e. ≥10 fatalities) have generally occurred every 6 to 7 years, whereas very high fatality years (i.e. ≥15 fatalities) occurred at an interval approximately two times longer, i.e. approximately every 15 years (Fig. 4).

When the annual number of entrapment-related fatalities is viewed in relation to the annual number of fires and area burned, additional trends can be inferred. Unfortunately, owing to the lack of high-quality data on US fire activity for all fire sizes before 1992 (Short 2015), the current analysis is limited to years with the best data, 1992 to 2015 (Fig. 5; Short 2017). The analysis indicated that the highest fatality rate by area burned occurred in 2013 (~0.6 per 40 469 ha (100 000 acres) burned) owing to the 19 fatalities on the Yarnell Hill Fire (Yarnell Hill Fire Investigation Report 2013), with the lowest average rates found in the late 1990s and early 2000s. Since 1992, the average number of fatalities per 40 469 ha (100 000 acres) burned has decreased by ~0.01 (9%) per decade, which is marginally significant (*P* value 0.099). However, the fatality rates based on the yearly number of fires show little change, with an average of ~0.5 fatalities per 10 000 fires or 1 fatality every 20 000 fires (Fig. 5*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.

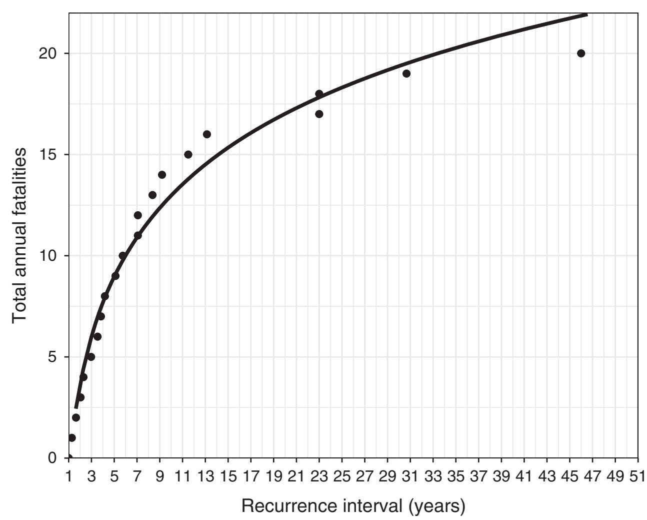

Fig. 4. Relationship between the total annual number of entrapment-related fatalities in the continental US between 1926 and 2017 with the corresponding recurrence interval or return time, i.e. the average time between years with at least a specific number of entrapment-related fatalities. The corresponding line of best fit was modelled based on the natural logarithm function.

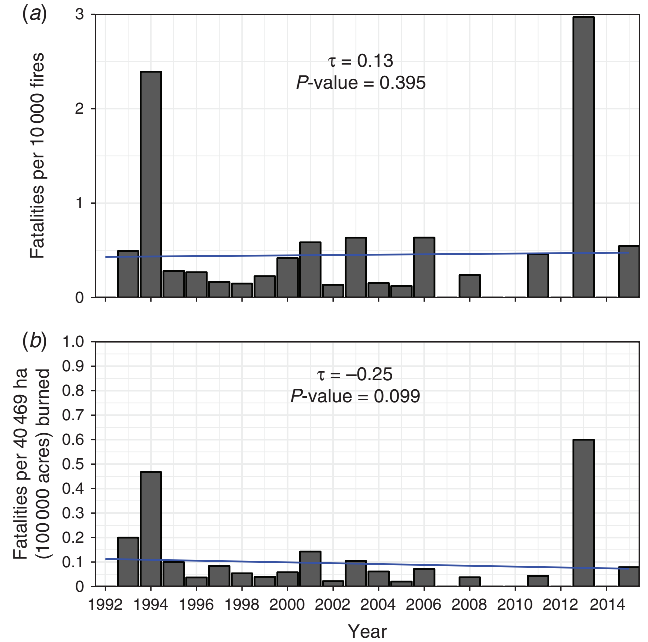

Fig. 5. Entrapment-related wildland firefighter fatality rates in the continental US from 1992 to 2015 by (*a*) the number of fatalities per 10 000 fires; and (*b*) the number of fatalities per 40 469 ha (100 000 acres) burned. The non-parametric Mann–Kendall test (Mann 1945; Kendall 1975) was used to 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).

All entrapment trends

Despite the valuable information provided by the previous entrapment summaries, they are missing key information related to non-fatal entrapments and other spatiotemporal data (e.g. time and location) that could be used to further our understanding of the factors that influence the likelihood of an entrapment. Here, we take the first steps to fill these gaps by merging information reported in the National Wildfire Coordinating Group Safety Grams, Wildland Fire Lessons Learned Incident Review database, the Always Remember! website and the National Institute for Occupational Safety and Health firefighter fatality investigation and prevention program. A database of firefighter entrapments, referred to as the Fire Sciences Laboratory Merged Entrapment Database (FiSL MED), has been assembled by the authors and made available online (see https://www.wfas.net/entrap/, accessed 17 April 2019). The database includes information on the location, date and approximate time (Greenwich Mean Time (GMT)), number of personnel involved, number of fatalities and location quality for entrapments that have occurred within the continental US since 1979. Location quality is currently classified into four 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 database currently only extends back to 1979 as this marks the beginning of the availability of high-quality gridded weather data (i.e. Abatzoglou 2013) and other dynamic fire environment data, such as fuel type information derived from Landsat imagery (e.g. Kourtz 1977), that can be combined with the FiSL MED to provide consistent and reliable

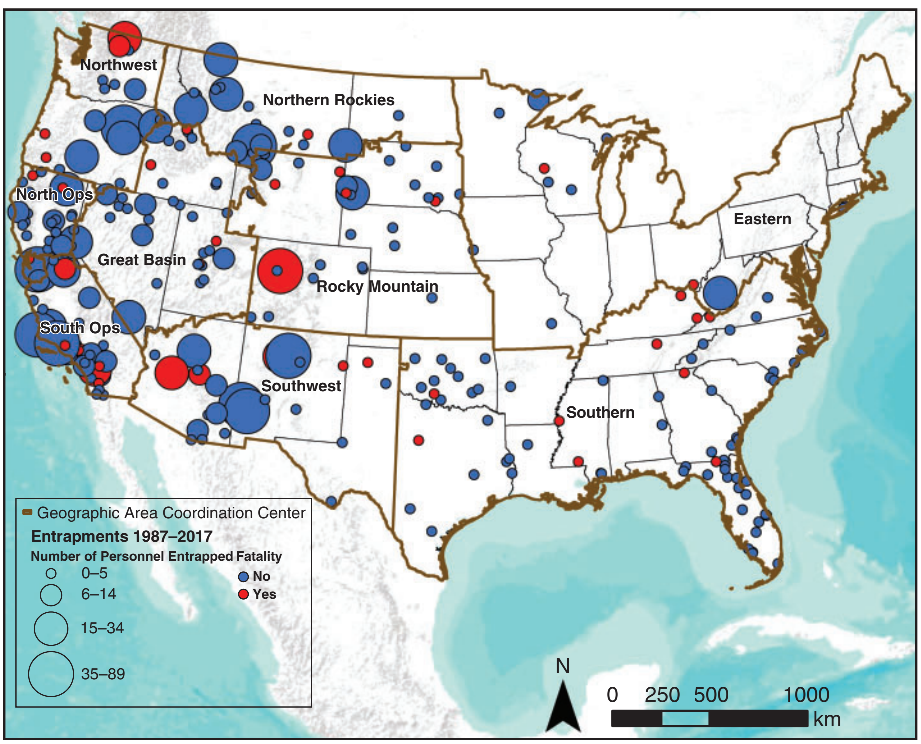

Fig. 6. Locations of 285 entrapments where there was a burnover in the US from 1987 to 2017. Data available online (see https://www.wfas.net/entrap/, accessed 23 April 2019) and in the online supplementary material.

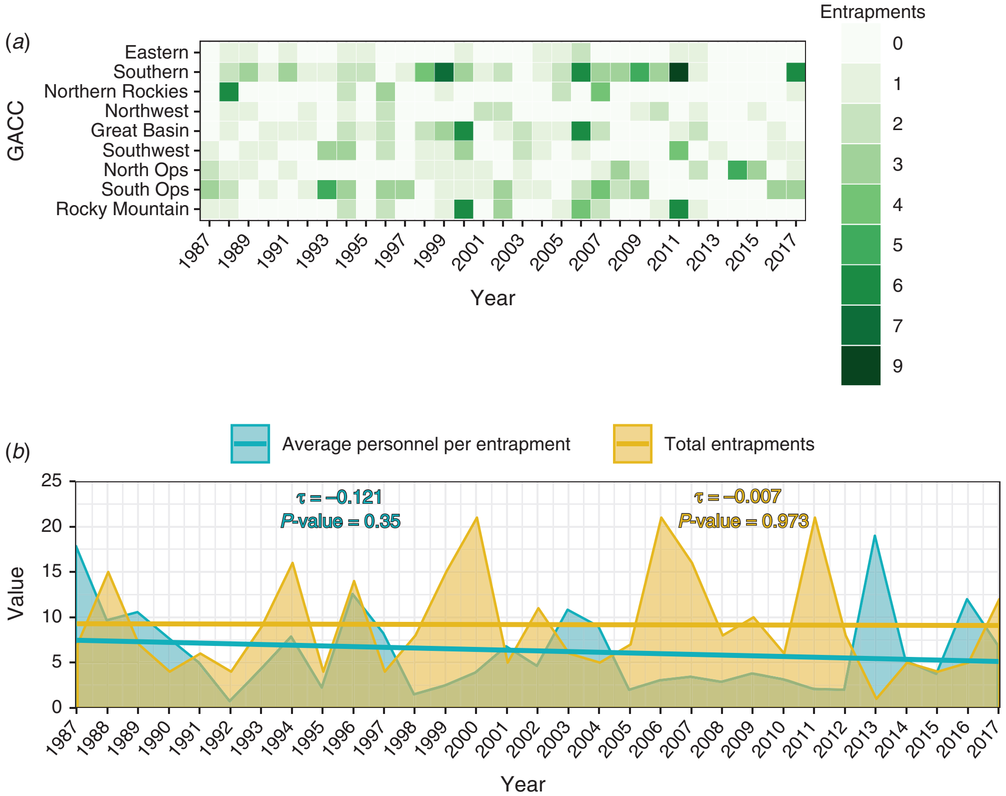

Fig. 7. Trends in all firefighter entrapments (i.e. with and without a fatality) where there was a burnover in the continental US between 1987 and 2017 by: (*a*) Geographic Area Coordination Center (GACC); and (*b*) the total number of entrapment incidents and the average number of personnel per entrapment incident. Note that North Ops and South Ops in (*a*) represent Northern and Southern California respectively. The non-parametric 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 Fig. 6. Data available online (see https://www.wfas.net/entrap/, accessed 23 April 2019) and in the online supplementary material.

information about the fire environment at the date and location of each entrapment. As of November 2018, the database contains accurate spatial locations for 187 (55%) of the known entrapments, with the remaining entrapments currently limited to the reported location of the fire origin with the entrapment (32%), estimated based on written descriptions (9%) and those entrapments with no known location information or considered near misses (4%).

Those entrapments that occurred between 1987 and 2017 (i.e. 285) represent the period that encompasses the most overlap between existing entrapment reporting databases, thus minimising the potential for under-reporting bias. The data during this time period (see Table S1, online supplementary material) reveal that entrapments in the US are highly clustered in space (Fig. 6) but not through time (Fig. 7*a*, *b*). When viewed over the entire period, there are no obvious trends in the annual number of entrapment incidents, which averaged approximately nine per year (Fig. 7*b*), but there does seem to be a declining trend in the average number of personnel entrapped per incident, decreasing at a rate of ~0.8 people (11%) per decade, although the trend is not statistically significant (*P* value 0.35; Fig. 7*b*). These findings are contrary to Loveless and Hernandez (2015), who reported a reduction in entrapment rates for wildland firefighters between 1994 and 2013. Although the reasons for the discrepancy are not fully known, it may be related to the fact that Loveless and Hernandez (2015) calculated entrapment rates using only the entrapments provided by the National Wildfire Coordinating Group, rather than all possible databases, and they used firefighter exposure indicators (i.e. number of fires and area burned from the National Interagency Fire Center) with known biases (Short 2015).

The highly clustered nature of US wildland firefighter entrapments indicates large spatial variability. Following Fig. 6, the majority of entrapment incidents have occurred in the Southern Geographic Area (25%) followed by Southern California (South Ops) (16%) and the Great Basin (13%). When corrected for the size of each geographic region, the highest numbers of entrapments per square kilometre are found in Southern California (1.8×10^{-4} per km^2), Northern California (North Ops) (1.5×10^{-4} per km^2) and the Great Basin (0.53×10^{-4} per km^2). The geographic regions with entrapments that affected the most firefighters were Southern California (356), the Southwest (261) and the Northern Rockies (178).

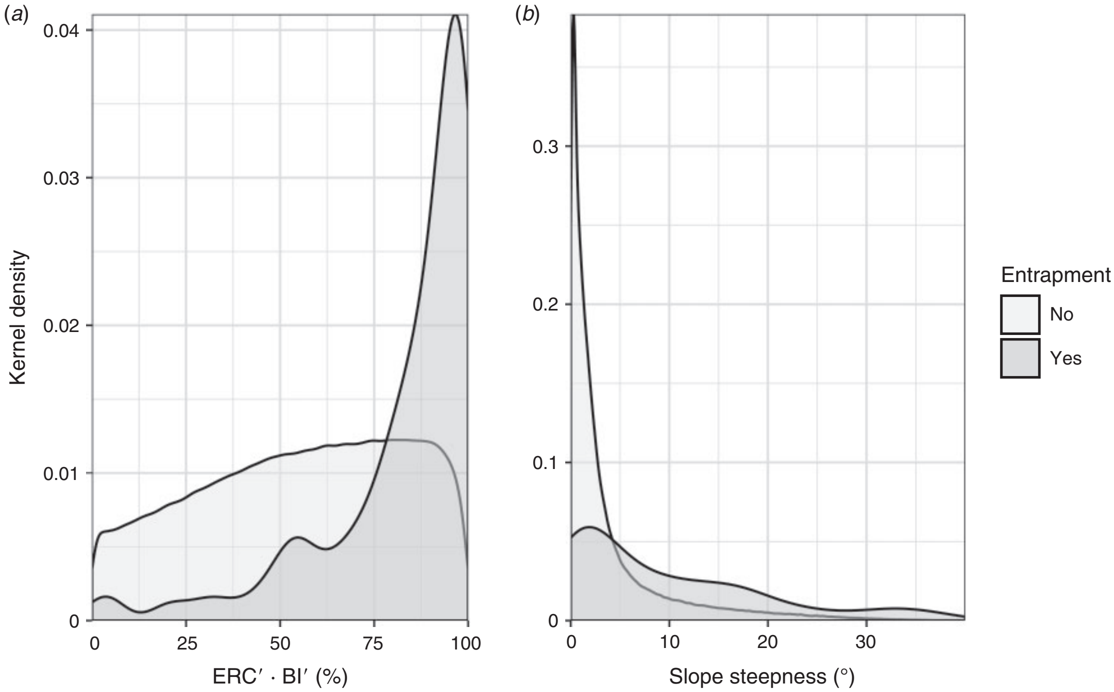

Fig. 8. The influence of: (*a*) the product of the historical percentiles for the Energy Release Component (ERC′) and Burning Index (BI′); and (*b*) slope steepness on kernel density estimates for fires with and without an entrapment the occurred in the continental US between 1992 and 2015.

Important environmental factors

Previously, the efficacy of assessing the influence of different combinations of environmental variables on firefighter entrapments has been challenged by gaps and inconsistencies in the fuels, weather and topography data collected during the official investigation. For those incidents in which the dates and locations of entrapments are recorded, the fire environment at a particular entrapment site can be extracted from historical records of time-series and spatial layers of fuels, weather and topographic information (Rollins 2009; Abatzoglou 2013). Further, coupling the entrapment data with wildfire occurrence data (e.g. Short 2015, 2017) allows the fires with entrapments to be analysed within the context of the historical fires that have occurred within a given region.

A preliminary analysis of the effects of weather and slope steepness on wildland firefighter entrapments in the US was completed by spatially and temporally intersecting the FiSL MED with a 39-year gridded 4-km fire danger climatology (1979–2017) (Jolly *et al.* unpubl. data) and a historical fire occurrence database for the years 1992 to 2015 (Short 2017) on the day each fire started and at the reported fire origin. The analysis indicated that the effects of both weather and slope steepness on wildland firefighter entrapments in the US are quite dramatic as fires with entrapments originated more often on steeper slopes and during extreme fire weather, as represented by the product of the historical percentiles for the Energy Release Component (ERC′) and Burning Index (BI′) (Deeming *et al.* 1977) (Fig. 8). Fire danger indices, which combine multiple fire environment factors into a single index, have been shown to be reliable indicators of potential fire behaviour, particularly when the original values are rescaled to represent their historical percentiles (Andrews *et al.* 2003; Jolly and Freeborn 2017), and related to the number of fatalities during entrapments involving both firefighters and members of the public in Australia (Blanchi *et al.* 2014).

Slope steepness and fire weather also had quite dramatic effects on entrapment rates for some geographic areas (Fig. 9). In the western US, fires that originated on steep slopes during historically dry and windy conditions between 1992 and 2015 were much more likely to have an entrapment, with maximum entrapment rates of 214, 108, 70, 62 and 54 entrapments per 10 000 fires within the Rocky Mountain, Southern California, Northern California, Southwest and Great Basin geographic areas respectively.

Potential future applications

Characterising the environmental conditions at the locations and times of entrapments allows the development and assessment of relationships that can be used to predict future entrapment potential. For example, spatially explicit data on both static (e.g. fuels and topography) and dynamic (e.g. fire weather) variables could be used with statistical models to produce maps that depict the locations and times when entrapment potential is high (Fig. 10). Various modelling tools and techniques could be leveraged to accomplish this, including maximum entropy (Phillips *et al.* 2006), logistic regression (Imai *et al.* 2008) and Random Forests (Breiman 2001). Page and Butler (2018) outlined a methodology to assess firefighter entrapment potential in Southern California using maximum entropy methods coupled with several

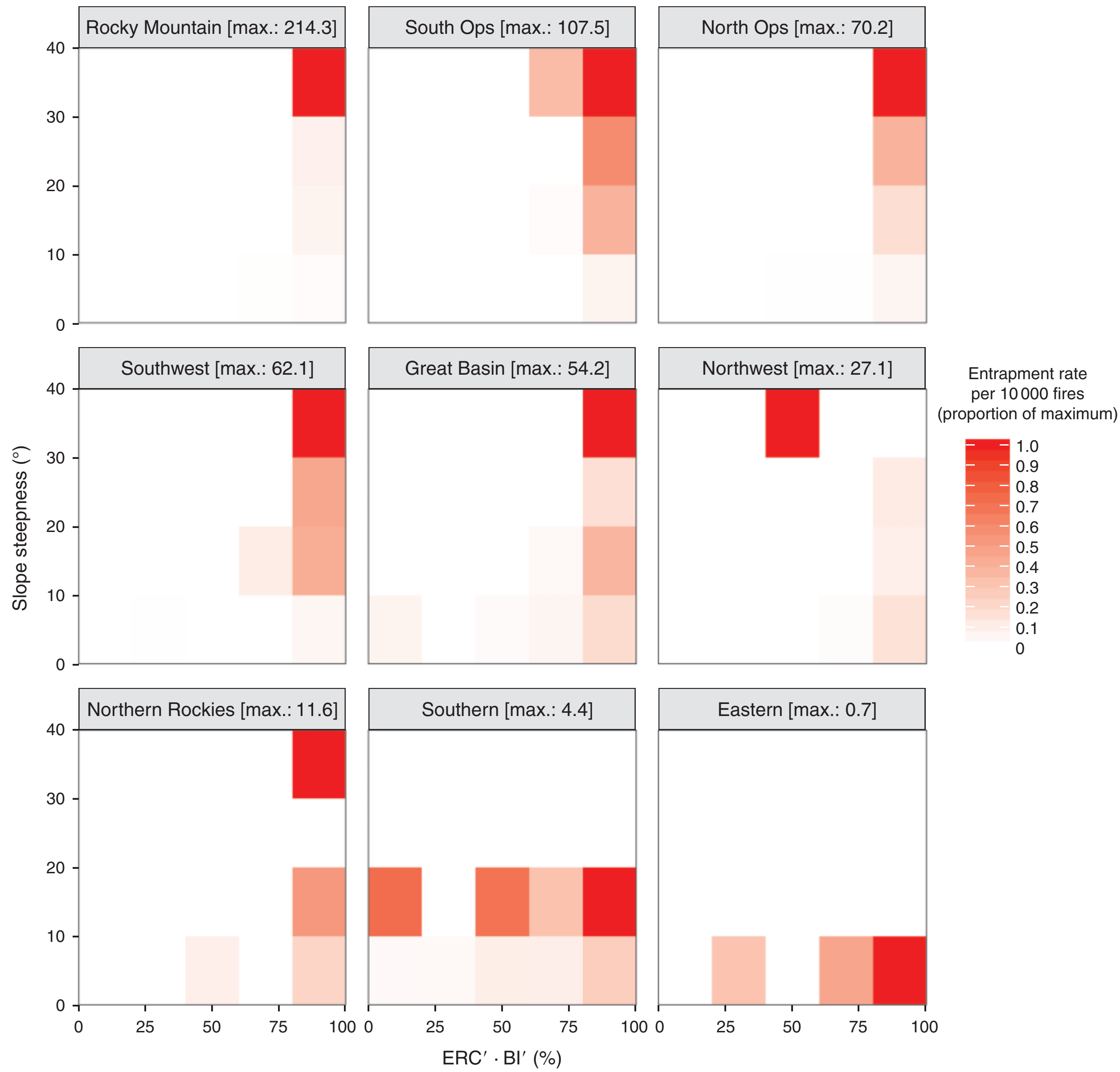

Fig. 9. Entrapment rates (entrapments per 10 000 fires) for the nine Geographic Area Coordination Centers in the continental US between 1992 and 2015 by slope steepness and the product of the historical percentiles for the Energy Release Component (ERC′) and Burning Index (BI′).

common fuel and topographic variables measured at locations where there were past firefighter fatalities. Similar methods and outputs that also incorporate important dynamic information (e.g. fire weather) may eventually be useful sources of information for wildland firefighters as they build on situational awareness before and during fire suppression operations.

Summary of research needs

In order to improve firefighter safety and reduce the number of entrapments, there are several items that should be investigated to enhance both fundamental knowledge and the tools used to disseminate that knowledge.

Improved knowledge

With regards to the prediction of extreme fire behaviour, we echo the research needs presented by Werth *et al.* (2011, 2016), which include a better understanding of plume dynamics and their effects on spotting, improvements in measuring and representing complex fuel structure, more observations of wind flow 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 behaviour. We also acknowledge the recommendations by Butler (2014*b*) who suggested that additional research is needed to address: (1) how convective energy affects safety zone size; (2) how clothing affects the

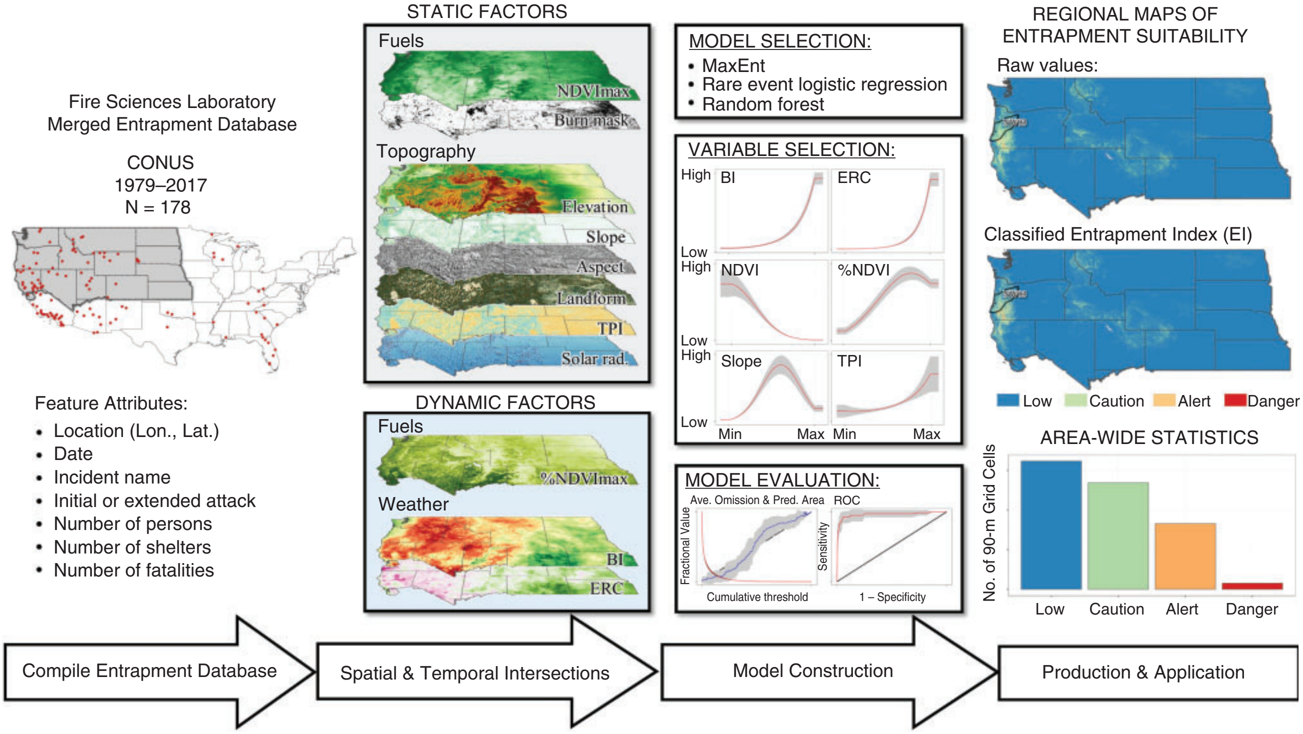

Fig. 10. Schematic representation of an example process to assess and predict firefighter entrapment potential across space and through time. Important environmental data gathered at previous entrapment locations are coupled with statistical models to derive relationships that can be used to predict future entrapment potential. Typical environmental data include, Burning Index (BI), Energy Release Component (ERC), Normalised Difference Vegetation Index (NDVI) and Topographic Position Index (TPI). ROC, receiver operating characteristic curve.

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 recommendations based on the findings from this review include:

- A better identification of the environmental factors that lead to rapid increases in fire rate of spread and intensity, including important interactions and their relative influences,
- The development of models (statistical or otherwise) capable of anticipating the times and locations where rapid increases in spread rate and intensity are possible, and
- Improved NWP models and 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.

Tool development

Little is known about how the current suite of tools capable of identifying relevant changes in the fire environment (Table 2) or making fire behaviour predictions (Table 3) are used by wildland firefighters. Although some evidence suggests that at least some crews use these tools on a regular basis to make quick assessments of the fire environment, especially when using concepts like the margin of safety (Beighley 1995), it seems likely that many firefighters rely on more experience-based methods to assess potential fire behaviour (Alexander *et al.* 2016), particularly when the observed fire behaviour is considered unpredictable (Wall *et al.* 2018).

Based on the findings and recommendations from previous firefighter entrapment investigations, there is a need for tools that can help firefighters anticipate sudden changes in fire behaviour, establish plausible fire suppression goals and understand what strategies and tactics might be appropriate for a specific situation (Weick 2002). Therefore, relevant tools need to capture or incorporate small spatial and temporal changes in the fire environment and produce outputs that are both timely and accurate enough to portray the magnitude of the changes. Additionally, they need to be able to operate in the field with limited connectivity and have the ability to incorporate updated information over the course of an operational period. Examples include tools that provide firefighters information on the effects of terrain or forecast meteorological events (e.g. thunderstorms) on near-surface wind speed and direction at fine spatial scales (Forthofer *et al.* 2014*a*, 2014*b*) or tools that can couple detailed topographic information (slope, terrain shape) with crew and fire position to help anticipate topographically driven increases in fire rate of spread and intensity (Sharples *et al.* 2012).

Table 2. Examples of common tools or systems that provide updated fire environment information in the US

Tool or system	Platform	Products	Temporal resolution	Spatial resolution	Availability
TOPOFIRE	Website	Geographic information on drought and wildfire danger	~24 h	Varies based on product	https://topofire.dbs.umt.edu/topofire_v3/index.php [accessed 24 April 2019] (Holden *et al.* 2013)
Fire Weather Alert System	Website	Issues alerts when user-specified weather thresholds are exceeded within radius of specified location	~1 h (depends on weather station temporal resolution)	Varies based on weather station locations	https://weather.firelab.org/fwas/ [accessed 24 April 2019]
WindNinja	Mobile app and computer software	Diagnostic wind model for complex terrain, includes ability to incorporate high-resolution weather forecasts	~1 h	User-specified (~100–1000 m)	https://weather.firelab.org/windninja/ [accessed 24 April 2019] (Forthofer *et al.* 2014*b*)
Wildland Fire Assessment System	Website	Provides a national view of weather and fire potential	~24 h	Varies based on product	https://www.wfas.net/ [accessed 24 April 2019] (Burgan *et al.* 1997)
Climate Engine	Website	Visualisation and retrieval of historical climate and fire danger data	~24 h	Varies based on product	https://app.climateengine.org/ [accessed 24 April 2019] (Huntington *et al.* 2017)
Various weather apps	Mobile app	Weather related applications that provide updated information on precipitation, storm movement, etc.	Varies based on application	Varies based on application	Many, see http://southern-fireexchange.org/Models_Tools/Weather_Apps.html [accessed 24 April 2019] for examples

Table 3. US-based fire behaviour prediction tools and guidelines that: (1) can be used in a field setting with no or limited connectivity, (2) are capable of rapidly incorporating updates to the fire environment inputs, and (3) run much faster than real time

Note that most of the tools described are at least partially based on Rothermel's (1972) surface fire spread model

Tool or guideline	Platform	Source
Fire Behaviour Nomograms	Paper-based	Albini (1976); Scott (2007)
Interpreting Fire Behaviour Characteristics	Paper-based	Andrews and Rothermel (1982)
Fireline Handbook – Appendix B	Tables	National Wildfire Coordinating Group (2006)
Fire Behaviour Field Reference Guide	Tables	National Wildfire Coordinating Group (2017*b*)
FireLine Assessment MEthod (FLAME)	Tables	National Wildfire Coordinating Group (2007)
Wildland Toolkit	Mobile app	http://peakviewsoftware.com/wildlandtoolkit.html [accessed 24 April 2019]
Wildfire Analyst Pocket Edition	Mobile app	Monedero *et al.* (2019)

In summary, to improve the ability of firefighters to make timely and risk-informed decisions and reduce the number of entrapments, we note that 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 behaviour (Wall *et al.* 2018), and
- Have the ability to merge the updated information with firefighter and equipment locations, in order to develop a comprehensive system similar to the one proposed by Gabbert (2013), i.e. the 'Holy Grail of firefighter safety'.

We note that many of the issues associated with inadequate tool use and availability, especially in regards to near real-time availability of fire position and firefighter locations, are currently being debated in the US Congress (S.2290 – Wildfire Management Technology and Advancement Act of 2018). The proposed legislation, among other things, would require US fire management agencies to develop protocols to utilise unmanned aircraft technologies to provide real-time maps of fire perimeter locations to firefighters.

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 centralised data repository that contains updated information on the details associated with past incidents is needed. Although several storage systems already exist, each of these has 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

Table 4. Recommended minimum data collection and reporting standards for the relevant fire environment variables associated with firefighter entrapments that involve a burnover

It is suggested that the measurements be made at or immediately adjacent to the burnover location

Factor	Comments
Fuels	
Fuel type	Fuel type should be reported based on the six 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, 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 or near entrapment site before 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 or near entrapment site before 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 or near entrapment site before 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 1 to 2 h preceding entrapment
Wind direction	Temporally averaged wind direction that was recorded or estimated at or near entrapment site before 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 1 to 2 h preceding entrapment
Measurement source and 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	Brief description of the dominate terrain characteristics around the entrapment location, including descriptions of terrain shape (e.g. canyons)
Refuge area	
Location	Latitude and longitude of entrapment location(s) as reported by a Global Positioning System (GPS)
Physical dimensions	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	
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 behaviour	
Rate of spread	Observed or estimated spread rate of fire at the time of the entrapment. Note any significant temporal variation in the 1-2 h before entrapment
Flame length and height	Observed or estimated flame characteristics at the time of the entrapment. Note any significant temporal variation in the 1-2 h before entrapment
General fire behaviour	General notes on fire behaviour including fire type (surface versus crown fire), spotting activity and any significant temporal variations leading up to the entrapment. Provide photos and video footage with time stamps whenever possible
How estimates were obtained	Details associated with how fire behaviour estimates were either measured or modelled. If fire behaviour 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 its 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 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

incident. Specifically, an unacceptably high proportion of investigative-type documents and reports of firefighter entrapments either fail to include or fail to adequately summarise 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 4).

Conclusions

Wildland firefighting is an inherently dangerous occupation that is affected by a variety of environmental, political and social pressures. Although many firefighters have died over the years, progress has been made in training, policy and equipment standards that has resulted in a general decrease in the annual number of entrapment-related firefighter fatalities. However, when entrapments without fatalities are included in assessments, there appears to be little evidence to suggest they are also on a decreasing trend. Although past firefighter fatalities have inspired the development of several tools and guidelines that have been incorporated into firefighter training, firefighter entrapments continue to occur in part owing to the inability of firefighters to anticipate rapid increases in fire rate of spread and intensity that are caused by changes in the fire environment that happen over small spatial and temporal scales. We identified several research needs related to a lack of knowledge, inadequate tools and improved methods for data collection and storage. Prioritising these needs will be difficult as they all would no doubt improve firefighter safety either directly or indirectly.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgements

This work was supported by the Joint Fire Science Program (Project 18-S-01–1) and the National Fire Plan through the Washington Office of the Forest Service Deputy Chief for Research. We gratefully acknowledge review of the manuscript by M. E. Alexander, the Associate Editor and two anonymous reviewers.

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