CSIRO PUBLISHING

International Journal of Wildland Fire
http://dx.doi.org/10.1071/WF12160

Wildland firefighter entrapment avoidance: modelling evacuation triggers

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Abstract. Wildland firefighters are often called on to make tactical decisions under stressful conditions in order to suppress a fire. These decisions can be hindered by human factors such as insufficient knowledge of surroundings and conditions, lack of experience, overextension of resources or loss of situational awareness. One potential tool for assisting fire managers in situations where human factors can hinder decision-making is the Wildland–Urban Interface Evacuation (WUIVAC) model, which models fire minimum travel times to create geographic trigger buffers for evacuation recommendations. Utilising multiple combinations of escape routes and fire environment inputs based on the 2007 Zaca fire in California, USA, we created trigger buffers for firefighter evacuations on foot, by engine and by heavy mechanised equipment (i.e. bulldozer). Our primary objective was to examine trigger buffer sensitivity to evacuation mode and expected weather and fuel conditions. Evacuation travel time was the most important factor for determining the size and extent of modelled trigger buffers. For the examined scenarios, we show that WUIVAC can provide analytically driven, physically based triggers that can assist in entrapment avoidance and ultimately contribute to firefighter safety.

Received 28 September 2012, accepted 28 March 2013, published online 23 July 2013

Introduction

Wildfire suppression sometimes entails firefighting in precarious, potentially life-threatening environments. In addition to the difficulty associated with physically fighting fires (i.e. steep terrain, heat, workload), firefighters are forced to make tactical decisions which can often be hindered by human factors such as insufficient knowledge of surroundings and conditions, lack of experience, overextension of resources or loss of situational awareness (Taynor *et al.* 1987; Putnam 1995; McLennan *et al.* 2006; Alexander *et al.* 2012). The risk of being trapped or overrun by a wildfire increases when fire personnel are confronted with these types of challenges (Munson 2000; Mangan 2007).

Entrapments, shelter deployments and burn-over fatalities occur when fire personnel are caught in situations where an escape route or safety zone either does not exist or has been compromised by a fire. Since the 1910 catastrophic wildfires that occurred in the US northern Rocky Mountains (Pyne 2001), there have been a total of 427 fatalities associated with fire fighter entrapment in the US (National Interagency Fire Center 2008). Entrapment fatalities have decreased significantly over time, due in part to doctrinal changes and implementation of risk mitigation guidelines (i.e. Lookouts-Communications-Escape Routes-Safety Zones (LCES), 10 Firefighting Orders and 18 Watchouts) (Cook 2004; Alexander *et al.* 2012). However, recent fatality fires such as the 2001 30-Mile, 2003 Cramer and 2006 Ezperanza fires in the United States, the summer 2003 fires in Portugal and the 2005 Guadalajara fire in Spain demonstrate that entrapment risk still exists for fireline personnel.

Fire frequency and area burned have increased in the western United States in recent years (McKelvey and Busse 1996; Stephens 2005; Westerling *et al.* 2006). Against this background of increasing fire activity, firefighters with varying degrees of experience and a diverse breadth of knowledge are asked to make decisions in potentially hazardous situations. Hence, tools are needed to enable firefighters to assess and standardise their safety concerns, communicate standards among other personnel and implement those standards in current and planned tactics (Beighley 1995).

One potential tool for assisting fire managers is the use of protective triggers. A protective trigger is set such that when a predetermined condition is met, firefighting resources can execute a pre-identified tactic such as evacuating to a safety zone, sheltering-in-place, turning down a tactical assignment or changing tactics altogether and re-engaging in suppression of the fire based on new or updated predicted conditions (Greenlee and Greenlee 2003). The Wildland–Urban Interface Evacuation (WUIVAC) model was developed to derive geographic triggers using minimum fire travel-times and estimated evacuation times (Cova *et al.* 2005; Dennison *et al.* 2007). WUIVAC models 'trigger buffers', which consist of a set of trigger points that encircle a vulnerable person, population, community or other asset.

This work investigates variability in geographic trigger buffer characteristics for a combination of predicted fire behaviour conditions, resource allocations and tactical assignments that can arise in wildfire suppression. Variability of trigger buffers in response to input parameters were used to assess the utility of the modelling framework for tactical and operational firefighting decision-making for the purpose of entrapment avoidance. All scenarios for this study were derived from the Zaca fire, a wildfire in Los Padres National Forest in southern California, and were based on the state of the fire on 5 July 2007.

Background

Wildfire entrapment avoidance

A common threat that firefighters regularly face when encountering a wildfire is the possibility of being trapped or overrun by the fire. Inadequate planning, poor situational awareness or underestimating potential fire-spread increases the chance of being entrapped. Most tactical decisions made in the fire environment rely on precise timing, and avoiding entrapment relies on situational awareness, knowing when and where to engage a fire and most importantly, when to disengage or change tactics altogether.

A small number of studies have taken a quantitative approach to studying the issue of entrapment avoidance. Butler and Cohen (1998*a*, 1998*b*) investigated the requirements for an adequate firefighter safety-zone and depicted how it is affected by the average sustained flame length at the edge of the safety zone. They determined a safety zone radius four times larger than the flame height would be sufficient for the fire to have limited or no effect on resources within the safety zone. Butler *et al.* (2000) illustrated effectiveness of various escape routes to safety zones, and Ruby *et al.* (2003) analysed the effect pack load had on the transit time and physiological processes of a firefighter utilising an escape route. Dakin (2002) and Baxter *et al.* (2004) measured travel rates for Alberta Type I, II and III firefighters in four common fuel types. Cheney *et al.* (2001) developed the 'Dead-Man Zone' concept to represent the area between the handline and fire's edge during a parallel attack, where a firefighter is suddenly in harm's way if a wind change alters the flank of the fire.

WUIVAC

To help properly assess and respond to risks presented by a situation, wildland firefighters use decision points called triggers, which can be easily identified or communicated, as a way to standardise risk thresholds (Cook 2003). The WUIVAC model (Cova *et al.* 2005) uses modelled fire spread and Geographic Information Systems (GIS) to derive geographic trigger buffers that circumscribe a designated protected asset (e.g. home, road, fire resource). WUIVAC uses a three-step process to establish trigger buffers at time intervals corresponding to user-designated evacuation times. The first step incorporates the fire behaviour model FlamMap (Finney 2006) to determine the rate a fire spreads in eight directions for each cell across a gridded geographic landscape. The second step involves establishing a rate-of-spread network, where the modelled time of a fire's travel from one cell to the next is determined. The final step reverses the spread rate network and then uses Dijkstra's (1959) shortest-path algorithm to create trigger buffers around the protected asset given a specified amount of warning and evacuation time. The resulting modelled trigger buffer represents the minimum time required for fire to travel from the edge of the buffer to the protected asset.

Cova *et al.* (2005) simulated a scenario in which a fire crew was forced to evacuate from the 1996 Calabasas fire in California by creating trigger buffers at 15-, 30- and 45-min intervals for their location. Dennison *et al.* (2007) established 1-, 2- and 3-h trigger buffers at the community scale in multiple 'worst case' scenarios involving maximum winds. Anguelova *et al.* (2010) incorporated the WUIVAC model in a risk management framework designed to model fire behaviour and pedestrian mobility in order to derive maps of wildland-fire risk to pedestrian immigrant traffic in the US–Mexico border region. Larsen *et al.* (2011) used data from the 2003 Cedar fire in California to validate dynamic WUIVAC-modelled evacuation trigger buffers. By adapting the model to adjust for changes in wind speed and direction, they created dynamic trigger buffers that followed the fire's movement with more precision throughout a designated time period.

Preliminary research has demonstrated the potential of WUIVAC in situations where the weather conditions and other behavioural aspects are known. However, there is a need for validation of the model in dynamic situations and for multiple types of protected assets. Also, further analysis of variability in trigger buffer outputs for a range of expected conditions may aid in validating the model's usefulness when future conditions can only be predicted, such as in tactical firefighting situations.

Direct, indirect and parallel attack

When engaging in fire suppression there are three tactical methods of attack that firefighting resources utilise: direct, parallel or indirect (Davis 1959; Cheney *et al.* 2001; NWCG 2004, 2010). Direct attack involves following the fire's edge and suppressing the flame using water, or constructing a fireline which creates a fuel break between the fire and combustible vegetation, ultimately removing the fire's heat and fuel source. If the fire's intensity is such that direct attack is not possible, firefighting resources can withdraw 1 to 5 m from the fire's edge and construct a fireline, by which the fire runs out of combustible fuel and its intensity is decreased substantially. This method is commonly referred to as parallel attack. In this paper, we address personnel engaged in indirect attack (e.g. firing operations, backfiring, line construction) where a fire resource will be at minimum 5 to 7 m, and can be up to several kilometres away from the uncontrolled fire edge, with unburned fuel between the two (Cheney *et al.* 2001).

During the processes of a firing operation, fire personnel not only are in a precarious situation of having unburned fuel between the main fire and their location, but they often find themselves a considerable distance from a designated safety zone. In these situations an important standard operating procedure is to establish an escape route – a pre-identified route of travel – used by fire personnel to travel to a pre-identified safety zone where all fire personnel can seek shelter from risk or injury while not being affected by the fire (Butler and Cohen 1998*a*, 1998*b*). Determining an accurate threshold between the time it takes to evacuate fire personnel to the safety zone, and the time it takes for the fire to overtake them before they reach safety, has a margin of safety. Beighley (1995) first determined a margin of safety metric, which was further illustrated by Baxter *et al.* (2004). A safety margin is mathematically defined as:

$$\text{Safety Margin} = T_1 - T_2 \tag{1}$$

where T_1 is the time for the fire to reach the safety zone and T_2 is the time it takes the firefighter to reach the safety zone. A positive safety margin indicates that a firefighter is able to reach the safety zone, whereas a negative safety margin indicates that the spreading fire entraps a firefighter. Hence, the greater the positive difference between T_1 and T_2, the greater the margin of safety (Baxter *et al.* 2004; Cova *et al.* 2011).

As wildfire behaviour can fluctuate depending on various types of terrain and vegetation that change over a given distance and under dynamic weather factors that change throughout the day, many different fire spread outcomes could occur in a day's burning period. Using the 'margin of safety' concept it is important to assess variability in evacuation travel times for different types of firefighting resources and the resulting variability in evacuation trigger buffers modelled by WUIVAC.

Methods

All data used for this analysis were derived from the 2007 Zaca fire, which occurred in and near Los Padres National Forest in southern California (Fig. 1). The fire started on 4 July 2007 at ~1100 hours and eventually grew to 972 km^2 (240 207 acres), becoming the second largest fire in Californian history. The fire burned through fuels consisting primarily of grasses and chaparral species, and took 2 months to contain and close to 1000 fire personnel to finally extinguish it (Cal-Fire 2007). Contributing to the Zaca fire's rapid growth were high temperatures, irregular offshore winds and a preceding 2-year drought which lowered live fuel moisture and contributed to extreme fire behaviour. However, of greater significance was the rugged terrain, which allowed for rapid fire spread despite the absence of strong winds. This terrain, which fostered unsafe working conditions and restricted access, forced fire personnel to attempt extensive indirect tactics (e.g. backfiring operations) (McDaniel 2007; Keeley *et al.* 2009).

An Incident Action Plan (IAP) is a central tool used for planning operations within an Incident Command System (ICS) for any type of disaster relief. It is a detailed written plan provided for the Incident Management Team, and is designed as a way to communicate and transfer important information (e.g. incident command structure, weather forecasts, operational objectives, safety plan, maps) throughout the organisation. The Incident Weather Forecast portion of the IAP forecasts maximum temperature, minimum humidity, 6 m (20 feet) elevation wind speed and direction, and expected changes in these parameters for the entire day. The IAP also breaks down the operational assignments for a fire into divisional segments for better management of resources. Within each division, besides a summary of supervisor names and radio frequencies, there is a breakdown of the number and type of resources and their operational instructions (e.g. construct line, establish safety zones). For the purposes of this research, the 5 July 2007 IAP for the Zaca fire provided weather and resource data that allowed for fire behaviour and WUIVAC modelling based on an actual situation.

Scenarios

Scenarios were established based on three potential containment lines and three modes of travel: on foot, using fire engines (Type 3 or larger) or using bulldozers (D6 or larger) (Table 1). The 5 July IAP described the operational directive for Division C to use available resources to 'construct line to Division Y'. The three potential containment lines were determined considering the approximate size and location of the fire, accessibility and adequate safety zones for personnel to evacuate to should the fire threaten their safety. These containment lines, labelled A, B and C in Fig. 2, could be used for establishing an indirect line and subsequently used to implement a backfiring operation.

Containment lines A, B and C were used as escape routes to safety zones labelled in Fig. 2. We established five escape route options for the three containment lines, depending on the destination safety zone and direction of travel (Table 1). For containment lines B and C, safety zones are located at the north and south ends of the lines. Containment line A, however, has only one safety zone located at the south-east end of the line. Containment line A is a US Forest Service road, which is accessible by Type 3 engines and on-the-ground firefighters travelling by foot. Containment lines B and C utilise undeveloped, often steep ridgelines which would have to be improved with dozers, thus being only accessible by foot or by dozer with no engine support.

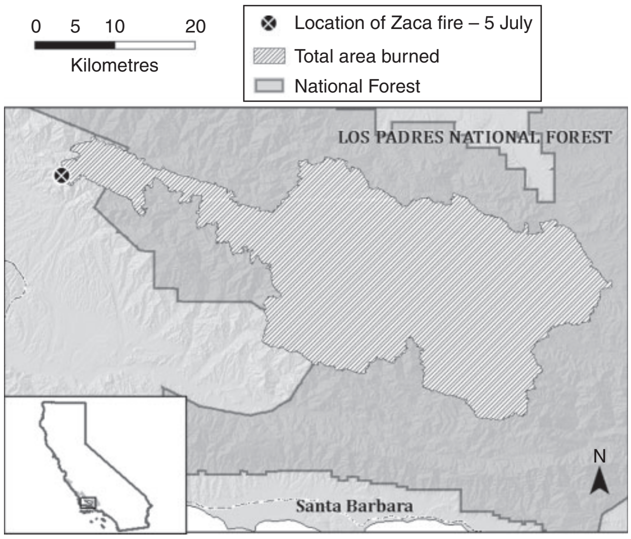

Fig. 1. A map showing the location of the Zaca fire in southern California, including the location of the fire for the modelling scenarios.

Table 1. Scenario parameters for containment lines A, B and C

Containment line	A	B	C
Mode of travel	Engine, on foot	Dozer, on foot	Dozer, on foot
Direction of travel	East	North, South	North, South
Wind direction and speed (km h^{-1})	NE 6.4, NE 12.9, SW 9.7, SW 19.3		
Fuel moisture	5%, 8%		

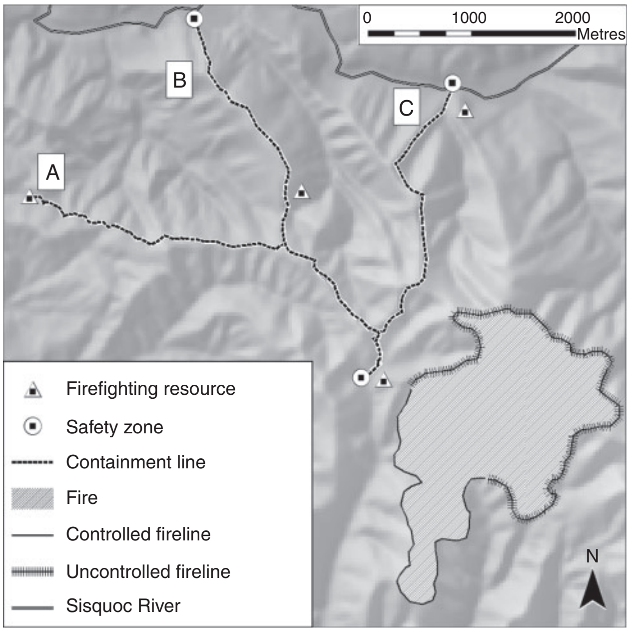

Fig. 2. Three hypothetical containment lines, labelled A, B and C, for the 5 July Zaca fire scenarios. Containment lines were designated as escape routes to safety zones (circles).

Trigger buffers must account for travel time, so that a firefighting resource located at any point on a containment line can safely evacuate to the safety zone. The containment line escape routes were rasterised using a 30-m grid, and travel times were calculated based on assumed travel rates adjusted by slope. Travel rates for each of the three transportation types at a 0% slope were set as: 90 m min^{-1} on foot (OF), 650 m min^{-1} in an engine (EG) and 65 m min^{-1} in a dozer (DZ). The on-foot rate was based on the Baxter *et al.* (2004) study of firefighter mean travel rates for a Type III crew on short grass while carrying both a pack and tool. They recorded a mean rate of 93 m min^{-1}, which we rounded down to 90 m min^{-1} for a slightly more conservative estimate of travel time. Estimated travel rates on flat ground for the engine and dozer were based on the experience of the first author in fighting other fires in the same geographic location with similar roads, terrain and fuel types. To adjust the travel rates for changes in terrain, Tobler's (1993) Hiking Function and the Path Distance tool in ArcGIS (ESRI, Redlands, CA) were used to create travel times for each mode of transportation to a designated safety zone. The result was a raster representing the escape route, with each cell containing the time (rounded to the nearest minute) required to travel from the cell to the safety zone. Each scenario was named based on the following convention: Escape Route (A, B or C), Direction of Travel and Mode of Travel. For example, 'B/N/FT' indicates a scenario where the evacuation occurs along containment line B, moving north to a safety zone, on foot. The maximum travel times for each scenario are listed in Table 2.

Modelling

Wind speed, wind direction and fuel moisture inputs were combined with fuel models and topography from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) (Rollins 2009) to model fire spread rates over a raster landscape. The containment line escape routes were then used as the protected asset in WUIVAC to calculate a trigger buffer that would allow each type of protected asset (i.e. firefighters on foot, engine, or dozer) to safely return to the safety zone. The forecast in the 5 July 2007 IAP called for winds out of the north-east at 6.4 to 12.9 km h^{-1} (4 to 8 miles h^{-1}) in the morning changing to south-west at 9.7 to 19.3 km h^{-1} (6 to 12 miles h^{-1}) later in the day. We utilised these wind directions and speed ranges for fire behaviour modelling. To simulate local, topographically driven winds, wind data went through further processing in WindNinja (Fire Sciences Laboratory, Missoula, MT, USA), a computer aided model for simulating terrain effects on wind at small scales (Forthofer *et al.* 2009). All elevation, aspect, slope and fuel characteristic (canopy cover, height, base height, bulk density) data were collected and organised through the LANDFIRE tools (Reeves *et al.* 2009; Rollins 2009). LANDFIRE provides national maps of wildland fuels and topography at 30-m spatial resolution that can be directly imported into the FlamMap fire behaviour modelling system. Scott and Burgan (2005) fuel models were used with GS2 (moderate load, dry climate grass-shrub), SH7 (very high load, dry climate shrub) and GR2 (low load, dry climate grass) comprising ~85% of the landscape. Slopes were highly variable, with a mean slope of 38% and a standard deviation of 17%.

To establish a range in fuel moisture, we utilised data from the Los Prietos remote automated weather station (RAWS). Located ~40 km south-east of the Zaca fire on 5 July, the Los Prietos RAWS produced the closest recorded weather observations to the fire on this date. We acquired the gravimetric 10-h fuel moisture low and high averages for the operation period of 0700 to 1900 hours on 4 July to predict the values for 5 July. The range for 4 July had a high fuel-moisture of 8% and a low fuel-moisture of 5%, and these values were consistent with the range over the previous 3 days. The two extreme values (5 and 8%) were assigned to 1-, 10- and 100-h fuel moisture inputs as the low and high fuel moisture cases for modelling. Live fuel moisture content was set at 60% based on typical seasonal low values for chaparral vegetation (Dennison *et al.* 2008).

Fire-spread rates across a raster landscape were calculated for all combinations of scenarios, wind speed and direction, and

Table 2. Travel time required to the farthest point on the escape route (A, B or C) used for each scenario
EN, engine; FT, on foot; DZ, dozer

Scenario (escape route/direction of travel/mode of travel)	Evacuation time (min)
A/E/EN	12
A/E/FT	86
B/N/FT	60
B/N/DZ	83
B/S/FT	58
B/S/DZ	80
C/S/FT	124
C/S/DZ	173
C/N/FT	109
C/N/DZ	151

fuel moisture (Table 1) using the FlamMap fire behaviour modelling system. FlamMap was designed to approximate fire behaviour given constant environmental conditions over a given geographical space (Finney 2006). FlamMap calculates the heading fire spread rate using equations developed by Rothermel (1972) and two-dimensional spread rate was derived using relationships between spread rate and fire shape (Anderson 1983). By including the ancillary, weather and fuel data, the spread rates and the azimuth of the maximum spread rate were calculated for each 30-m cell within a 9-km^2 area (100×100 cells) encompassing the fire and firefighting activities. Spread rate in eight directions was then linked to surrounding cells to create a network of fire travel-time. Using escape route travel times, WUIVAC calculated trigger buffers based on the combination of fire spread rates in adjacent cells that could reach the escape route in less than the cumulative travel time for each cell along the route.

The total number of trigger buffers produced by WUIVAC was dependent on the number of containment line escape routes, modes and directions of travel, wind speeds and directions and fuel moistures (Table 1). Three escape routes were modelled, with two modes of travel and one or two directions of travel for each route. Four combinations of wind speed and direction and two fuel moisture values were modelled. Including all of these variables, a total of 80 trigger buffers were created. The trigger buffers were mapped and variability in trigger buffers was compared using the area within each buffer and the maximum distance and direction from the edge of the buffer to the escape route. All area and distance calculations were done using ArcGIS.

Results

Varying fuel moisture, wind speed and wind direction affected the size and shape of the modelled trigger buffers. In all 10 scenarios, the highest fuel moisture (8%) and lowest wind speed (6.4 km h^{-1}) produced the smallest trigger buffer area (Table 3). The lowest fuel moisture (5%) and highest wind speed (19.3 km h^{-1}) produced the largest area, resulting in an average 52% increase in total buffer area. More influential in dictating each trigger buffer's area was a route's evacuation travel time. For example, the trigger buffers for A/E/FT (Fig. 3) are all distinctly larger buffers than those of A/E/EN (Fig. 4). Travel on foot was much slower than travelling in an engine (Table 2); thus, the buffers needed to be large enough to adjust for the longer period of time required to reach the safety zone. A/E/EN's buffers are smaller and tight to the road, giving the resource greater time to complete the tactical objective safely than on-foot traffic would have. The majority of the trigger buffer area was on the south side of escape route A, which indicates fuel characteristics and wind direction make fire spread from that direction more of a threat (Figs 3, 4). Travel rates for on-foot and dozer travel were more similar, so there was a less dramatic difference in buffer area in the B and C escape route scenarios (Table 3).

Trigger buffers were largest near the safety zone, to allow time for the resource to safely evacuate from the farthest point from the safety zone as fire approaches the safety zone. As shown in Fig. 3, a firefighter on foot can leave the west end of the escape route shortly before the fire reaches the route, and still travel away from the fire to the safety zone. The trigger buffer increases in size closer to the safety zone, because a firefighter on the west end of the escape route could be cut off from the safety zone by a fire closer to the safety zone.

Fuel type and topography did have a relatively minor influence on total area but played a stronger role in determining a trigger buffer's shape (i.e. fire spread is typically more rapid in light flashy fuels and the buffer direction extended further in these fuel types to compensate), and modelled fire spread was consistent with typical fire spread in grass and chaparral fuel types. One distinctive feature of the buffers modelled for containment line C was the peninsula-like features extending from the area near the safety zone. For evacuation to the south, the buffer extends much further to the south of the safety zone than in other directions (Figs 5, 6). For evacuation to the north, a portion of the buffer extends to the south on the north-eastern side of the buffer (arrows in Figs 7, 8). This phenomenon was a result of the model adjusting for terrain that was in alignment for rapid fire spread. All other things being equal, fire spreads faster uphill than on the level or downhill due to the enhanced convection and radiant heat transfer caused by advancing flames being brought closer to the unburned fuels.

The trigger buffers indicate which containment lines, and conditions associated with them, could be compromised before tactics are fully implemented. As shown in Figs 5 and 6, all

Table 3. Total area and range (max – min) of modelled trigger buffers (km^2) for each scenario and set of conditions
Escape routes: A, B or C; mode of travel: EN, engine; FT, on foot; DZ, dozer

Wind direction and speed (km h^{-1})	Fuel moisture (%)	Scenario (escape route/direction of travel/mode of travel)										Range
		A/E/EN	A/E/FT	B/N/FT	B/N/DZ	B/S/FT	B/S/DZ	C/S/FT	C/S/DZ	C/N/FT	C/N/DZ	
NE 6.4	8	0.24	0.90	0.26	0.26	0.44	0.56	1.50	2.26	0.90	1.20	2.02
NE 6.4	5	0.25	1.00	0.28	0.28	0.47	0.61	1.71	2.58	0.97	1.34	2.34
NE 12.9	8	0.32	1.37	0.33	0.33	0.64	0.86	2.23	3.37	1.04	1.49	3.05
NE 12.9	5	0.34	1.54	0.38	0.38	0.70	0.96	2.53	3.90	1.15	1.69	3.55
SW 9.7	8	0.26	1.19	0.26	0.26	0.57	0.73	1.84	2.95	0.99	1.36	2.70
SW 9.7	5	0.28	1.29	0.29	0.29	0.62	0.81	2.12	3.46	1.09	1.54	3.18
SW 19.3	8	0.41	1.72	0.46	0.46	0.79	1.07	2.80	4.50	1.20	1.71	4.09
SW 19.3	5	0.43	1.89	0.51	0.51	0.86	1.24	3.27	5.15	1.32	1.96	4.71
	Range	0.19	0.99	0.25	0.25	0.42	0.68	1.77	2.89	0.42	0.76	

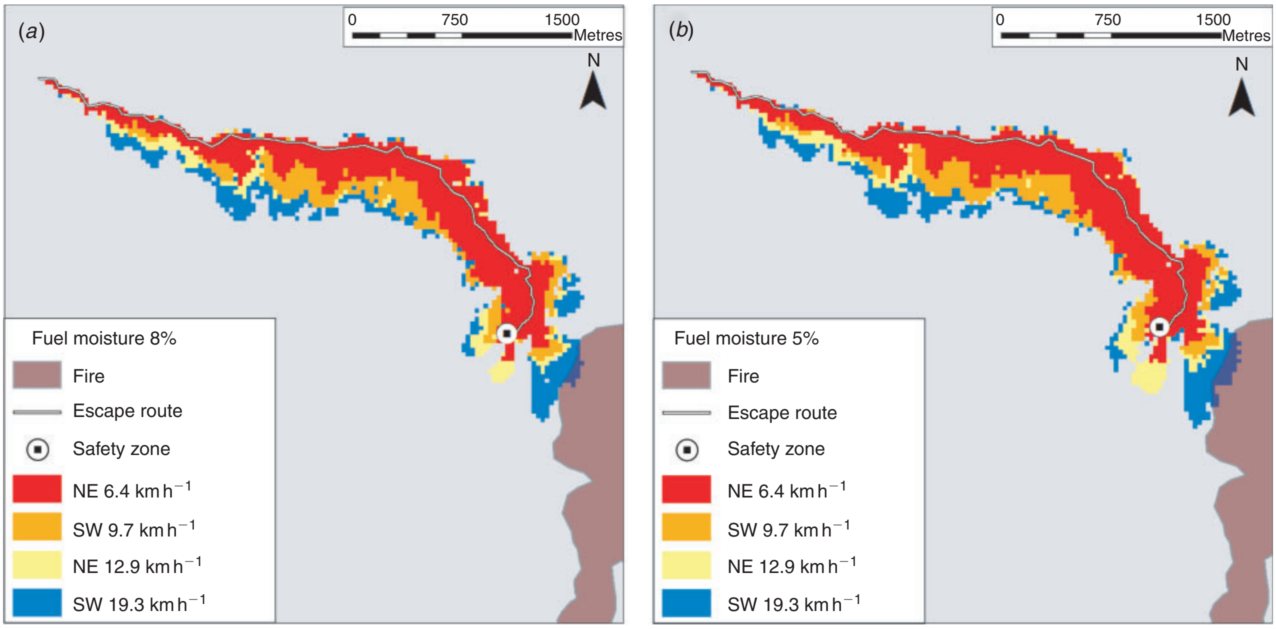

Fig. 3. Trigger buffers for escape route A, for travel on foot: (*a*) Buffers for scenarios using 8% fuel moisture, (*b*) Buffers for scenarios using 5% fuel moisture.

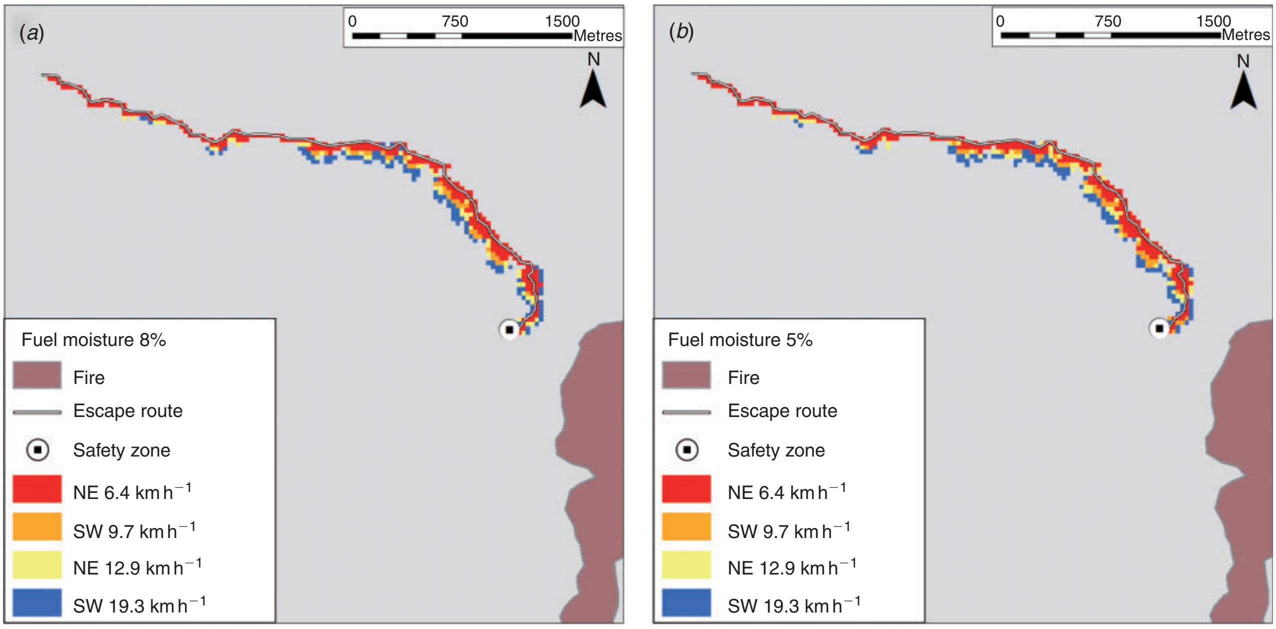

Fig. 4. Trigger buffers for escape route A, for travel by engine: (*a*) Buffers for scenarios using 8% fuel moisture, (*b*) Buffers for scenarios using 5% fuel moisture. Smaller buffer size relative to Fig. 3 indicates the faster rate of travel of an engine.

of containment line C's trigger buffers for a southward evacuation overlap with the perimeter of the Zaca fire on the morning of 5 July. Implementing containment line C with using the southern safety zone could put resources in harm's way before construction on the line was completed. Using 19.3 km h^{-1} SW winds, trigger buffers modelled for containment line A travelling on foot to the east (Fig. 3), and containment line C travelling by dozer to the north (Fig. 8) also overlap with the Zaca fire perimeter. However, the northern escape route puts less buffer area closer to the fire than the southern escape route for containment line C.

Both wind direction and speed, as well as vegetation location and type, influenced the maximum distance of each buffer from the escape route (Fig. 9). Even though containment lines B and C

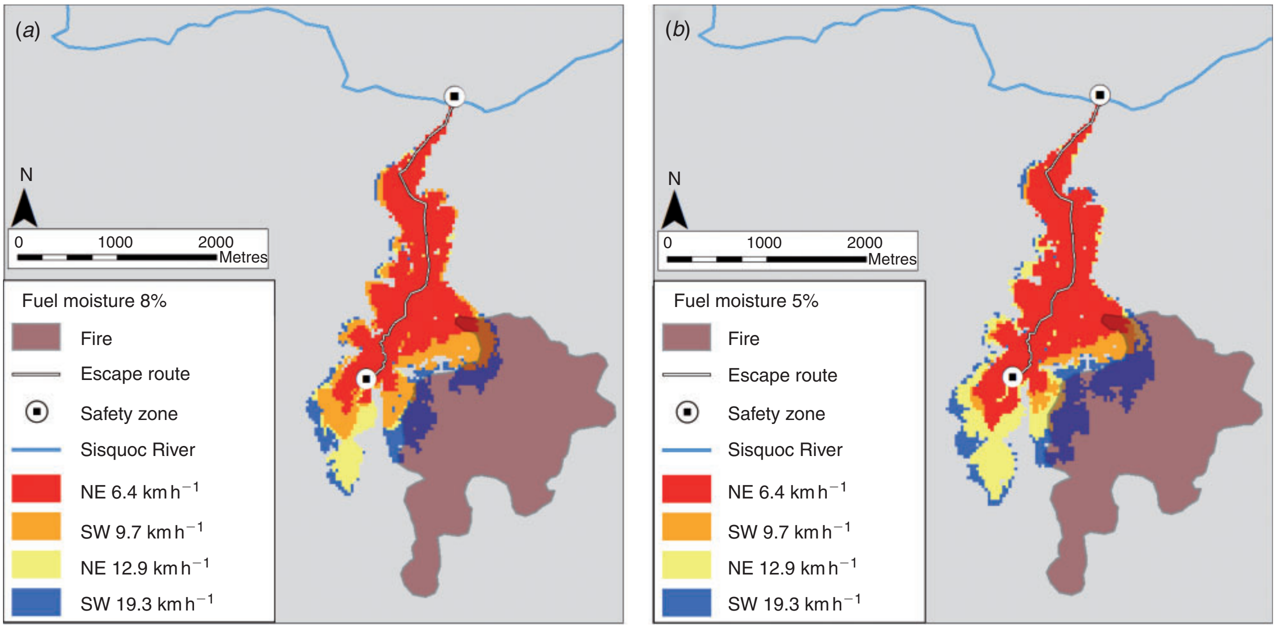

Fig. 5. Trigger buffers for escape route C evacuating to the south safety zone, for travel on foot: (*a*) Buffers for scenarios using 8% fuel moisture, (*b*) Buffers for scenarios using 5% fuel moisture.

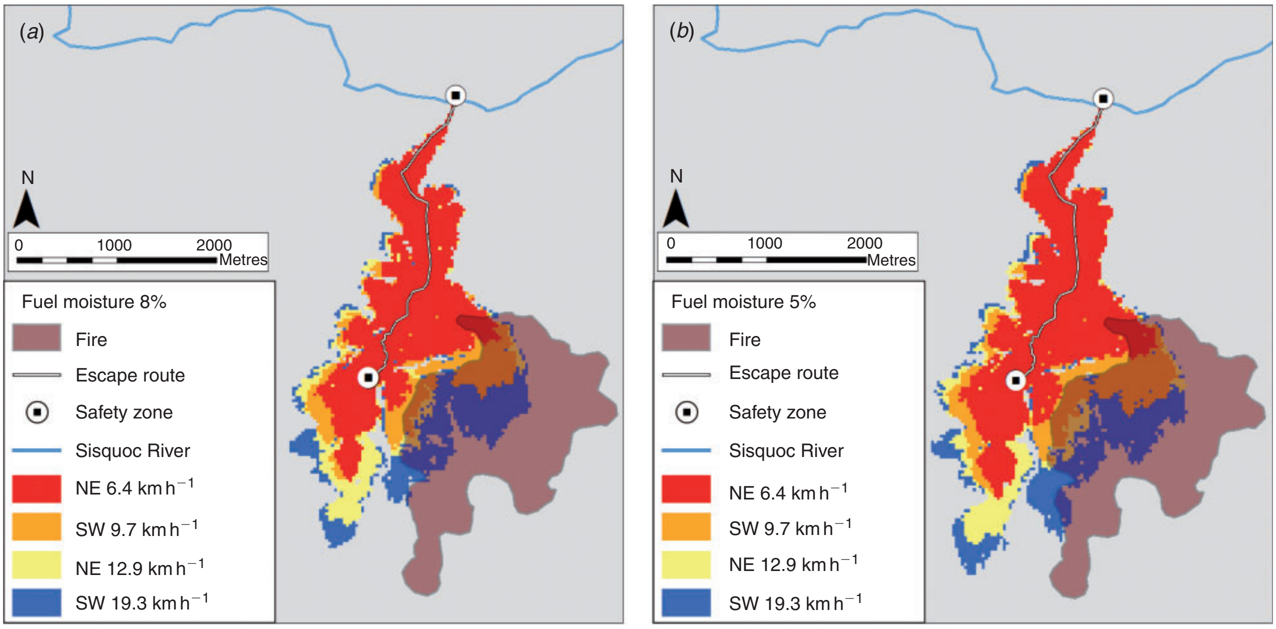

Fig. 6. Trigger buffers for escape route C evacuating to the south safety zone, for travel by dozer: (*a*) Buffers for scenarios using 8% fuel moisture, (*b*) Buffers for scenarios using 5% fuel moisture. Larger buffer size relative to Fig. 5 indicates the slower rate of travel of a bulldozer.

run mainly north–south and containment line A runs north-west–south-east, the maximum extents for the trigger buffers run in a south-west–north-east direction due to wind direction. The trigger buffers extend in the direction of oncoming winds to establish enough time for resource evacuation for a fire coming from the upwind direction. Although there was a north-east–south-west trajectory of maximum buffer extent, the 8 trigger buffers for each of the 10 tactical scenarios are mostly grouped together, demonstrating that the range of wind speeds and fuel moistures can produce similar maximum buffer extents within the same scenario. Most buffer maximum extents were towards the south-west, likely due to terrain and fuels creating more rapid fire spread in a north-easterly direction to the south and west of the containment lines.

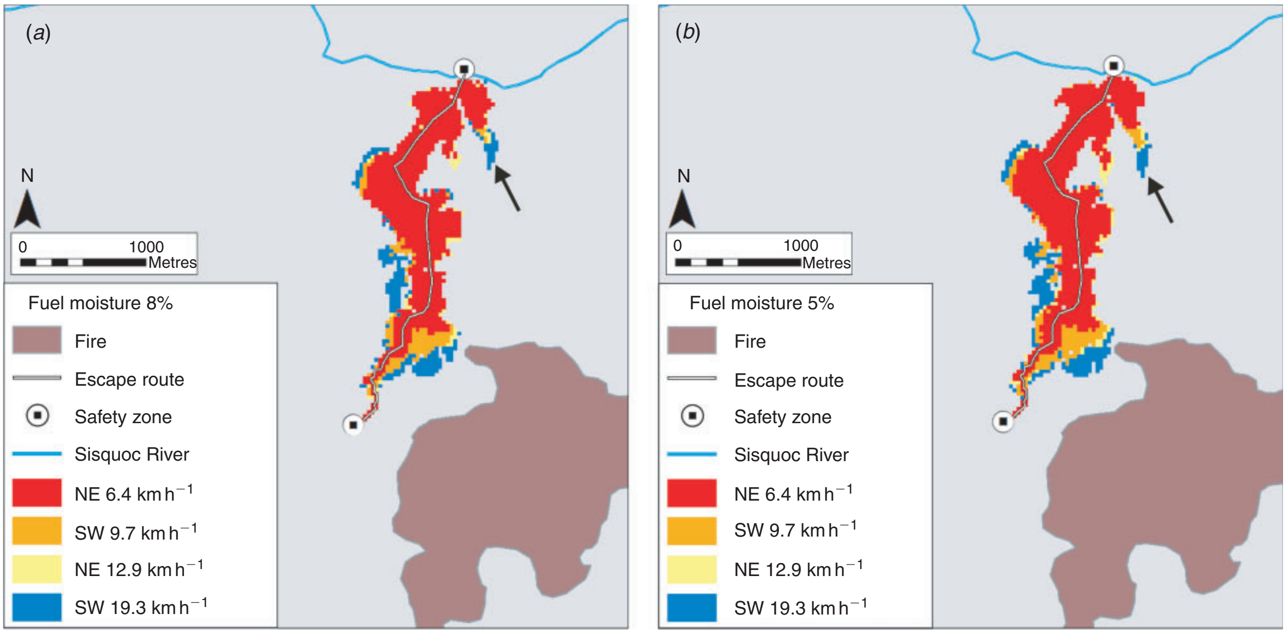

Fig. 7. Trigger buffers for escape route C evacuating to the north safety zone, for travel on foot: (*a*) Buffers for scenarios using 8% fuel moisture, (*b*) Buffers for scenarios using 5% fuel moisture. The arrows indicate lobes of the trigger buffers produced by slope and fuels adjacent to the safety zone.

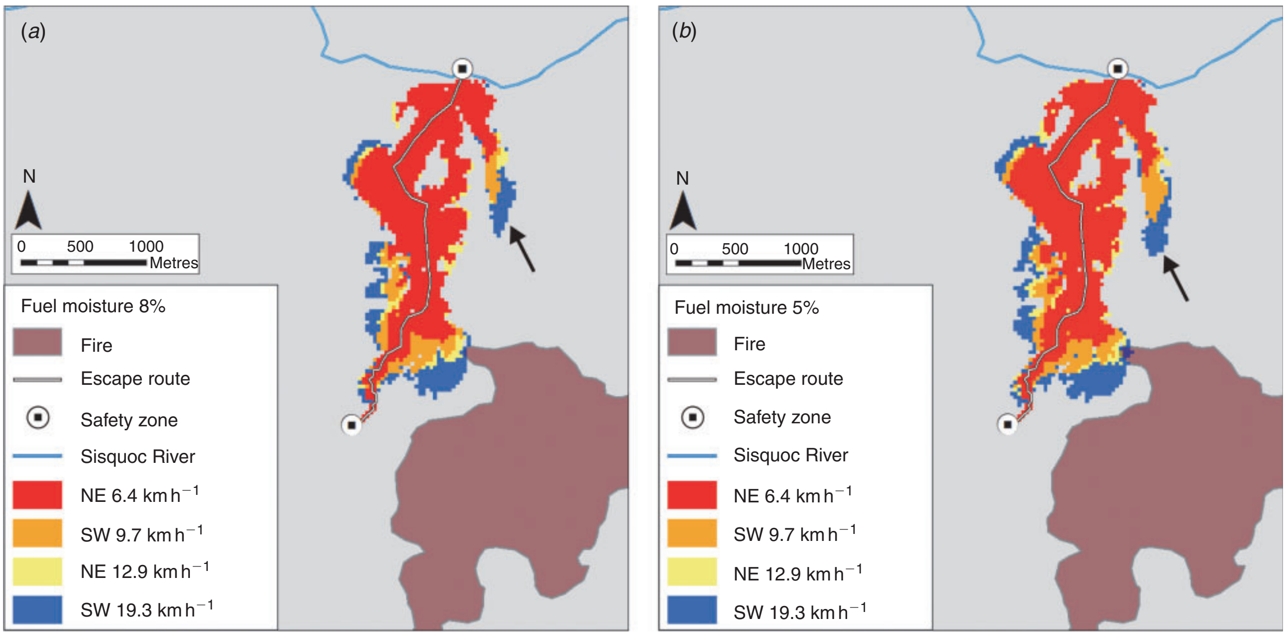

Fig. 8. Trigger buffers for escape route C evacuating to the north safety zone, for travel by dozer: (*a*) Buffers for scenarios using 8% fuel moisture, (*b*) Buffers for scenarios using 5% fuel moisture. The arrows indicate lobes of the trigger buffers produced by slope and fuels adjacent to the safety zone.

Discussion

Tactical decision-making in highly stressful and time sensitive situations is extremely challenging and can often be problematic, potentially leading to unsuccessful outcomes (USFA-NFPA 2002). Analytical tools have the ability to aid in what is most often an intuitive decision process conducted in complex and demanding situations by firefighters with a wide range of experience, knowledge and capabilities. However, uncertainty and limitations associated with GIS and fire behaviour models are well documented (Bachmann and Allgöwer 2002; Zhang and Goodchild 2002; Alexander and Thomas 2004; Jimenez *et al.* 2008), and decisions based solely on model outputs are unwarranted in most tactical situations involving fire suppression. For example, problems would arise if the trigger buffer

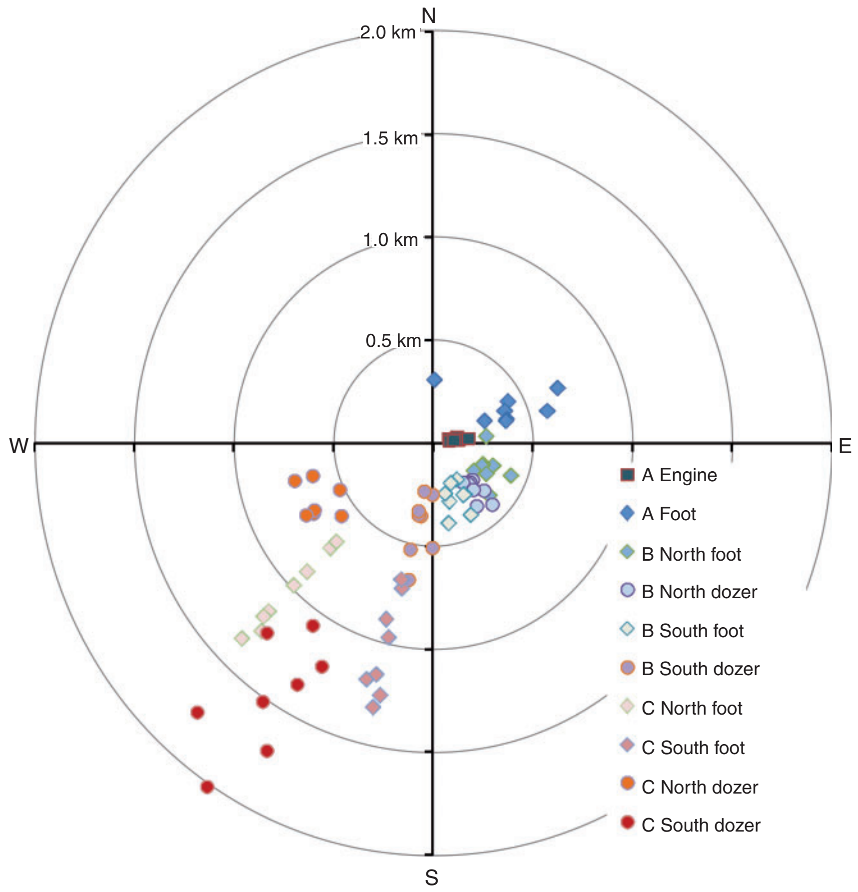

Fig. 9. Distance and direction of the maximum extent of all 80 trigger buffers.

size needed for evacuation fell beneath the cell resolution size (30 m in this case), or the fuel and weather conditions were outside the range of the predicted conditions. As weather conditions are dynamic, real time weather observations taken onsite at designated intervals could be used to update models to match current conditions.

A trigger buffer's size and shape varied strongly between the 10 scenarios, due to differences in travel route and travel time. However, variations between the high and low wind and fuel moisture inputs across the 10 scenarios were relatively small (Table 3). We only tested for a range of expected conditions for one day of one fire and were unable to address increases in trigger buffer variability that would result from more extreme conditions. For example, gusts above the predicted wind speeds, which would affect fire spread rates, were not accounted for in the model (Crosby and Chandler 1966). Accuracy of modelled trigger buffers is constrained by the accuracy of modelled fire spread. WUIVAC is currently linked to Rothermel-based fire spread as implemented in FlamMap. Spotting was not included in the modelled fire spread, and spotting ahead of the fire front could lead to firefighter entrapment. However, WUIVAC could alternatively use any deterministic fire spread model that provides a directional spread rate or an ensemble modelling approach (e.g. Cruz 2010).

Operational firefighting uses 'lookouts' to monitor the positions of both the fire and firefighting resources (NWCG 2010). Trigger buffers could be utilised by lookouts to give ample warning if a fire advances in a way that threatens those resources. Tying trigger buffers to salient features in the landscape (e.g. ridges, rivers or roads) could assist lookouts in visually determining whether fire has breached the buffer and evacuation is advisable. Adjustments can be made to the triggers to accommodate understanding, or lack of understanding, of the fire dynamics connected to an area.

This study standardised escape route time to determine uncertainty in modelled trigger buffers given a range in weather and fuel conditions. Escape route time can change dramatically during an evacuation due to changes in terrain, changes in physical ability and limitations in visibility due to smoke along any given route. If the WUIVAC model is used in future tactical situations, adjustments for containment lines, escape route travel times, designated safety zones and resource capabilities would theoretically be determined and assessed by fire managers on the ground and communicated to the person running the model. Safety protocols already dictate that escape routes should be walked out and timed, and that safety zones are agreed upon in advance (NWCG 2010).

Modelled trigger buffers can also be used for protective actions other than evacuation (Cova *et al.* 2009). Fig. 10 shows a shelter-in-place (SIP) trigger buffer for containment line C assuming travel by dozer, 5% fuel moisture and a south-west 19.3 km h^{-1} wind. The trigger buffers for the south safety zone

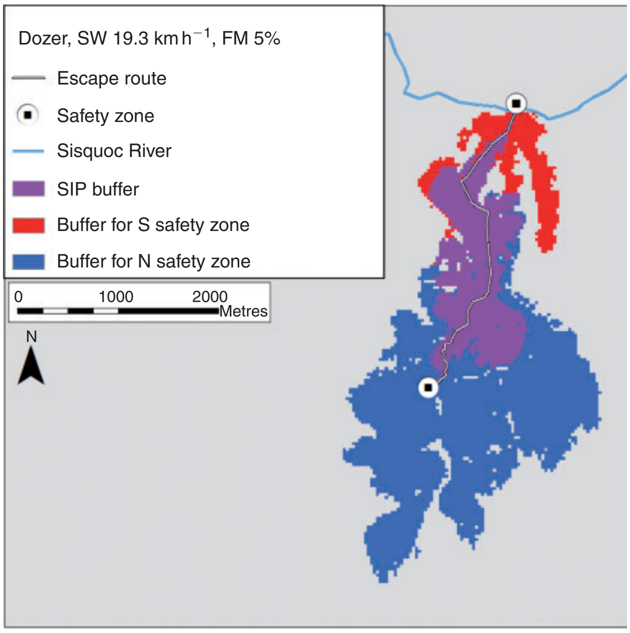

Fig. 10. An example of a shelter-in-place (SIP) trigger buffer, where a dozer on containment line C may not be able to reach either safety zone (circles) if the fire crosses into the area coloured magenta.

(blue) and north safety zone (red) are overlaid. The intersection of these two buffers, shown in magenta, is an area where both the north and south safety zones may be unreachable if the fire takes a direct path towards the escape route. Within the overlap area, the best option for an escaping firefighter may be to shelter in place, rather than risk an unsuccessful evacuation to one of the two potentially inaccessible safety zones. The threatened firefighter could use time that would normally be dedicated to travelling the remaining distance of the escape route to pick the best immediate shelter and prepare before burnover occurs (e.g. remove vegetation, set a backfire), providing greater potential for survival.

Conclusions

The 80 modelled scenarios, which span a range of escape routes, modes of travel and predicted fire behaviour conditions for the 5 July 2007 operational period for the Zaca fire, were derived in order to analyse the variability in output trigger buffers. Travel time was the most important factor in determining trigger buffer area and maximum extent. Travel time and distance to a safety zone are predictable for a known route; however, it should be noted that the predetermined escape route travel time could be increased by unforeseen obstacles (e.g. reduced visibility due to smoke, trees falling across the route). Overall, variability in output trigger buffers was relatively low under the tested ranges of conditions, allowing for a firefighting resource to use them as a reference in planning indirect tactical objectives.

Additional research is needed to assess the use of WUIVAC in different fuel and terrain types along with applying the model to different tactical scenarios. Further analysis should also include determining the variability associated with buffers generated from observed conditions in intervals throughout the day (e.g. hourly). Real-time modelling could be useful in fire operations at the divisional level, where fire personnel would be able to get on-the-spot trigger buffer outputs, and allow for more informed decision-making.

Acknowledgements

This research was supported by NSF grants CMMI-IMEE 0653752 and 1100890. We also thank the reviewers for their thoughtful reviews.

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