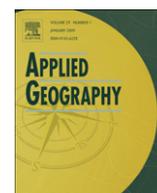




Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Evaluating dynamic wildfire evacuation trigger buffers using the 2003 Cedar Fire

Jeremy C. Larsen^a, Philip E. Dennison^{a,*}, Thomas J. Cova^a, Charles Jones^b^a Department of Geography, Center for Natural and Technological Hazards, University of Utah, 260 S. Central Campus Dr., Room 270, Salt Lake City, UT 84112, USA^b Institute for Computational Earth System Science, University of California, Santa Barbara, Santa Barbara, CA, USA

A B S T R A C T

Keywords:

Wildfire
Wildland–urban interface
Evacuation modeling
California

Despite threats posed to communities from wildfire, few tools exist to aid emergency managers in recommending evacuations. An evacuation trigger buffer is a pre-established boundary encompassing a community or asset that triggers an evacuation recommendation should a fire cross the edge of the buffer. The Wildland–Urban Interface Evacuation model (WUIVAC) delineates evacuation trigger buffers based on modeled fire-spread rates and estimated evacuation times. A point along the edge of a WUIVAC-generated trigger buffer represents the modeled shortest time required for a fire to travel to a community. The objective of this research is to use data from the 2003 Cedar Fire in southern California to evaluate the temporal and spatial differences between evacuation trigger buffers as generated by WUIVAC and the perimeter and spread of a historical fire. Three trigger buffers surrounding a test community were created for hourly increments and analyzed in conjunction with the equivalent hourly locations of the leading edge of the Cedar Fire. The novel use of forecast winds yielded dynamic trigger buffers that varied with changes in wind speed and direction. The modeled trigger buffers exceeded the actual fire front by as much as 126 m for the 1-h buffer and 1400 m for the 3-h buffer, which implies that evacuees would have had slightly more time for evacuation than indicated by the trigger buffers. Had WUIVAC been used operationally during this event in the manner presented in this paper, it would have likely been successful in triggering an evacuation with enough time for the community to safely evacuate. This research represents a first step towards validating WUIVAC-modeled evacuation trigger buffers.

© 2010 Elsevier Ltd. All rights reserved.

Introduction

Wildfire represents a significant hazard for inhabitants of the wildland–urban interface (WUI), which is defined as the areas where homes meet or intermix with fire-prone wildlands (Radeloff et al., 2004). Theobald and Romme (2007) estimated that there are 12.5 million homes located within the WUI in the continental United States. Communities within the WUI are particularly susceptible to wildfire as they are often surrounded by abundant fuel sources that rarely see controlled burns. In October 2003, WUI fires in southern California were responsible for 26 deaths and the destruction of 3361 homes, representing the single worst WUI fire event in U.S. history (Keeley, Fotheringham, & Moritz, 2004).

The large, at-risk population in the WUI represents a significant problem for emergency response and incident commanders. Decision-makers must determine when and where an evacuation is warranted, often using incomplete information (Gill & Stephens,

2009). Factors considered in recommending an evacuation include fire location, environmental data (e.g. forecast winds, relative humidity), fuels ahead of the fire, topography, locations of residents, mobility, evacuation route capacity, and many others. The decision to evacuate a community is generally subjective and based on prior experience and the best available information. Common errors in recommending evacuations include those associated with zoning (who should be evacuated?), timing (when should an evacuation occur?), and routing (which way should evacuees leave?).

As WUI fire hazard continues to increase (Moritz & Stephens, 2008), protective actions have become an increasing focus of recent research (Angelova, Stow, Kaiser, Dennison, & Cova, 2010; Cohn, Carroll, & Kumagai, 2006; Cova, Dennison, Kim, & Moritz, 2005; Cova, Drews, Siebeneck, & Musters, 2009; Dennison, Cova, & Mortiz, 2007; Handmer & Tibbits, 2005; Kim, Cova, & Brunelle, 2006; McCaffrey & Rhodes, 2009; Mozumder et al., 2008; Paveglio, Carroll, & Jakes, 2008; Wolshon & Marchive, 2007). One technique used for assessing when an evacuation should be recommended is a trigger buffer. An evacuation trigger buffer is an established boundary that circumscribes a community, such that

* Corresponding author. Tel.: +1 801 585 1805.

E-mail address: dennison@geog.utah.edu (P.E. Dennison).

when a fire coming from any direction crosses the buffer, an evacuation is advised. Trigger buffers have been applied to determine evacuations for natural hazards such as hurricanes (FEMA, 2000), yet few studies have modeled them in the context of wildfires.

The Wildland–Urban Interface Evacuation (WUIVAC) model was created to model evacuation trigger buffers for wildfires (Cova et al., 2005; Dennison et al., 2007). This study investigates the temporal and spatial differences between evacuation trigger buffers generated by WUIVAC and the perimeter and spread of a historical fire, the 2003 Cedar Fire in southern California. Unlike previous WUIVAC simulations that assumed constant wind conditions, this study extends WUIVAC into a dynamic context where wind can change direction and speed during a scenario. Evacuation trigger buffers were created using information that was available prior to the fire, including temporally and spatially dynamic winds.

Background

WUIVAC uses a three-step process to create an evacuation trigger buffer for selected cells in a raster. The first step relies on the FLAMMAP software package developed by the United States Department of Agriculture Forest Service (USFS) Fire Sciences Lab. FLAMMAP is used to determine the rate and direction of fire spread across a rasterized landscape. FLAMMAP uses equations developed by Rothermel (1972) to calculate fire-spread rate in one direction. Relationships between spread rate and fire shape developed by Anderson (1983) and implemented by Finney (1998) are used to calculate the two-dimensional spread rates. Inputs to FLAMMAP used for WUIVAC include wind speed and direction, fuel type, fuel moisture, slope, and aspect.

For the second step, WUIVAC uses the spread rates calculated by FLAMMAP to create a fire-spread network that connects each cell in a raster with its eight adjacent neighboring cells. Each arc within the network defines the estimated travel time between adjacent cells. To determine the time required for fire to spread from one cell in the raster to any other cell, the fire travel-time arcs between cells are summed (Finney, 2002; Miller, 2003). The third step involves reversing all arcs in the fire travel-time network starting from one or more protected “community” cells and traveling outward until a specified time interval is reached (Dijkstra, 1959). This step generates a trigger buffer for any estimated evacuation time

interval specified by the user (Cova et al., 2005). Using the shortest path from a community to the other cells in the grid, WUIVAC determines all cells from which fire could reach the community within the specified time period.

Fig. 1 shows an example of a WUIVAC trigger buffer for a simple scenario that assumes homogeneous fuels and no slope. The user in this case selects a 3 h evacuation time. Wind, fuel, and topography inputs are used to create the trigger buffer represented by the dashed line. A fire crossing any point along the dashed line can reach the community in 3 h. This time represents “shortest path” fire travel time, and the fire can take longer to reach the community along alternate paths. A fire that starts inside the trigger buffer may be able to reach the community in less than 3 h.

In Fig. 1, the trigger buffer has an elliptical shape based on fire-spread rates produced by Rothermel (1972) and Anderson (1983). This ellipse is pointed upwind, since fire may travel further during a given period of time in the downwind direction. The upwind elongation of the trigger buffer increases with wind speed. Heterogeneous topography and fuels can create an irregularly-shaped trigger buffer (Fig. 2). Fires move more slowly through fuels that contain more live vegetation, since the moisture that is present in live vegetation must be driven off before the vegetation can combust. Fires also move more rapidly up a slope than down a slope, due to increased efficiency of radiative and convective heat transfer to unburned fuels (Pyne, Andrews, & Laven, 1996). Faster fire-spread rates will result in extensions of the trigger buffer away from the community (Fig. 2).

Cova et al. (2005) demonstrated how WUIVAC might be used to create evacuation trigger buffers for fire-fighting personnel in an operational context. Trigger buffers were modeled for a fire-fighting crew injured in the 1996 Calabasas Fire in southern California. Fuel and topography rasters with a 10 m spatial resolution and covering 1.6 km² were used to model evacuation trigger buffers that would have provided 15, 30, and 45 min of warning. Dennison et al. (2007) used WUIVAC to create strategic trigger buffers for a community-scale evacuation in Julian, California. Maximum wind speeds from multiple directions over an eight year period were used to create evacuation trigger buffers for “worst-case” scenarios for the community. Trigger buffers were modeled to provide 1, 2, and 3 h of warning. Multiple trigger buffers were combined to find those areas around the community that had high strategic importance for wildfire evacuation. Anguelova et al. (2010) used WUIVAC

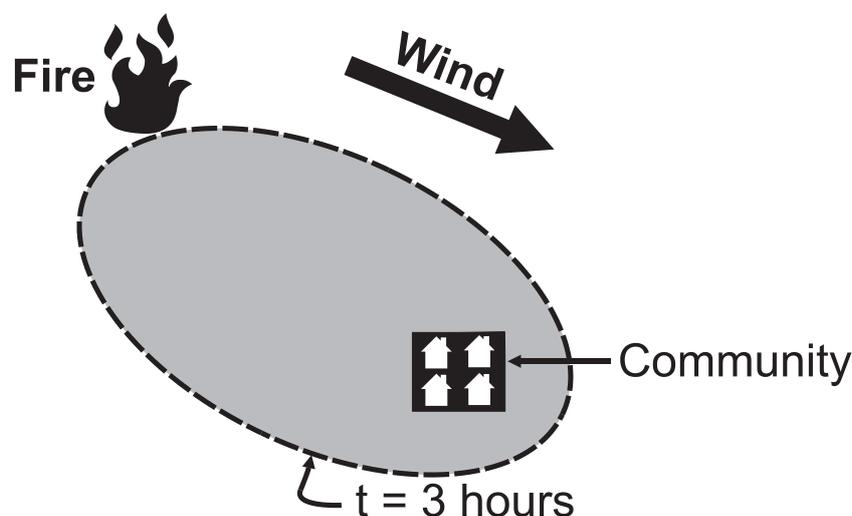


Fig. 1. A conceptual diagram of a WUIVAC trigger buffer.

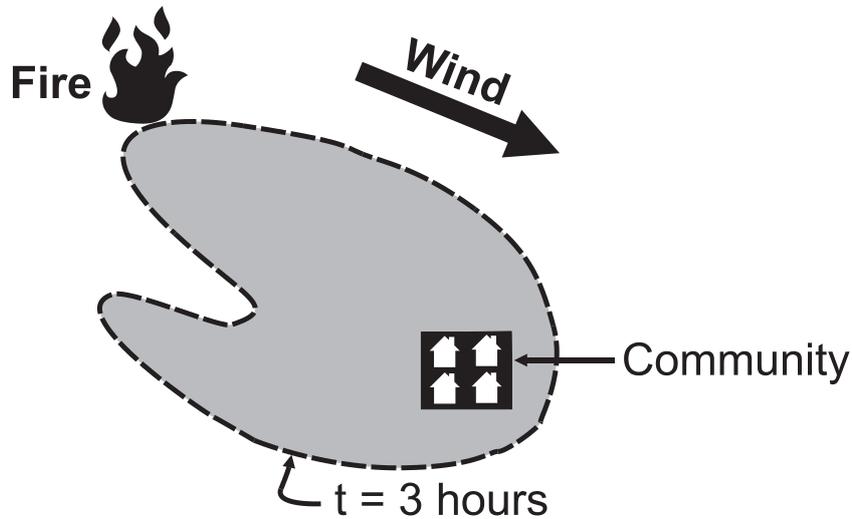


Fig. 2. The trigger buffer shown in Fig. 1 becomes irregular when heterogeneous fuels and topography are considered.

in combination with a pedestrian mobility model to examine fire hazard for immigrants and law enforcement in an area of California adjacent to the United States–Mexico border. Trigger buffers produced by WUIVAC were compared to pedestrian travel times to find those areas where travel time exceeded the minimum time available for evacuation to a safe location.

The prior applications of WUIVAC have relied on constant (i.e. static) winds. There is a need to both extend the model to incorporate dynamic wind data and to quantitatively compare modeled evacuation trigger buffers to actual fire behavior. Should WUIVAC

overestimate the minimum time required for a fire to reach a community, the result could be an evacuation when insufficient time remains for all residents to reach safety (Cova et al., 2009; Handmer & Tibbitts, 2005). This study uses fire perimeters from the 2003 Cedar Fire in southern California to assess how accurately evacuation trigger buffers modeled by WUIVAC reflect actual times for fire to spread from the edge of the buffer to a community within the buffer. The results of this research represent the first attempt to validate the WUIVAC model, albeit one in the context of hindcasting for a prior event.

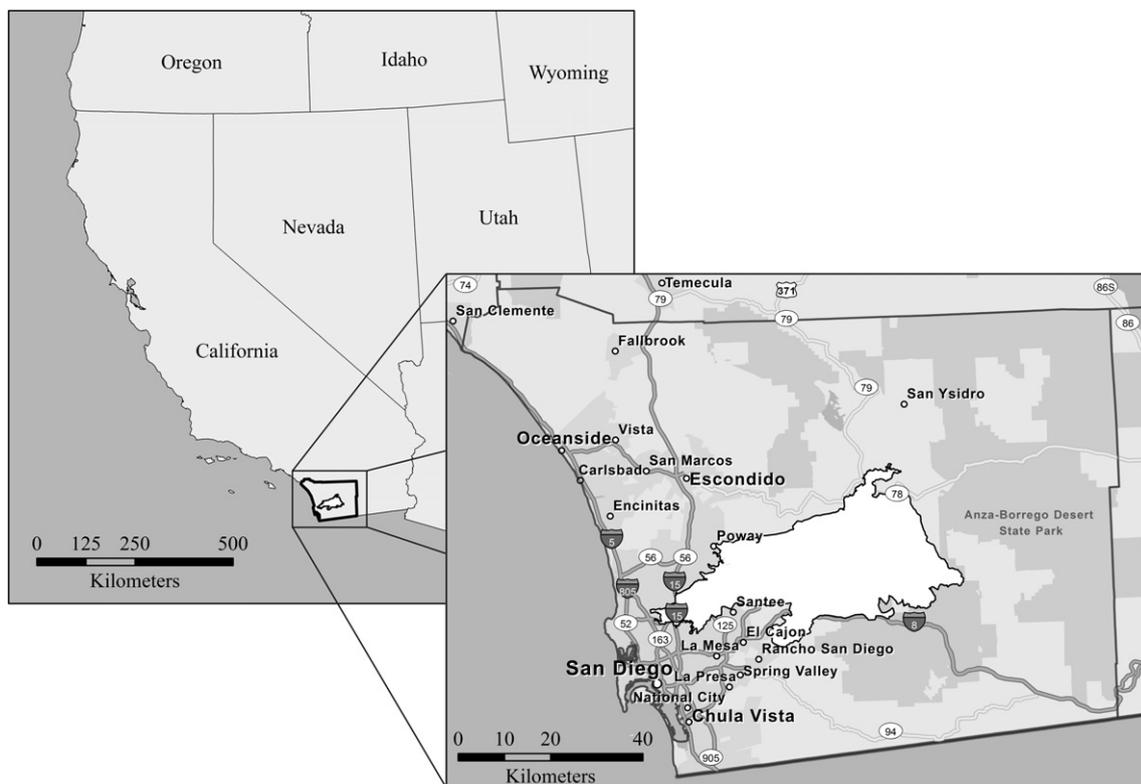


Fig. 3. The left panel shows San Diego County with respect to the state of California. The right panel shows the extent of the 2003 Cedar Fire (white polygon) with respect to cities in San Diego County.

Methods

2003 Cedar Fire

The Cedar Fire burned large areas of San Diego County, California, USA in late October 2003 (Fig. 3). The fire was ignited on the evening of October 25 by a lost hunter in the rugged hills of Cleveland National Forest. The fire rapidly grew towards the west, driven by the prevailing Santa Ana winds. After burning nearly 48 km towards the coast, the winds shifted and drove the heel of the fire eastward. By the time the fire was contained 11 days later, a total of 24 communities comprising more than half a million residents had been issued an evacuation recommendation. The event destroyed 2232 residential homes, and 14 lives were lost (Blackwell & Tuttle, 2003). The fire was responsible for burning over 1100 km², and was one of the largest fires in California's history.

A neighborhood within the Cedar Fire perimeter, on the edge of Poway, California, was selected for WUIVAC modeling. Poway is located approximately 35 km² north of San Diego. The city is bordered immediately to the east by hills covered with chaparral fuels. A residential development consisting of approximately 160 homes and surrounded by vegetation and steep slopes on three sides was selected (Fig. 4). Garden Road is the only evacuation route for residents in this community. As the Cedar Fire spread west during the early morning hours of October 26, 2003, it consumed the hills surrounding the development. The fire initially reached this community at approximately 6 a.m. and continued to burn west until it reached the city of Poway by 10 a.m. (Fig. 4).

Data

Thirty-meter spatial resolution topography and fuels data were used to model both the evacuation trigger buffers and intermediate

fire perimeters that represent the fire's progression. Slope and aspect were calculated from a United States Geological Survey digital elevation model. Pre-fire fuels data were extracted from a California Department of Forestry and Fire Protection (CalFire) data set. Fuel models for vegetation types in San Diego County range from grass and brush to various types of surface litter and timber. However, the two most common fuel models are models 4 and 5, which correspond to chaparral and light brush, respectively (Table 1). Both fuel types are typical of southern California and possess high fuel loads (Anderson, 1982). Chaparral and light brush fuel models are further characterized by rapid fire-spread rates. Fuels in the immediate area of the Garden Road community dominantly consist of chaparral (fuel model 4) and light brush (fuel model 5), though light conifer (fuel model 8) and grasses (fuel model 1) are also present to a much smaller degree.

Fire perimeter data from the 2003 Cedar Fire was also provided by CalFire. Perimeters in the vicinity of the Garden Road community were recorded for 3 a.m., 6 a.m., and 10 a.m. local time on the morning of October 26, 2003 (Fig. 4). Over the 3-h period between 3 a.m. and 6 a.m. the fire front moved 1.6 km west. Since the fire was estimated to have reached the Garden Road community by 6 a.m., only one CalFire perimeter (3 a.m.) was available for comparison with a WUIVAC trigger buffer. To provide higher spatial and temporal resolution information on the progression of the Cedar Fire, we used the FARSITE fire-spread model (Finney, 1998) to model the Cedar Fire perimeter at hourly intervals between 3 a.m. and 6 a.m. FARSITE is an operational, vector-based model used by the USFS to model fire spread and behavior. Like FLAMMAP, the FARSITE model is based on equations developed by Rothermel (1972) and Anderson (1983). FLAMMAP models fire-spread rates within cells, but does not propagate a fire from cell to cell. In contrast, FARSITE can simulate fire events and propagates a vector fire front from multiple vertices along the fire front using Huygens' Principle (Richards, 1990).

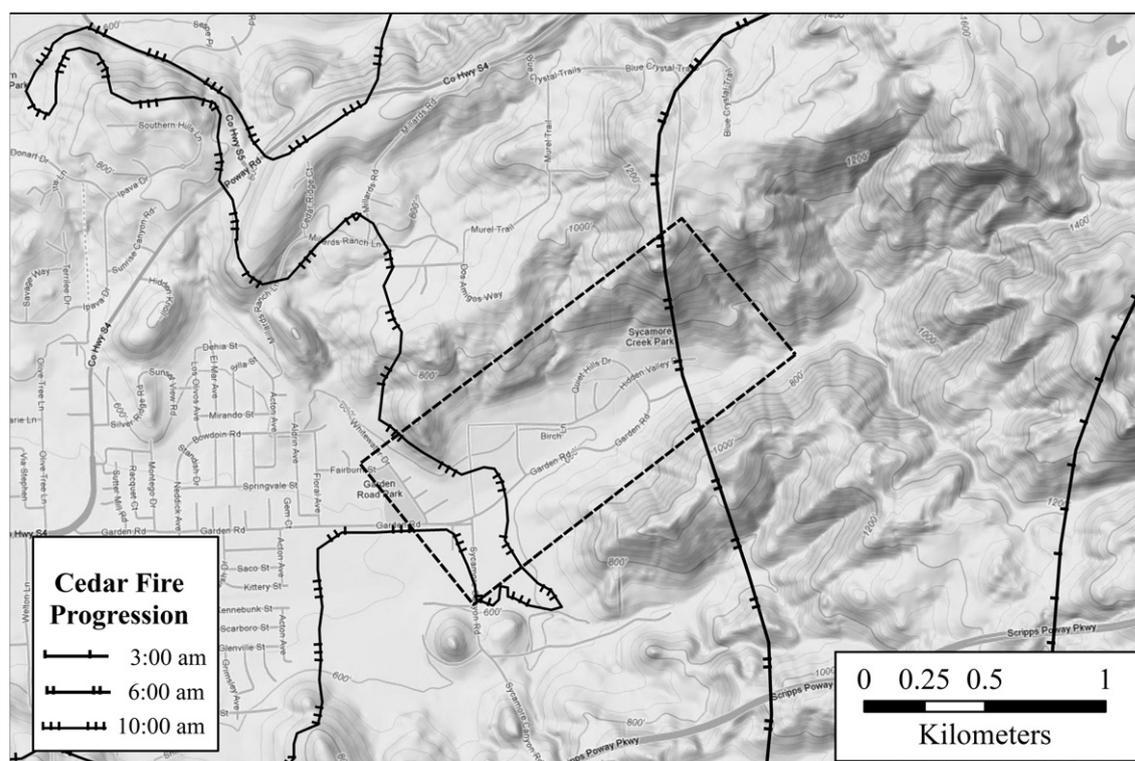


Fig. 4. A map showing the location of the Garden Road neighborhood (inside the dashed box) in relation to the city of Poway, California, as well as the position of the Cedar Fire during the morning of October 26th, 2003.

Table 1

San Diego County fuel models. "Fuel Model Number" corresponds to Albini's (1976) fuel model classification system, along with two custom models specific to the CalFire fuels database (models 15 and 28). "Area (km²)" describes the total spatial extent of each fuel model within San Diego County.

Fuel model number	Fuel description	Area (km ²)
1	Grass	1114
2	Pine/grass	401
4	Tall chaparral	2317
5	Light brush	2311
6	Intermediate brush	189
8	Hardwood/conifer light	222
9	Medium conifer	131
10	Heavy conifer	108
15	Desert	2019
28	Urban	1384
97	Agriculture	537
98	Water	46

The 30 m resolution topography and fuels layers were used as inputs into the FARSITE simulation. Wind speed and direction inputs were varied until the modeled 6 a.m. perimeter matched the CalFire 6 a.m. perimeter in the vicinity of the Garden Road community. The final wind variables used were a static wind speed of 21 km² per hour coming from an azimuth direction of 100°. Ten- and 100-h dead fuel moisture measured at two local Remote Automated Weather Stations (RAWS), and 52% live herbaceous and woody fuel moisture based on local fuel sampling measurements, were also used as inputs for FARSITE. The simulation was initialized using the CalFire 3 a.m. fire perimeter. The FARSITE simulation time step was set to 30 min, and from these time steps, modeled fire perimeters were produced at hourly intervals from 4 a.m. to 6 a.m. The perimeter and distance resolution variables in FARSITE were set to 60 m, while the fuel adjustment file, which allows for burn rate modifications to each fuel type, was left at the default value of 1 (no adjustment) for all fuels.

WUIVAC modeling

One, two, and three-hour evacuation trigger buffers were modeled for the Garden Road community using WUIVAC. An *n*-hour trigger buffer is one that provides at least *n* hour(s) of advance time before the fire arrives at the community. The 30-m cells containing homes were selected as the community area. The fuel model layer, topography layers, and fuel moisture values described earlier were used as inputs into FLAMMAP. To evaluate the predictive performance of WUIVAC, forecast wind speed and direction from the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model 5 (MM5, version 3; Grell, Dudhia, & Stauffer, 1994) were used (Table 2). The MM5 implementation used for this research has 37 vertical levels, each with three nested horizontal grids of 36 km, 12 km and 4 km spatial resolution. The numerical model solves the fully compressible non-hydrostatic equations allowing the three grids to interact among themselves (two-way nesting). The model also

uses parameterizations for cloud microphysics, cumulus convection, atmospheric radiation transfer, planetary boundary layer processes and land-atmosphere interaction. In this study, hourly MM5 forecasts were produced for the Cedar Fire event and the outputs from the 4 km grid were used as inputs into FLAMMAP. The MM5 simulation did not resolve topography below the 4 km spatial resolution, so the effects of finer scale topography on wind speed and direction were not modeled.

MM5 forecast wind speed and direction were compared to wind speed and direction measured at two RAWS in the vicinity of the Cedar fire: the Julian station, which is located approximately 39 km ENE from the Garden Road community, and the Alpine station located approximately 25 km ESE from the community. RAWS measure wind speed and direction for the last 10 min of each hour, so wind inputs may not reflect actual conditions over the entire hour. Wind speed and direction values measured at the RAWS are shown in Table 2.

Fire-spread rates calculated from FLAMMAP were used to create the reverse fire travel-time network away from the community, and the shortest path travel times were used to calculate 1, 2, and 3-h evacuation trigger buffers. The trigger buffer locations were then compared to the corresponding CalFire and FARSITE-modeled fire perimeters. Since the 6 a.m. fire perimeter touches the eastern edge of the community, the 1-h trigger buffer was compared to the 5 a.m. modeled fire perimeter. The 2-h trigger buffer was compared to the 4 a.m. modeled fire perimeter, and the 3-h trigger buffer was compared to the CalFire 3 a.m. fire perimeter.

Results

Wind speeds measured at the Julian and Alpine RAWS varied from 10 to 27 km/h (Table 2). Wind direction was consistently from the ENE, although at 5 a.m. and 6 a.m. the wind direction at Alpine turned slightly more northward compared with the previous 2 h at this station. MM5 forecast wind speed and direction did not closely match the wind speed and direction measured at the two RAWS (Table 2). At 3 a.m., MM5 forecast wind speeds were much higher than those actually measured, although the forecast wind direction generally agreed with the wind direction measured at the RAWS. At 4 a.m., the forecast wind direction turned towards the north, but wind speeds came in closer agreement with those measured by the RAWS. At 5 and 6 a.m., the forecast wind direction further shifted to the northwest.

The evacuation trigger buffers modeled by WUIVAC are shown in Fig. 5. The 1-h trigger buffer was modeled using the 5 a.m. MM5 wind field. As a result, the 1-h trigger buffer points towards the northwest, although there is a small extension of the buffer towards the east. This is explained by a small area of hardwood/light conifer (fuel model 8) just to the north of this extension, which is modeled as having lower fire-spread rates, serving as a partial barrier to eastward fire spread. The "holes" within the buffer, as well as the irregular pattern towards the upper left, result from unburnable fuels, in this case water bodies and localized zones of

Table 2

Modeled and measured wind speed and direction for the morning of October 26, 2003. MM5 data is spatially variable at the scale of the event, which is why values are presented as a range.

Time	WUIVAC trigger buffer	MM5		Julian RAWS		Alpine RAWS	
		Wind direction (°)	Wind speed (km/h)	Wind direction (°)	Wind speed (km/h)	Wind direction (°)	Wind speed (km/h)
3 a.m.	N/A	64–68	45–55	79	27	74	14.5
4 a.m.	3 h	313–62	10–42	70	21	74	10
5 a.m.	2 h	336–39	10–21	70	16	59	13
6 a.m.	1 h	298–333	16–21.5	71	13	60	14.5

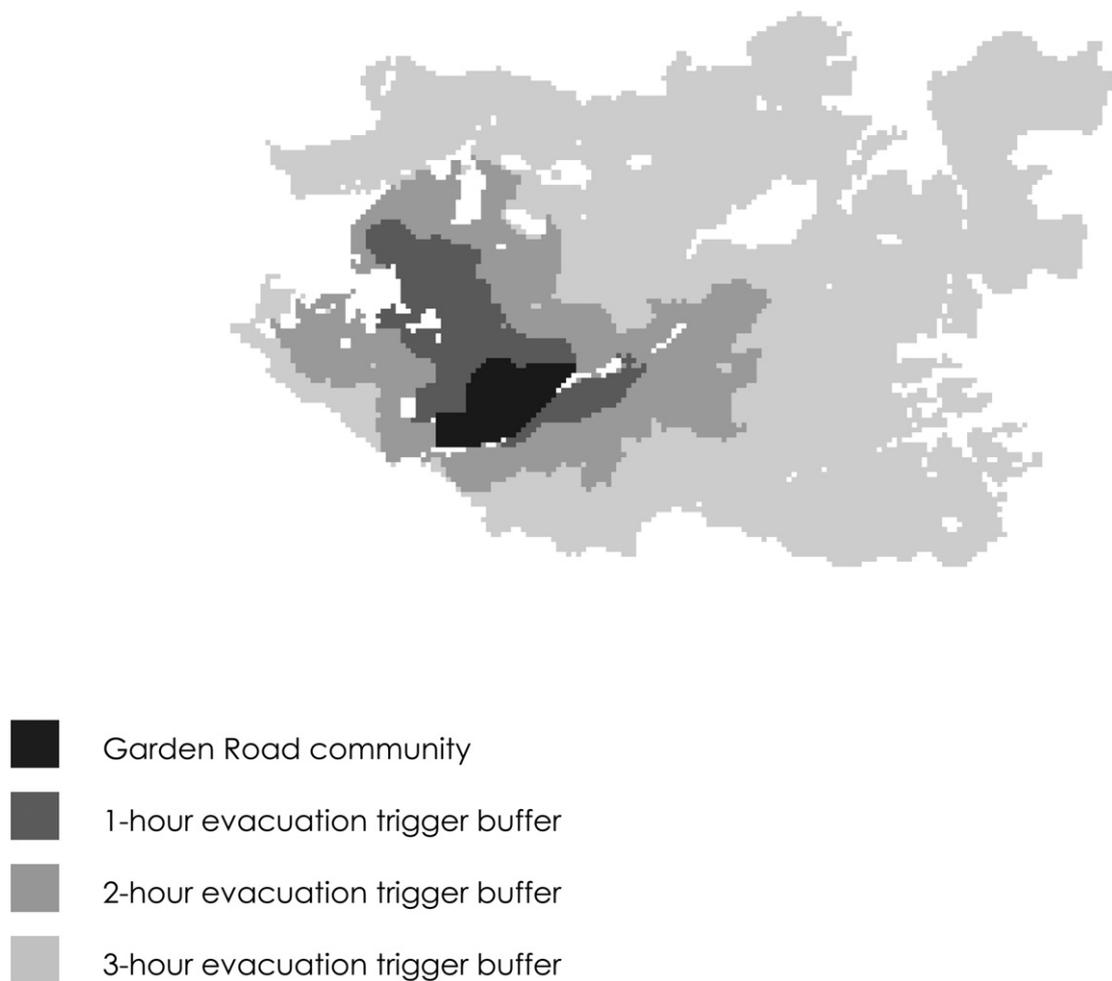


Fig. 5. Evacuation trigger buffers for time intervals of 1, 2, and 3 h.

urban built-up areas. Topography in the area of the 1-h buffer consists of rolling hills at primarily NW or SE aspects.

The evacuation trigger buffers modeled by WUIVAC are nested, such that the 1-h trigger buffer becomes the starting point for calculating the 2-h trigger buffer. The 2-h trigger buffer was modeled using the 4 a.m. MM5 wind field. Spatially variable fuels and wind direction combined to create a complex buffer shape, with lobes of the 2-h trigger buffer extending in the northwest, north, and northeast directions (Fig. 5). The small extension to the east from the 1-h buffer extends much more dramatically in the 2-h buffer, due in part to the presence of fuel model 4, the highly burnable chaparral model, in the newly buffered area.

The 2-h trigger buffer was the starting point for the 3-h trigger buffer, which was modeled using the 3 a.m. MM5 wind field. At 3 a.m., winds were modeled as out of the northeast, though spatially the modeled speeds were highly variable. Towards the city of Poway in the western portion of the event area, the wind speeds were approximately 45 km/h, whereas the winds in the topographically diverse, fuel covered eastern portion of the event area were blowing at approximately 55 km/h. WUIVAC predicts a much larger trigger buffer extending into the strong wind during this time step (Fig. 5). The 3-h buffer could have extended even further east; however, the predicted buffer is bounded on the east by unburnable fuels, as evidenced by the irregular eastern edge of this buffer. In the northwest portion of the buffer, the concavity in the buffer coincides with an area containing fuel model 8 (hardwood/

light conifer), which creates lower spread rates. A large hole in the central portion of the predicted buffer is not due to unburnable fuels, but rather is the result of the two lobes from the 2-h trigger buffer (one lobe from the north, the other from the east) coming together around a topographic high point and merging on its northeastern limb.

Using the 3 a.m. CalFire fire perimeter as a starting point, FARSITE was used to model fire perimeters at 4 a.m. and 5 a.m. The 6 a.m. FARSITE perimeter intersected the Garden Road community at the same location as the 6 a.m. CalFire perimeter. Fig. 6 shows both the FARSITE perimeters and the WUIVAC-modeled 1, 2, and 3-h trigger buffers. The 3 a.m., 4 a.m., and 5 a.m. FARSITE perimeters appear to converge in the upper right portion of the figure due to the agriculture fuel model which represents an unburnable barrier to modeled fire progression. Between 3:00 a.m. until 6:00 a.m., the Cedar Fire traversed a distance of approximately 1600 m. Overlaying and intersecting the trigger buffers with the corresponding fire perimeters shows the relative error between the two datasets. The eastern edge of the 1-h trigger buffer roughly aligns with the 5 a.m. modeled fire perimeter (Fig. 6). Measuring the distance between the trigger buffer and the fire perimeter at the first time step shows that the WUIVAC trigger buffer extends east of the fire location by 126 m at its furthest point (Table 3). The 2-h trigger buffer intersects and extends beyond the fire perimeter calculated for 4 a.m. (Fig. 6). At the greatest extent, the 2-h trigger buffer exceeds the 4 a.m. perimeter by as much as 280 m. The 3-h trigger

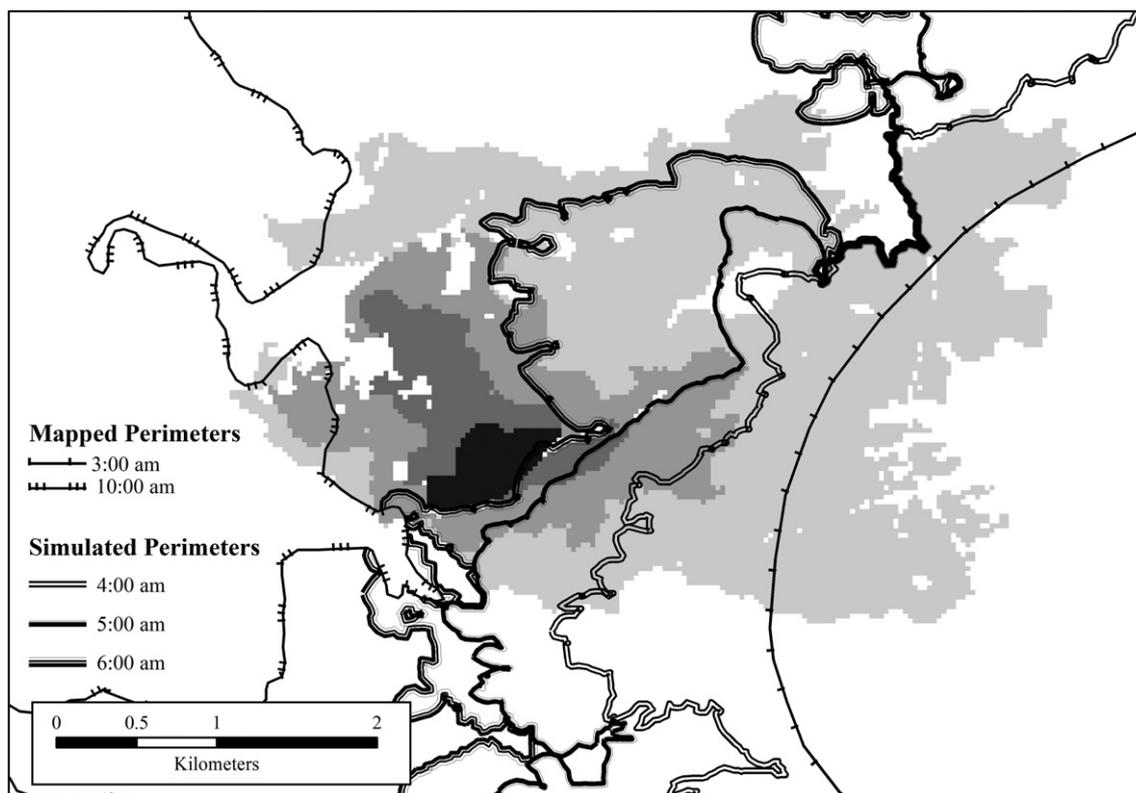


Fig. 6. WUIVAC predicted evacuation trigger buffers compared to mapped and modeled hourly fire perimeters.

buffer extends a much greater distance to the east and north than the previous two trigger buffers and also overlaps the corresponding fire perimeter by the greatest amount (Fig. 6). The 3-h buffer exceeds the 3 a.m. perimeter by approximately 1410 m at its greatest extent. Thus, at each of the three time steps, the trigger buffer exceeds the corresponding fire perimeter, indicating that WUIVAC would have triggered an evacuation recommendation that offered more time to evacuate than intended. The difference between outer edge of the trigger buffer and the corresponding fire perimeter increases from 1 to 2 and from 2 to 3 h (Table 3).

Discussion

WUIVAC modeled the minimum travel time for fire to reach the Garden Road community. When compared to the actual travel time of the Cedar Fire, WUIVAC “under-predicted” the time necessary for fire to reach the community for all three time steps. For example, based on the FARSITE modeling results the Cedar Fire took longer than 1 h to traverse the distance indicated by the 1-h trigger buffer. Under-prediction of the actual fire travel time would have triggered an earlier evacuation, as the fire would take longer to spread from the edge of the trigger buffer to the community. Since evacuation trigger buffers represent the minimum time required to traverse the given distance, some under-prediction is expected, as fire is unlikely to travel along an optimal path. Under-prediction of the

fire travel time allows additional time for evacuation, so it is much more desirable than over-prediction. In the case of over-prediction of fire travel time, the fire arrives at the community before the WUIVAC-modeled shortest path time has elapsed. Over-prediction is a very serious error, since the fire could arrive before an evacuation is complete.

The wide range of wind speed and direction inputs used in this analysis indicates the large degree of uncertainty associated with conditions during actual fire events. There are no wind measurements close to the Garden Road community, so there is no way of knowing which set (if any) of the wind speed and direction values is most accurate. The RAWs provide on-the-ground measurements, but this is an aspatial measurement at a distance of many kilometers from the fire front. MM5 provides spatial predictions of wind speed and direction, but can deviate greatly from the RAWs data and cannot resolve the effects of local topography. Due to the sparse network of RAWs and difficulty modeling complex, high spatial resolution wind fields, it is unlikely that our ability to measure wind speed and direction will dramatically improve in the near future. However, even with modeled winds with a different direction and speed than the winds measured at the RAWs, WUIVAC was still able to provide useful trigger buffers.

Both WUIVAC and FARSITE are based on the same semi-empirical fire-spread model. Like any model, the Rothermel (1972) fire-spread model is an imperfect representation of actual fire spread. In particular, Rothermel (1972) does not account for fire spread through spotting and interactions between fire and winds. As errors introduced by the Rothermel model will be included in WUIVAC, trigger buffers may be less accurate under extreme wind and fuel moisture conditions or fire spread predominantly through spotting. It should be noted that WUIVAC is not limited to using the Rothermel (1972) model; it is capable of incorporating fire-spread rates from any deterministic fire-spread model. However, fire-spread models that do take into account interactions between fire

Table 3

Maximum distance between the WUIVAC evacuation trigger buffers and the modeled or mapped hourly fire perimeters.

Trigger buffer	Distance from fire perimeter to buffer
1 h	+126 m
2 h	+280 m
3 h	+1410 m

and winds may require stochastic elements which are incompatible with creating a single reverse fire-spread network.

In general, the uncertainty in predicting fire-spread rates and associated warning time is significant (Jimenez, Hussani, & Goodrick, 2008). Underestimation of the time required for fire to reach a community will result in evacuations being recommended earlier than needed, which may result in an unnecessary evacuation if the fire deviates away from the community. Recommending evacuations that turn out to be unnecessary would result in direct costs (e.g. evacuation expenses) and indirect costs (e.g. economic losses) to the community. The location of the fire perimeter is a source of uncertainty for determining the effectiveness of WUI-VAC-modeled trigger buffers and for potential deployment. In an actual fire, accurate trigger buffers do not have much utility unless the location of the fire perimeter is also known. Uncertainty in the location of a fire front can be greatly reduced by utilizing airborne and ground-based remote sensing. Airborne infrared sensors can map the location of the fire front with a high temporal frequency. Emerging technologies, such as Unmanned Aerial Vehicles (UAVs) could be of particular benefit for this purpose as they can collect data throughout the course of an event at no physical risk to personnel.

Conclusions

This work demonstrates the feasibility of operational use of the WUIVAC model. It also represents the first use of forecast dynamic wind data in the creation of evacuation trigger buffers that are based on more realistic environmental variables. Both of these points highlight WUIVAC's emerging potential for improving protective action decision making in wildfires. Since this study only examined one community during one fire, additional case studies are needed to validate the ability of WUIVAC to generate accurate evacuation trigger buffers that err on the side of community safety. Additional research is needed to quantify evacuation trigger buffer uncertainty, and the impacts of trigger buffer and fire perimeter uncertainty on protective action decision making.

In the past, triggering an evacuation has been more of an art than a science, due to the lack of real-time knowledge of environmental conditions and fire location, as well as corresponding modeling tools to take advantage of these data. As the availability of GIS data, weather model data, and real-time remote sensing data increases, tools will be needed that can take advantage of this valuable information. Improved, informed evacuation decision making can help protect lives in the continually expanding WUI.

Acknowledgment

Tom Cova is supported by the NSF under Grant No. CMMI-065372.

References

- Albini, F. A. (1976). *Estimating wildfire behavior and effects*. Dept. of Agriculture Forest Service general technical report INT-30. Ogden, UT: Intermountain Forest and Range Experiment Station.
- Anderson, H. E. (1982). *Aids to determining fuel models for estimating fire behavior*. Dept. of Agriculture Forest Service general technical report INT-122. Ogden, UT: Intermountain Forest and Range Experiment Station.
- Anderson, H. E. (1983). *Predicting wind-driven wildland fire size and shape*. Dept. of Agriculture Forest Service general technical report INT-305. Ogden, UT: Intermountain Forest and Range Experiment Station.
- Angelova, Z., Stow, D. A., Kaiser, J., Dennison, P. E., & Cova, T. (2010). Integrating fire behavior and trafficability models to assess fire danger to pedestrians within the US–Mexico border zone. *The Professional Geographer*, 62, 1–18.
- Blackwell, J. A., & Tuttle, A. (2003). *Fire story: California fire siege, 2003*. Sacramento, CA: California Department of Forestry and Fire Protection and USDA Forest Service.
- Cohn, P. J., Carroll, M. S., & Kumagai, Y. (2006). Evacuation behavior during wildfires: results of three case studies. *Western Journal of Applied Forestry*, 21, 39–48.
- Cova, T. J., Dennison, P. E., Kim, T. H., & Moritz, M. A. (2005). Setting wildfire evacuation trigger points using fire spread modeling and GIS. *Transactions in GIS*, 9, 603–617.
- Cova, T. J., Drews, F. A., Siebeneck, L. K., & Musters, A. (2009). Protective actions in wildfires: evacuate or shelter-in-place? *Natural Hazards Review*, 10, 151–162.
- Dennison, P. E., Cova, T. J., & Mortiz, M. A. (2007). WUIVAC: a wildland–urban interface evacuation trigger model applied in strategic wildfire scenarios. *Natural Hazards*, 41, 181–199.
- Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, 1, 269–271.
- FEMA. (2000). *HURREVAC and inland winds: Documentation and user's manual*. Version 1.0. Washington, D.C.: Federal Emergency Management Agency.
- Finney, M. A. (1998). *FARSITE, fire area simulator-model development and evaluation*. Ogden, UT: U.S. Dept. of Agriculture Forest Service Rocky Mountain Research Station.
- Finney, M. A. (2002). Fire growth using minimum travel time methods. *Canadian Journal of Forest Research*, 32, 1420–1424.
- Gill, A. M., & Stephens, S. L. (2009). Scientific and social challenges for the management of fire-prone wildland–urban interfaces. *Environmental Research Letters*, 4, 034014.
- Grell, G. A., Dudhia, J., & Stauffer, D. R. (1994). *A description of the fifth generation Pennsylvania State University/NCAR mesoscale model*. NCAR/TN-398+IA. Boulder, CO: National Center for Atmospheric Research.
- Handmer, J., & Tibbitts, A. (2005). Is staying at home the safest option in bushfires? Historical evidence for an Australian approach. *Environmental Hazards*, 6, 81–91.
- Jimenez, E., Hussani, M. Y., & Goodrick, S. (2008). Quantifying parametric uncertainty in the Rothermel model. *International Journal of Wildland Fire*, 17, 638–649.
- Keeley, J. E., Fotheringham, C. J., & Moritz, M. A. (2004). Lessons from the October 2003 wildfires in Southern California. *Journal of Forestry*, 102, 26–31.
- Kim, T. H., Cova, T. J., & Brunelle, A. (2006). Exploratory map animation for post-event analysis of wildfire protective action recommendations. *Natural Hazards Review*, 7, 1–11.
- McCaffrey, S. M., & Rhodes, A. (2009). Public response to wildfire: is the Australian 'stay or leave early' approach an option for wildfire management in the United States? *Journal of Forestry*, 107, 9–15.
- Miller, C. (2003). The spatial context of fire: a new approach for predicting fire occurrence. In *Proceedings of fire conference 2000: The first national congress on fire ecology, prevention, and management* (pp. 27–34). Tallahassee, FL: Tall Timbers Research Station.
- Moritz, M. A., & Stephens, S. L. (2008). Fire and sustainability: considerations for California's altered future climate. *Earth and Environmental Science*, 87, S265–S271.
- Mozumder, P., Raheem, N., Talberth, J., & Berrens, R. P. (2008). Investigating intended evacuation from wildfires in the urban–wildland interface: application of bivariate probit model. *Forest Policy Economics*, 10, 415–423.
- Paveglione, T., Carroll, M. S., & Jakes, P. J. (2008). Alternatives to evacuation: protecting public safety during wildland fire. *Journal of Forestry*, 106, 65–70.
- Pyne, S. J., Andrews, P. L., & Laven, R. D. (1996). *Introduction to wildland fire*. New York: Wiley.
- Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. S. (2004). The wildland–urban interface in the United States. *Ecological Applications*, 15, 799–805.
- Richards, G. D. (1990). An elliptical growth model of forest fire fronts and its numerical solution. *International Journal for Numerical Methods in Engineering*, 30, 1163–1179.
- Rothermel, R. C. (1972). *A mathematical model for predicting fire spread in wildland fuels*. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station.
- Theobald, D. M., & Romme, W. (2007). Expansion of the U.S. wildland urban interface. *Landscape and Urban Planning*, 83, 340–354.
- Wolshon, B., & Marchive, E., III (2007). Emergency planning in the urban–wildland interface: subdivision-level analysis of wildfire evacuations. *Journal of Urban Planning and Development*, 133, 73–81.