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WUIVAC: a wildland-urban interface evacuation trigger model applied in strategic wildfire scenarios

Philip E. Dennison · Thomas J. Cova · Max A. Moritz

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Abstract An evacuation trigger is a point on the landscape that, once crossed by a wildfire, triggers an evacuation for a community. The Wildland-Urban Interface Evacuation (WUIVAC) model can be used to create evacuation trigger buffers around a community using fuels, weather, and topographic inputs. A strategic, community-scale application of WUIVAC for the town of Julian, California was investigated. Eight years of wind measurements were used to determine the worst-case (strongest) winds in 16 directions. Surface fire rate of spread was used to calculate evacuation trigger buffers for the communities of Julian and nearby Whispering Pines, and for three potential evacuation routes. Multiple trigger buffers were combined to create fire planning areas, and trigger buffers that predict the closure of all evacuation routes were explored. WUIVAC trigger buffers offer several potential benefits for strategic evacuation planning, including determination of when to evacuate and locating potential evacuation routes.

Keywords Fire behavior · Wildfire · Evacuation modeling · Natural hazards

Introduction

Fire hazard to life and property are highest in the area where fire-prone ecosystems and human settlement meet, a zone known as the wildland-urban interface (WUI). Stewart et al. (2003) found that approximately 11.5 million homes in the Western US were within the WUI in 2000, representing 44% of the total number of homes in this region. California led all states with more than 5 million WUI homes (Stewart

P. E. Dennison (✉) · T. J. Cova
Center for Natural & Technological Hazards, Department of Geography, University of Utah, 260 S. Central Campus Dr., Rm. 270, Salt Lake City, UT 84112-9155, USA
e-mail: dennison@geog.utah.edu

M. A. Moritz
Center for Fire Research and Outreach, Department of Environmental Science, Policy, and Management, University of California Berkeley, Berkeley, CA 94720, USA

et al. 2003). Seasonal drought and extreme wind events make the WUI especially susceptible to fire. In late October, 2003, Southern California experienced the worst WUI fire event in US history. Multiple large wildfires driven by Santa Ana winds consumed more than 300,000 ha. These fires were responsible for the loss of 26 lives and 3,361 homes (Keeley et al. 2004).

Although the 2003 fires were unprecedented in structural loss, Keeley et al. (2004) noted that several such catastrophic fires have occurred in the past and warned that similar fires are likely to occur in the future. The specific timing of low fuel moisture and high wind speeds that cause large wildfires in Southern California may not be predictable; however, it is inevitable that fuel and weather conditions will align again at some point in the future to produce comparable fires. Fuel conditions, such as live fuel moisture, and weather conditions, such as wind speed and direction, can be anticipated, and used to prepare for future fire events. One way to prepare for future events is to determine triggers for fire evacuation in advance. An evacuation trigger is a point on the landscape where an evacuation order for a proximal community is recommended once a wildfire crosses this point. Multiple evacuation trigger points can be joined to create a trigger buffer. The Wildland-Urban Interface Evacuation (WUIVAC) model is designed to help decision-makers set fire evacuation trigger buffers using fuel and weather condition inputs (Cova et al. 2005). WUIVAC can be used to model buffers around a community that, if crossed by a fire, will trigger an evacuation order. Once these trigger buffers have been mapped, they can be used to determine the necessity of and timing for ordering a community evacuation in future fire events. This paper uses the WUIVAC model to demonstrate planning of strategic evacuation trigger boundaries for several potential worst-case scenarios for the town of Julian, California.

Background

The WUIVAC model creates an evacuation trigger buffer for a specific set of locations using environmental variables such as fuels, topography, and winds (Cova et al. 2005). WUIVAC determines the amount of time required for fire to spread to a protected zone, or "community" (Fig. 1). The evacuation trigger buffer is the area

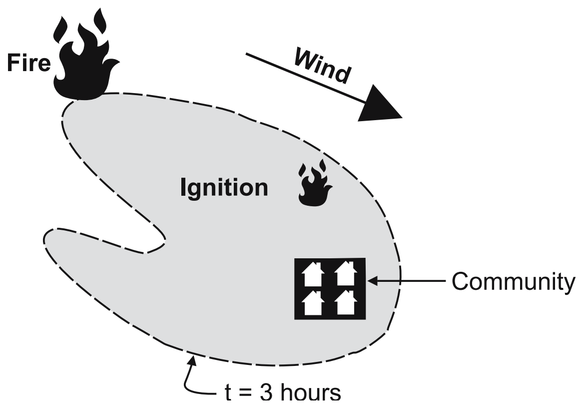

Fig. 1 A conceptual representation of the WUIVAC model

for which a fire could reach a community within a specified period of time. Figure 1 displays an example evacuation trigger buffer, shaded in gray. This example depicts the 3-h evacuation trigger buffer, where a fire crossing any point along the dotted line that defines the trigger buffer boundary may reach the community in three hours (Fig. 1). A fire that ignites within the trigger buffer may reach the community in fewer than 3 h.

The shape of the evacuation trigger boundary depends primarily on wind, fuels, and topography. For example, fire spreads faster downwind than upwind. This causes a fundamental asymmetry in the evacuation trigger buffer. Since fire is able to travel further in the downwind direction during a given period of time, the trigger buffer extends farther upwind of the community (Fig. 1). A fire that is upwind of the community will travel much further in 3 h than a fire that is downwind of the community. The asymmetry of the trigger buffer increases as the wind speed increases, with the evacuation trigger buffer extending further in the windward direction. Fuels and topography also impact the shape of the evacuation trigger buffer. 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. Fire also moves more rapidly up a slope than down a slope, due to increased efficiency of radiative and convective heat transfer to unburned fuels (Pyne et al. 1996).

The WUIVAC model uses a three-step process to model evacuation trigger buffers. The first step utilizes the FLAMMAP software package developed by the United States Department of Agriculture Forest Service 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 (1982) and implemented by Finney (1998) are used to calculate the two-dimensional spread rates. Spatial inputs to FLAMMAP as implemented for WUIVAC include fuel type, slope, and aspect. Aspatial inputs include wind speed, wind direction, and fuel moisture.

For the second step, WUIVAC uses the spread rates to create a fire-spread network that connects all adjacent cells. Each arc within the network defines the estimated time required for fire to spread from one cell to another. The network extends from each cell to all eight of its neighbors. To determine the total time required for fire to spread from one cell to another, connected arcs between cells are added (Finney 2002; Miller 2003). The third step involves reversing all arcs in the fire travel-time network and traversing it starting from a ‘‘community’’ cell and traveling outward until a specified time interval is reached. For each cell within the community, the shortest path (in travel time) is found from the community cell to the other cells in the grid using Dijkstra’s (1959) algorithm. The user must specify the time period (e.g., community evacuation time) the trigger buffer will represent. Using the shortest path from a community to the other cells in the grid, WUIVAC determines all cells from which fire could spread to reach the community within the specified time period.

Cova et al. (2005) demonstrated how WUIVAC could be used operationally to derive evacuation trigger buffers for small scale scenarios. Evacuation trigger buffers for a fire fighting crew injured in the 1996 Calabasas Fire in Southern California were determined using a 1.6 km^2 grid of fuels and topography at 10-m resolution. Evacuation trigger buffers were modeled for 15-, 30-, and 45-min periods and included the protection of a single evacuation route. For larger scale evacuations, 45 min may be insufficient for evacuating a community. Larger evacuation trigger buffers will also require larger spatial extents, on the scale of tens of kilometers. Fortunately, WUIVAC is scaleable to longer time period buffers and larger areas by using coarser spatial resolution input data and temporal wind data.

The Wildland-Urban Interface Evacuation model can be applied in a variety of temporal and spatial application contexts for fire evacuation modeling. The model can be used operationally, to determine evacuation trigger buffers for current wind and fuel conditions. It can also be used tactically, to determine evacuation trigger buffers for forecast future wind and fuel conditions. Finally, WUIVAC can be used with hypothetical wind and fuel conditions to strategically determine long-term evacuation trigger buffers. WUIVAC can also be applied across a continuum of spatial scales. At the smallest scale, it can model evacuation trigger buffers for a fire fighting crew or household. At larger scales, WUIVAC can model trigger buffers for an entire community, and at even larger scales, it could be used to model trigger buffers for multiple communities within a region. Cova et al. (2005) used an operational application of WUIVAC at a scale similar to that of a household. In contrast, this paper presents a strategic application of WUIVAC at the community scale.

Study site

The town of Julian in San Diego County was selected for community-scale modeling using WUIVAC due to its manageable size, relative remoteness, and high wildfire hazard (Fig. 2). Located in the Cuyamaca Mountains, Julian is a popular tourist destination with several historical buildings dating to Julian's past as a mining town. The census tract containing Julian and its neighboring community, Whispering Pines, had a total population of 1,621 residing in 902 housing units in 2000. The largest of the 2003 Southern California fires was the Cedar Fire in San Diego County. This fire directly affected Julian and surrounding communities. The Cedar Fire was started by human ignition on October 25, 2003. Over a period of 24 h, Santa Ana winds and dry fuel conditions caused the fire to grow to more than 60,000 ha toward the west. On October 28, winds reversed direction and the fire burned east toward the town of Julian, resulting in evacuation orders for Julian and the surrounding communities (Kim et al. 2006). While the town of Julian was successfully defended, houses were lost in several nearby communities. In addition to providing a realistic case study location, the proximity of Julian to the Cedar Fire also permits indirect comparison of modeled fire spread with historical fire data.

Methods

Inputs for the fire behavior component of the WUIVAC model of Julian included topography, fuel type, fuel moisture, wind speed, and wind direction. Spatial inputs were resampled to a common resolution of 90-m and a common extent of 45 km, centered on the town of Julian (Fig. 3). Terrain slope and aspect were calculated from a United States Geological Survey 1:24,000 scale digital elevation model that was spatially averaged to 90 m resolution. A 2003 (pre-Cedar Fire) California Department of Forestry and Fire Protection (CDF) Fire and Resource Assessment

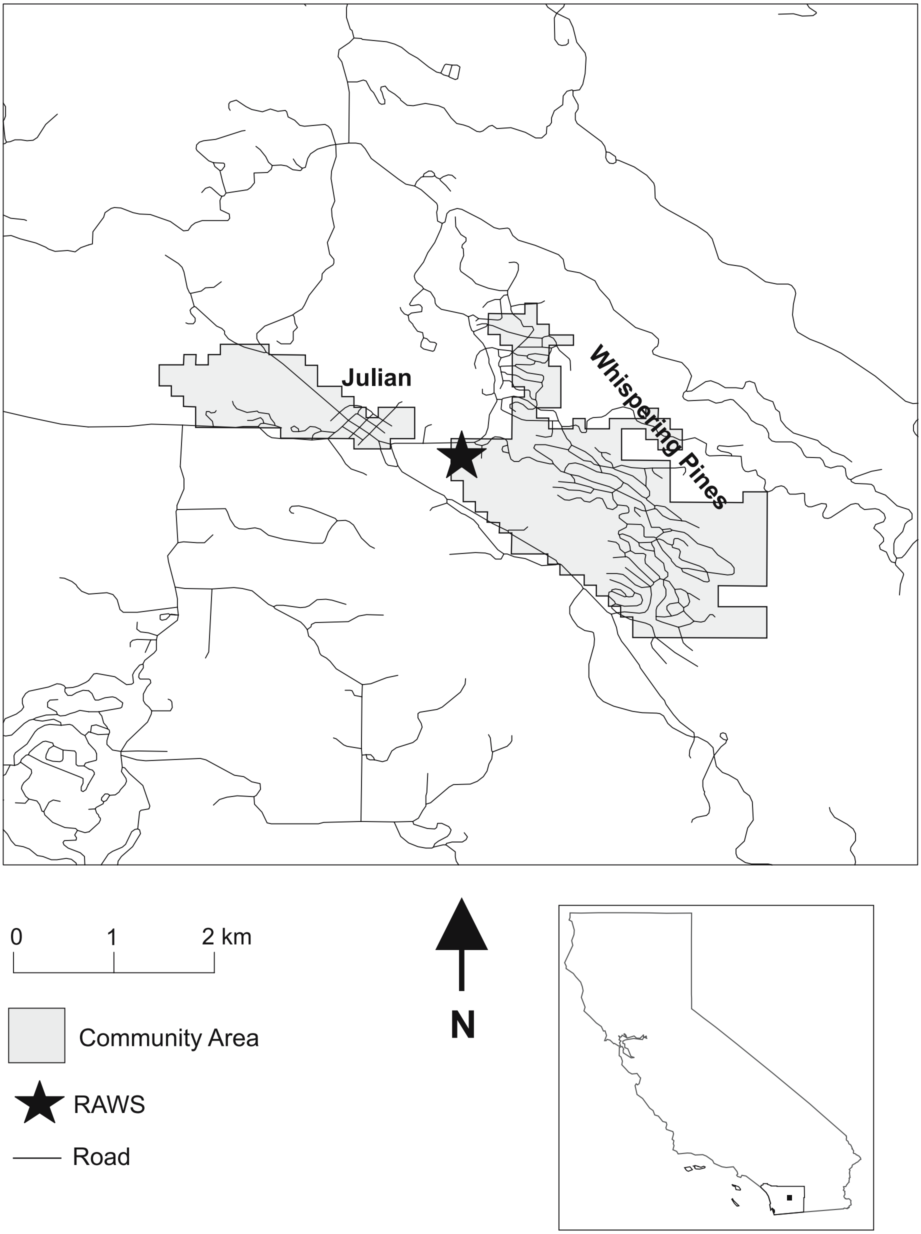

Fig. 2 Locations of the RAWS and community area relative to the communities of Julian and Whispering Pines in San Diego County, California, USA

Program (FRAP) map of surface fuels was used to create fuel type inputs for WUIVAC. A corresponding map of crown fuel properties was not available, so the model was limited to surface fire spread and did not include crown or spotting fire spread mechanisms. The 30-m resolution FRAP surface fuels map contained 11

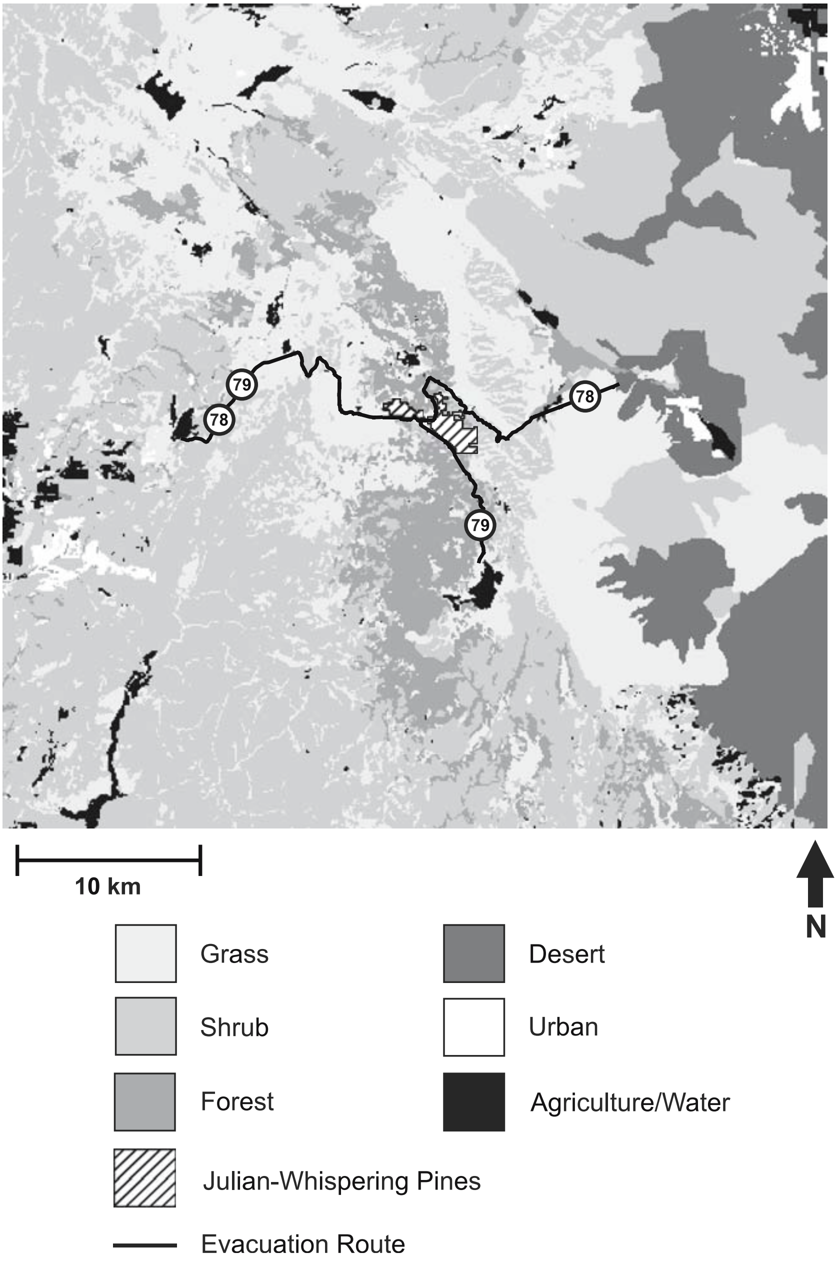

Fig. 3 The 90-meter aggregated fuel classes derived from the California Department of Forestry and Fire Protection Fire and Resource Assessment Program surface fuels map. Three grass, three shrub, and three tree fuel classes are lumped together for display purposes. The extent of the Julian and Whispering Pines community areas, and three potential evacuation routes are also shown

Table 1 Fuel class descriptions, from Anderson (1982), and CDF (David Sapsis 2005, pers. comm.)

Fuel Class	Description
1	Short grass
2	Timber (grass and understory)
3	Tall grass
4	Chaparral
5	Brush
6	Dormant brush, hardwood slash
8	Closed timber litter
9	Hardwood litter
10	Timber (litter and understory)
15	Desert
28	Urban

flammable fuel classes and 3 unburnable fuel classes within the study area. These fuel classes are listed in Table 1. The FRAP surface fuels map was resampled to 90-m resolution by assigning the most common fuel type within each 90-m cell (Fig. 3). Where fuel classes were equally common, the tie was broken in favor of the fuel class with a highest rate of spread, so as to error on the side of a larger trigger buffer that would provide a greater safety margin. Fuel classes displayed in Fig. 3 are grouped by dominant vegetation functional type, but were maintained as individual classes for modeling. Fuel moisture was assigned based on values present during the Cedar Fire. Dead fuel moisture was fixed at 4% of dry vegetation weight, and live fuel moisture was fixed at 65% of dry vegetation weight. The 4% dead fuel moisture is typical of daily low dead fuel moisture in late summer and fall in Southern California, and 65% live fuel moisture value is typical of seasonal lows reached annually in October and November in Southern California (Dennison et al. 2005; Roberts et al. 2006 *in press*).

The spatial distribution of fuel types is dependent on elevation and precipitation (Fig. 3). Grasses (fuel classes 1, 2, and 3) and shrubs (fuel classes 4, 5, and 6) were the most prevalent fuels within the study area. Close to Julian, grass and shrub fuels were found to the east and west of the community (Fig. 3). Forests (fuel classes 8, 9, and 10) were more prevalent along the higher elevation Cuyamaca Mountains to the north and south of Julian. Desert fuels were located further west of Julian, while isolated urban fuels occurred in a few widely separated portions of the study area. Areas mapped by FRAP as agriculture or water were considered unburnable.

Wind speed and direction are highly variable and thus more difficult to quantify for worst-case scenarios. The highest winds in Julian tend to come either from the east or west. West winds are typical of Santa Ana winds, which have been responsible for the most destructive fires in Southern California history (Keeley and Fotheringham 2003; Moritz et al. 2004). Remote automated weather stations (RAWS) are used to measure weather at remote locations such as Julian. RAWS measure wind speed and direction as a 10 min average once each hour, at a height of 6.1 m (20 feet). A RAWS very close to Julian (Fig. 2) has recorded hourly wind speed and wind direction for over 8 years (March 31, 1997–present), providing archived wind speed and direction data for the analysis (California Data Exchange Center 2005). Data from the Julian RAWS were assumed to represent wind speed and direction over the entire study area, although this assumption clearly is dependent on both local conditions at the RAWS and regional spatial variation in wind speed and direction. For example, local topography surrounding the station location and Julian may impact wind speed and direction at the RAWS site. The proximity of the RAWS to Julian does permit some confidence that wind speed and direction measured by the RAWS closely approximates the wind speed and direction in the immediate vicinity of Julian.

Determining the worst-case wind speed and direction is not as simple as finding the maximum recorded wind speed. High winds produced by wet-season storms, when fuel moisture is high and fires rarely occur, represent little threat in terms of wildfire. To determine the worst-case winds likely within fire season, RAWS data analysis was limited to the months of June through November, when fires are most likely to occur in Southern California. Since wind speeds in Julian are highest in the east and west directions, the worst-case wind speed has a directional dependence. In other words, the worst-case wind from the north will likely have a lower wind speed than the worst-case wind from the east. RAWS observations were binned by 16 different wind directions, centered on 22.5° intervals starting with 0° (north). Within each wind direction, the maximum hourly wind speed during the 8 years of June–November data (1997–2004) was determined to be the worst-case wind speed in that direction. Figure 4 plots the maximum hourly wind speed in each of the 16 binned wind directions. The highest maximum hourly winds occurred in the southwest (11.2 m/s), west (10.7 m/s), and east (10.7 m/s) directions. A general trend of higher maximum hourly winds from the west-to-southwest directions and east directions is apparent (Fig. 4). The lowest maximum hourly winds were found coming from the north-to-northwest directions, with the absolute lowest maximum hourly wind coming from the NNW at just 3.1 m/s.

The Wildland-Urban Interface Evacuation model inputs of slope, aspect, fuel type, fuel moisture, and wind speed in 16 directions were used to generate surface fire spread rates. Model cells that were within the communities of Julian and Whispering Pines

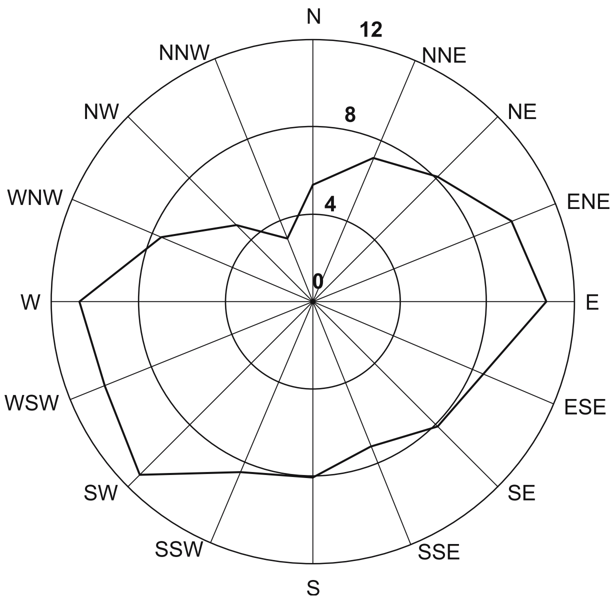

Fig. 4 RAWS maximum wind speed, in meters per second, plotted in 16 directions

were determined using a FRAP map of housing density based on the USGS National Land Cover Dataset data derived from the 2000 United States Census. Housing density was resampled from 100-m resolution to 90-m resolution to match the resolution of the fuels and topography data. The extents of Julian and Whispering Pines were determined by selecting all cells with a housing density greater than 1 housing unit per 2 ha (5 acres). The selected community areas are shown in Fig. 2.

The WUIVAC trigger buffers modeled for Julian and Whispering Pines are based on the time necessary for a fire that breaches the buffer to reach the community's edge. While evacuating the community within the specified time can prevent loss of life within the community, the evacuation routes themselves may also be vulnerable to fire. If a fire cuts off an evacuation route before the evacuation can be completed, loss of life may occur (Cova 2005). Trigger buffers were, therefore, also modeled for three potential evacuation routes for Julian and Whispering Pines (Fig. 3). California state routes 78 and 79 can be used to travel west from Julian. These two routes split at Julian with state route 78 running to the east of Julian and state route 79 running to the south of Julian. The purpose of modeling these evacuation routes was not to model an evacuation network, but to determine buffers within which fire might close an evacuation route within a specified period of time. These three routes are not the only possible evacuation routes for Julian and Whispering Pines, but they are the largest, most direct routes out of these communities.

To model trigger boundaries for the three evacuation routes, the extent of the routes was greatly simplified. Each of the three routes begins at the junction of the three routes. Furthermore, the routes were terminated at a place judged to be a ''safe zone'' or large area with little or no fuel present. The western evacuation route was terminated at a large agricultural area. The southern evacuation route was terminated at Lake Cuyamaca. There were no apparent large, unburnable areas for the eastern evacuation route, so this route was terminated where it met the desert fuel type. The desert fuel type produces much lower rates of spread and is subject to a lower fire recurrence frequency, but in the modeling sense is not as ''safe'' as the unburnable areas at the termini of the western and southern evacuation routes.

The Wildland-Urban Interface Evacuation model generated a rate of spread network for each of the 16 maximum hourly wind conditions, and these were used to generate evacuation trigger buffers for 4 scenarios. The first scenario calculated trigger buffers for the communities of Julian and Whispering Pines, based on the shortest path for fire spread to all exterior cells within the community areas defined by housing density. Community interior cells were not included in the calculations because the shortest path for any interior cell would have to travel through a cell on the community's edge. The shortest path buffers for all cells in the community area were then combined (i.e., unioned) to produce 16 evacuation trigger buffers for Julian and Whispering Pines, one for each major wind direction. In a similar way, the remaining scenarios involved calculating the trigger buffers for each of the three potential evacuation routes. The shortest path that fire could take to an evacuation route was calculated for each cell in a raster representation of the evacuation route, and the shortest path buffers for all cells for a single evacuation route were joined to produce 16 trigger buffers for that evacuation route.

The time required for a fire to spread to the community is a variable within the shortest path component of WUIVAC. This time should be set based on the expected time required for an evacuation, plus additional time accounting for possible uncertainty in the expected evacuation time. The Julian simulations utilized multiple time variables to account for multiple possible situations in evacuating during a wildfire threat. The 3-, 2-, and 1-h trigger buffers were generated for each of the four scenarios. An evacuation of 2 h in duration was assumed. Based on this assumption, a 3-h trigger buffer allows for a 1-h cushion in case unforeseen difficulties in evacuation do occur. Once the 3-h trigger buffer is crossed, some portion of the community could expect to have at least 3 h before the fire reaches that part of the community. Once the 2-h trigger buffer is crossed, a 2-h evacuation must take place immediately, or a portion of the community may be threatened by the fire within the time required for evacuation. Once the 1-h trigger buffer is crossed, the fire may threaten at least some portion of the community before the assumed time required for evacuation has expired. In this case, protective actions such as ‘‘shelter-in-place’’ may be required because evacuees may be overcome by the fire in transit with less protection than offered by a shelter.

Results

The Julian–Whispering Pines scenario exhibited variation in trigger buffer shape due to wind speed, wind direction, fuel type, and topography. Trigger buffers for 8 of the 16 wind directions are displayed in Fig. 5. As expected, wind speed was dominant in determining the size of the trigger buffers. The 1-, 2- and 3-h trigger buffers point into the direction of the wind, as fire will spread more rapidly towards Julian and Whispering Pines in the downwind direction. Northwest and north possessed the lowest wind speeds of the eight directions displayed. These directions also had the

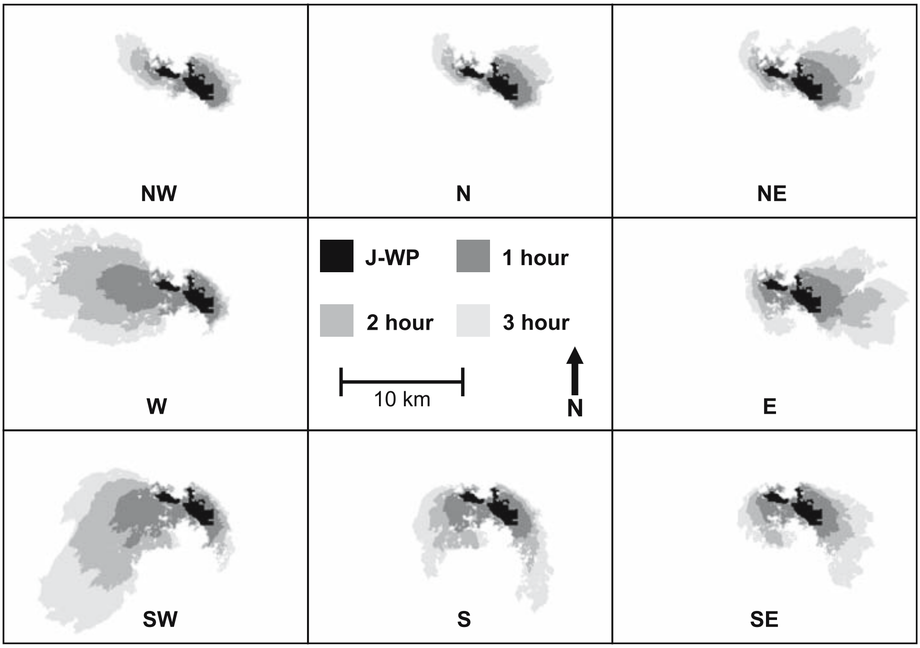

Fig. 5 The 1-, 2- and 3-h trigger buffers for the maximum wind speed in 8 directions. Julian and Whispering Pines (J–WP) are shown in black

smallest trigger buffers of the eight directions at all three time steps. Fuel type also partially determined the size and shape of the trigger buffers. Fuel types with larger amounts of dead fuel and high surface area, such as grass model 1 and shrub model 4, produced trigger buffers with larger areas. Fuel types with smaller amounts of fuel, lower surface area, or more live fuels reduced the rate of spread, and thus produced smaller trigger buffers. Abundant grass and chaparral fuels to the west of Julian resulted in very large trigger buffers when modeled with west and southwest winds. Forest fuel types, which contain less ground fuel than grass or shrub fuel types, predominate directly to the north and south of Julian. The trigger boundary seldom penetrated very far into forest fuel types, even when high winds speeds were modeled. The modeled rate of spread of fire through forest fuels assumed that crown fires and spotting behavior were not present. The addition of these fire spread mechanisms would probably have increased the size of the trigger buffers to the north and south of Julian. Lastly, the increased extents of the trigger buffers to the west and southwest of Julian were partially due to topography. Julian has a higher elevation than areas to the west and southwest, so the spread rates of fires traveling toward Julian from these directions reflect the positive slope of the terrain.

The trigger buffers from all 16 maximum hourly wind speeds can be joined together to produce a FPA (Fig. 6). Any fire that enters or ignites within the FPA is of great concern for evacuation planning. The FPA represents the area for which a fire could reach the community within the given time if the fire has worst-case wind speed and direction conditions. A fire within the FPA may not represent an immediate threat that requires evacuation, but an increase in wind speed and/or a change in wind direction could endanger the community. The FPA for Julian and Whispering Pines has two large lobes that extend to the west and east of the communities. The shape of the FPA was caused by the higher maximum hourly wind speeds in the east and west directions, and by lower rates of spread within fuels to the north and south of Julian.

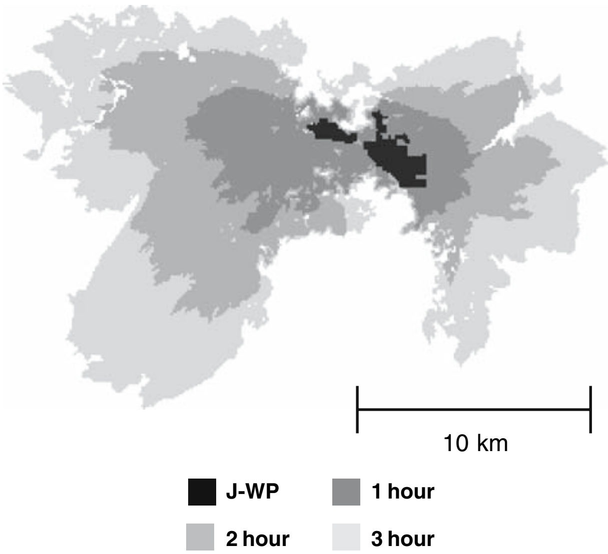

Fig. 6 The 1-, 2- and 3-h fire planning areas for Julian and Whispering Pines

Multiple evacuation routes offer essential flexibility in evacuating a community. A single evacuation route may be cut off by a fire, forcing a shelter-in-place strategy and greatly increasing the hazard to any persons trapped within the community. If multiple evacuation routes are available, then the loss of a single evacuation route will reduce capacity to evacuate but will not halt the evacuation. For evacuation planning, it is thus important to know the trigger buffers for evacuation routes in addition to the trigger buffers for a community. For the evacuation routes, the trigger buffers do not represent the time available for evacuation from a community, but the time before an evacuation route may be blocked by a wildfire.

The areas contained within trigger buffers for multiple evacuation routes may overlap. A fire that breaches or ignites within the area of overlap is, therefore, capable of cutting off multiple evacuation routes within the specified time. In the case of three evacuation routes, overlap areas exist within which fire could cut off one, two, or all three evacuation routes. Within a trigger buffer for one route but where no overlap occurs is the ‘‘one route impact area.’’ The overlap area that affects two evacuation routes can be referred to as the ‘‘two route impact area,’’ while the overlap area that affects all three evacuation routes can be referred to as the ‘‘three route impact area.’’ Fig. 7 displays the 3 h trigger buffer overlap areas for 8 wind directions. For all wind directions the one route impact area was much larger than the two-route or three-route impact areas. Within the one-route impact area, a fire that enters or ignites within this area could affect any, but only one, of the three-routes. For the west, southwest, and south wind directions the two-route and three-route impact areas were very similar. In this case, any fire that cuts off access to two

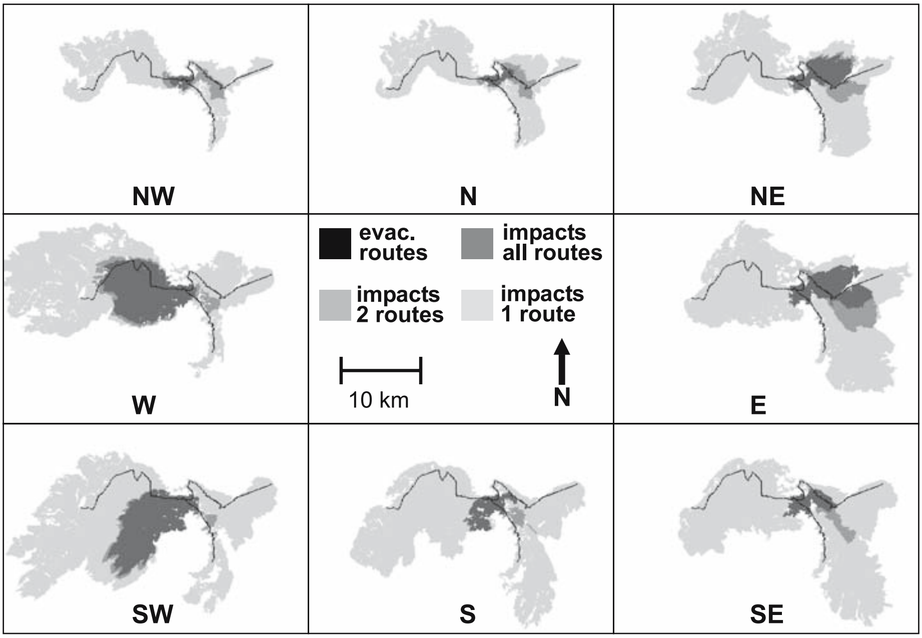

Fig. 7 The 3-h evacuation areas for three different evacuation routes, modeled using the maximum wind speed in eight directions. The evacuation routes are indicated by the black cells. Fires that breach or ignite within each area will impact some portion of at least one evacuation route within 3 h

evacuation routes is also likely to cut off access to the third evacuation route. The three-route impact area was largest for the wind directions with the highest maximum hourly wind speed, including the west, southwest, east wind directions. The large three-route impact area for the northeast wind direction is more surprising since the maximum hourly wind speed in this direction was moderate compared to other directions. A corridor of grass fuel types, which produce high fire spread rates, was northeast of the eastern evacuation route. The presence of this fuel increased the area of the three-route impact area, even for a relatively moderate maximum hourly wind speed of 8 m/s.

The three-route impact area is the most important because the loss of all three primary evacuation routes could trap residents within the community, forcing them to shelter-in-place. A FPA can also be calculated for the three-route impact area, where the FPA is the combination of the three-route impact areas for all 16 wind directions. All three evacuation routes could be impacted by a fire within this FPA if the worst-case wind speed and direction are present. Figure 8 displays the FPA that impacts all three evacuation routes within 1-, 2-, and 3-h. The size of the 1-h FPA is relatively small at 820 ha. The size of the 2-h FPA is more than 5 times the size of the 1-h FPA, and the size of the 3-h FPA is more than 14 times the size of the 1-h FPA. As the specified time period increases, the FPA that may impact all three evacuation routes rapidly grows.

Discussion

Evacuation trigger buffers modeled for 16 different wind directions reveal that fires to the west and southwest of Julian represent the greatest threat. Under worst-case conditions, strong west or southwest winds are capable of producing very high fire

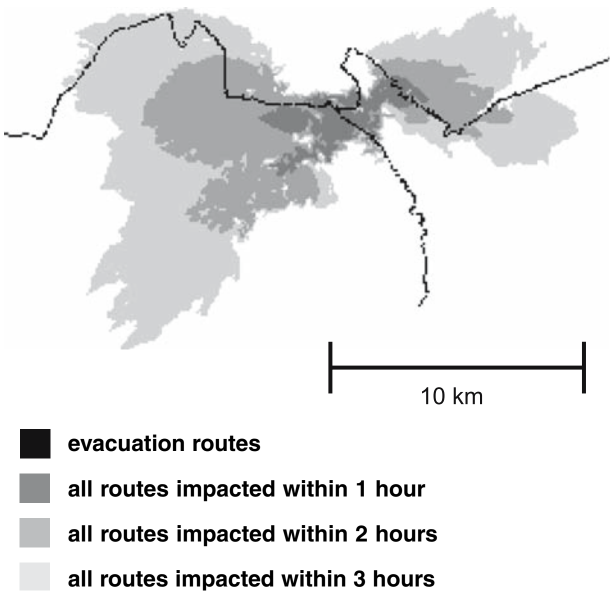

Fig. 8 The fire planning areas for which all evacuation routes could be impacted from the maximum wind speed in any direction, for 1-, 2-, and 3-h

spread rates toward Julian and Whispering Pines. Grass and shrub fuels to the west of Julian and steep slopes between these areas and Julian also promote high fire spread rates. The combination of wind and fuels characteristics in these directions produced a 3-h evacuation trigger buffer that extends as far as 15 km away from Julian. In contrast, fires to the east of Julian appear to represent a more moderate threat. The maximum hourly wind speed for the east direction was nearly as high as the maximum hourly wind speed for the southwest direction, but fuels to the east of Julian create lower potential for rapid fire spread when compared to fuels to the west and southwest of Julian. This is surprising given that the dominant direction of Santa Ana winds is typically out of the east and northeast, directions for which smaller trigger buffers were generated. This variation in trigger buffers demonstrates not only the inherent tradeoffs in the relative importance of fuels versus weather in controlling fire spread patterns (Moritz 2003), but also local interactions with topography (i.e., increasing elevation to the east of Julian). North and south wind trigger buffers are very close to Julian, due to lower wind speeds and sparser ground fuels. Since this simulation did not model crown fires, trigger buffers within forest fuel types will be too close to the community if a crown fire occurs. To accurately model trigger buffers within regions with large amounts of forest fuels, crown fire spread and spotting models will need to be incorporated.

Surface fire rates of spread produced by FLAMMAP and evacuation trigger buffers produced by WUIVAC have not been validated using actual fire data. Observational evidence from the Cedar Fire does provide some support for the large trigger buffers generated by the WUIVAC in the Julian simulation. Between midnight and 3 a.m. local time on October 26, Santa Ana winds drove the front of the Cedar Fire approximately 19 km. During this period the fire moved through fuels similar to those found to the west of Julian. Wind speeds along this portion of the Cedar Fire are unknown. The Julian RAWS, the closest weather station to this section of the fire, measured a wind speed of 7.6 m/s from 76° at 2:00 a.m. and from 79° at 3:00 a.m. Winds along the fire front were almost certainly much higher than those measured at Julian, and were potentially higher than the 11 m/s maximum hourly wind speed measured at the Julian RAWS over the 8-year period. Analysis of the sensitivity of model outputs to changes in model inputs is also needed. Previous work has demonstrated that fire spread rate is sensitive to the resolution of the input fuels map (Miller and Yool 2002).

Figure 9 shows mapped fire patterns for the Julian area over roughly the last 90 years, based on data from the California Department of Forestry. For example, the Cedar fire of 2003 came extremely close to burning the town of Julian, and all of the trigger buffers generated here would have been crossed. From these data, it is clear that the areas to the west and southwest of Julian burn more frequently than those in other directions. WUIVAC has, therefore, generated large evacuation trigger buffers in directions that are more than simply a hypothetical concern. Indeed, some portions of the landscape surrounding Julian have burned 4 or more times, and many of these fall within the FPA and in areas that could impact all the major evacuation routes examined here. Examining fire history in this area serves as preliminary validation that WUIVAC is able to highlight areas of high strategic importance.

Knowledge of wildfire location is often imprecise due to the obscuring effects of smoke and large distances between fire fighting crews. The trigger buffers and FPA produced by WUIVAC do not correspond to real-world landmarks. Operationally, it

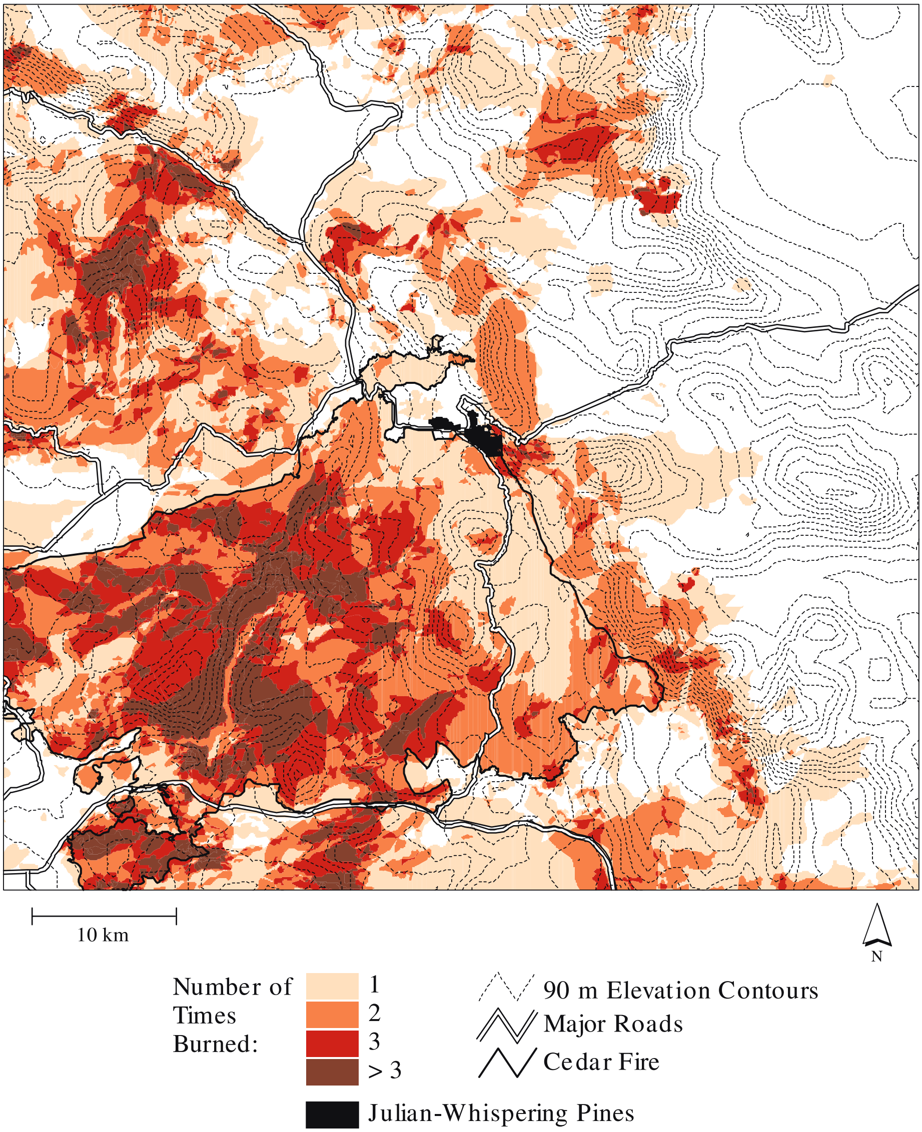

Fig. 9 Historical fire patterns in the vicinity of Julian, California. The blue line indicates the northeastern final boundary of the Cedar fire in 2003, and the darker red patches indicate higher fire frequencies (since ~1910). The elevation contour lines are also shown, which demonstrate that fires to the west and southwest of Julian would generally be burning uphill (i.e., faster) as they approached the town

may be difficult to determine when a fire has crossed the edge of a trigger buffer due to the combination of uncertainty in the location of the fire and uncertainty in the location of the trigger buffer on the landscape. To assist in operational evacuation decision-making, the edges of trigger buffers can be adjusted to match prominent physical and cultural landmarks, including roads, streams, lakes, ridgelines, and valley bottoms. Landmarks outside the trigger buffer are desirable, since landmarks inside the trigger buffer could decrease the actual time available for evacuation. An example of how real-world landmarks could be used to define the edge of a trigger buffer is shown in Fig. 10. The edge of the 3-h evacuation trigger buffer using the maximum hourly west wind was assigned to the nearest road. In cases where no road could be found near the trigger buffer edge, proximate water features were selected. Roads or water features were found for most of the trigger buffer (Fig. 10), with gaps in the new edge of the trigger buffer occurring where ridges or valleys ran perpendicular to the trigger buffer (Fig. 10). Since roads and streams tend to follow the terrain, finding landmarks to bridge these gaps may be difficult. The edge of the new trigger buffer is almost entirely outside of the WUIVAC-generated trigger buffer, so the trigger buffer is greatly increased in size. The original trigger buffer possessed an area of 11,640 ha, while the trigger buffer mapped to real-world features had an area of 17,250 ha.

Evacuation trigger buffers and the FPA can be used to guide evacuation decision-making, and Table 2 summarizes a set of guidelines proposed for WUIVAC outputs. Given reasonable estimates of evacuation time requirements, a fire outside an FPA will not require an evacuation unless worst-case conditions are present or predicted in the near future. Any fire near an FPA boundary should be carefully watched, because the fire may move closer to the community in the future. Preparations for an

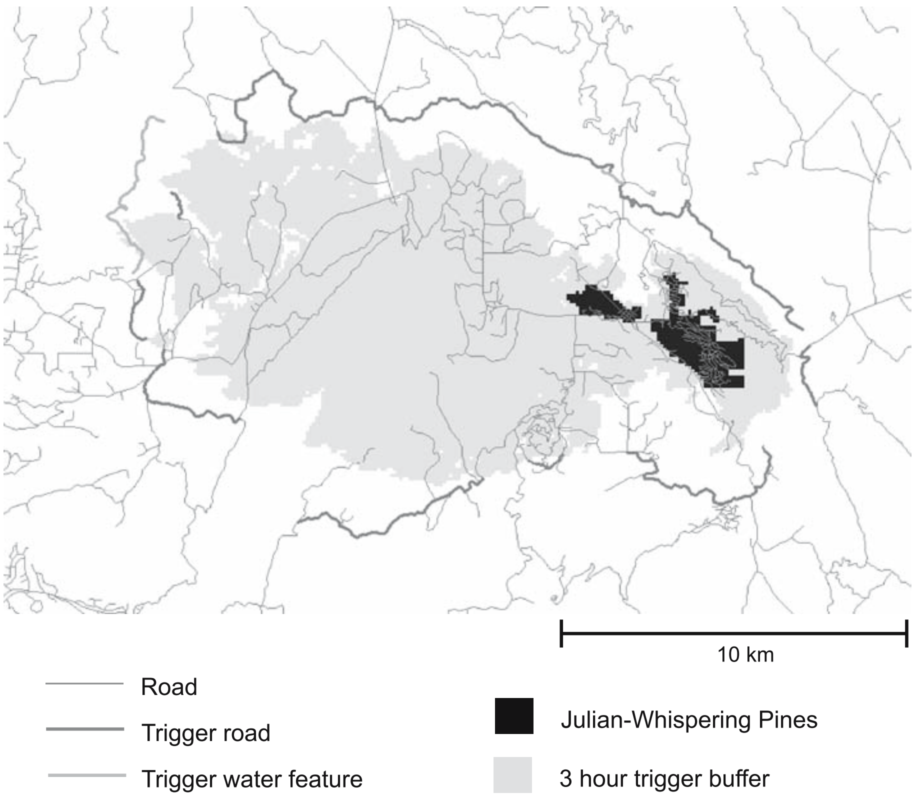

Fig. 10 Trigger roads and water features closest to the 3-h evacuation trigger buffer for the worst-case west wind model

Table 2 Evacuation rules utilizing WUIVAC outputs. "Outside" and "Inside" represent the position of the fire with respect to the feature specified in that column

FPA	Worst-case trigger buffer for current and expected wind direction(s)	Trigger buffer for actual or expected conditions	Action
Outside	Outside	Outside	Merits close attention, but will not require an evacuation unless the fire moves closer and/or conditions change
Inside	Outside	Outside	May soon require an evacuation. A change in wind direction, wind speed, or fuel moisture in the near future could trigger an evacuation. Preparations for evacuation should me made
Inside	Inside	Outside	An evacuation is likely. The wind direction is or is expected to be moving the fire towards the community. An increase in wind speed or decrease in fuel moisture could require immediate evacuation
Inside	Inside	Inside	Immediate action should be taken. An evacuation should be ordered if time permits and evacuation route safety can be assured

evacuation should be made if a fire crosses into or is ignited within the community's FPA, because changes in wind speed, wind direction, or fuel moisture that approach or exceed historical worst-case scenarios can quickly produce a fire that threatens the community. An evacuation trigger buffer can also be modeled for actual or expected (non-worst case) conditions (Table 2). If the fire exceeds or ignites within this buffer, immediate action must be taken. If the time period specified for the evacuation trigger buffer is greater than the amount of time required to evacuate, then an evacuation should be ordered. If the time period specified for the evacuation trigger buffer is less than the amount of time required to evacuate, then a shelter-in-place action should be ordered. The safety of the evacuation routes and their potential exposure to the fire should also be considered when ordering the evacuation.

The Wildland-Urban Interface Evacuation model can also be used to help plan potential evacuation routes out of a community. As was demonstrated by the three Julian evacuation routes, the area within the trigger buffer for a single evacuation route is quite large. If a community has only one evacuation route, an evacuation should be ordered as early as possible, to ensure that the only exit out of the community is useable for the entire duration of the evacuation. In addition, the fire fighting resources that are called on to protect a community will be required to defend a much larger area if only one exit for the community exists. Multiple exits reduce the area that must be protected in case of fire, thus reducing the fire fighting resources needed. If additional evacuation routes are needed for a community, WUIVAC can be used to highlight which additional routes are least likely to result in all evacuation routes being cut off in worst-case fire scenarios.

Conclusions

The Wildland-Urban Interface Evacuation model was used to model worst-case trigger buffers for the communities of Julian and Whispering Pines in the Cuyamaca Mountains of Southern California. Eight years of RAWS data were used to determine the maximum hourly wind speed in 16 directions. The resulting trigger buffers demonstrated that fires to the west and southwest of Julian represent the highest level of fire hazard for the community. Trigger buffers were combined to create a broader FPA, which defines the buffer for all worst case-conditions. Trigger buffers and the FPA were also calculated for three primary evacuation routes and used to find buffers, which if crossed by a fire, could result in the closing of all three evacuation routes.

Trigger buffers and FPAs generated by WUIVAC have immense value for strategic evacuation planning. Extreme fire behavior, such as that seen during the Cedar Fire, allows little time for evacuation planning. Strategic trigger buffers can be modeled long before any wildfire event, allowing for advance planning. Trigger buffers and FPAs designed for worst-case scenarios can be updated as fuel type or knowledge of the potential worst-case conditions changes, but are likely to be stable for many years. This long lead time allows the public to be informed of evacuation plans before an evacuation is imminent. Evacuation routes can be designated based on the potential for fire cut off in worst-case scenarios, and new evacuation routes can be planned that further minimize cut off potential. Eventually, integration of real-time weather conditions will allow WUIVAC to dynamically generate evacuation trigger buffers. All of these potential benefits will hopefully lead to a reduced loss of life and property in WUI fires.

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