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A household-level approach to staging wildfire evacuation warnings using trigger modeling

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ABSTRACT

Wildfire evacuation trigger points are prominent geographic features (e.g., ridges, roads, and rivers) utilized in wildfire evacuation and suppression practices, such that when a fire crosses a feature, an evacuation is recommended for the communities or firefighters in the path of the fire. Recent studies of wildfire evacuation triggers have used Geographic Information Systems (GIS) and fire-spread modeling to calculate evacuation trigger buffers around a location or community that provide a specified amount of warning time. Wildfire evacuation trigger modeling has been applied in many scenarios including dynamic forecast weather conditions, community-level evacuation planning, pedestrian evacuation, and protecting firefighters. However, little research has been conducted on household-level trigger modeling. This work explores the potential uses of wildfire evacuation trigger modeling in issuing household-level staged evacuation warnings. The method consists of three steps: 1) calculating trigger buffers for each household; 2) modeling fire-spread to trigger the evacuation of all households; and 3) ranking households by their available (or lead) time, which enables emergency managers to develop a staged evacuation warning plan for these homes. A case study of Julian, California is used to test the method's potential and assess its advantages and disadvantages.

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1. Introduction

Wildfires are a growing hazard in the western U.S. (Dennison, Brewer, Arnold, & Moritz, 2014) and pose significant risks to households in the Wildland–Urban Interface (WUI), defined as the area where residential development and wildlands meet (Davis, 1990). Wildfires cause significant losses of life and property in the western U.S. every year, and public safety for the communities vulnerable to wildfires has attracted significant research attention (Brenkert-Smith, Champ, & Flores, 2006; Cova, 2005; McCaffrey & Rhodes, 2009; Paveglio, Carroll, & Jakes, 2008). Increasing trends in fire activity in the American West have coincided with rapid population growth in WUI areas (Theobald & Romme, 2007). These dual trends have become a challenge for public safety.

When wildfire approaches a community, common protective actions for the residents include evacuation or shelter-in-place, which can be further classified into shelter-in-home and shelter-in-refuge (Cova, Drews, Siebeneck, & Musters, 2009). If enough time is available, evacuation provides a high level of life protection to threatened residents because they will be clear of the risk area. Shelter-in-place may be adopted when the residents are trapped by a rapidly spreading fire or when homeowners want to stay to protect property (Handmer & Tibbits, 2005). Although the government policy in Australia offers homeowners a choice to stay and defend their homes (McLennan, Cowlishaw, Paton, Beatson, & Elliott, 2014; McNeill, Dunlop, Heath, Skinner, & Morrison, 2013), evacuation is the primary protective action in the U.S. Selecting appropriate protective action remains a challenge for emergency managers because they need to take into account both the hazard dynamics and population distributions. Hazard assessment is generally performed to determine the immediacy and impact of the hazard, while population monitoring is conducted to inform decision makers of the population vulnerable to the hazard (Lindell, Prater, & Perry, 2006). Protective action decision making is typically done at the spatial scales of communities or regions, but further research may be needed for variation in hazard at finer scales such as that of the household.

Protective action selection is influenced to a large degree by timing—how much time is available for the residents to take action, and how much time is needed for the best option to be safe and effective? In practice, incident commanders (ICs) usually use prominent geographic features as trigger points to time protective-action recommendations. For example, when a fire crosses a ridgeline, evacuation recommendations may be issued to residents in the fire's path (Cook, 2003). In order to better understand the mechanism of wildfire evacuation triggers and facilitate wildfire evacuation decision-making, Cova, Dennison, Kim, and Moritz (2005) proposed a method that uses geographic information systems (GIS) and fire spread modeling to delimit

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a trigger buffer around a vulnerable geographic asset. Trigger modeling has been applied to create evacuation trigger buffers for firefighters (Cova et al., 2005; Fryer, Dennison, & Cova, 2013), and predefined communities (Dennison, Cova, & Mortiz, 2007; Larsen, Dennison, Cova, & Jones, 2011). However, little research has been conducted in setting triggers at the household level to help define evacuation warning zones. Moreover, fire-spread rates influence evacuation decision making and the timing of protective-action recommendations (Kim, Cova, & Brunelle, 2006). Existing applications of trigger modeling neglect the modeling of wildfire spread toward a trigger buffer, and integrating fire-spread modeling with trigger modeling may improve situational awareness during wildfire evacuations.

The aim of this study is to perform trigger modeling at the household level and to use fire-spread modeling to recommend departure times and associated staged evacuation warning zones. The first question concerns the spatial scale of trigger modeling: can trigger modeling be performed at the household level and what are the advantages and disadvantages of this scale? The second question is: can fire-spread modeling and household-level trigger modeling be integrated to develop staged evacuation warning zones and recommended departure times at the most detailed scale? The rest of this paper is organized as follows. Section 2 provides a literature review of evacuation modeling and planning, fire-spread modeling, and trigger modeling. Section 3 presents the three steps of the proposed method as well as the principles and theories underlying them. A case study of Julian, California is given in Section 4, and Section 5 ends the paper with discussions and conclusions.

2. Background

2.1. Trigger modeling

The raster data model represents the world with a regular grid and is a fundamental spatial data model in GIS (Chang, 2012). Trigger modeling uses a raster data model to represent the landscape and then employs fire spread modeling and GIS to create a buffer using the shortest path algorithm around a given location (P) with a given time (T) (Cova et al., 2005). Dennison et al. (2007) formulated trigger modeling into a three-step model—the Wildland Urban Interface Evacuation (WUIVAC) model. In the first step, the FlamMap software package is used to calculate the spread rates of the fire in eight directions. The second step calculates fire travel times between adjacent raster cells and constructs a directional fire travel-time network. The third step reverses the arcs between adjacent cells and performs shortest path calculation using Dijkstra's algorithm (Dijkstra, 1959) from a given location P with a given time interval T. It is important to note that the input P can be geographic objects at different scales, for example, the position of a firefighter or a firefighting crew, a house, a road, or a community. When P is the location of a firefighter or a house surrounded by fuels, it can be represented with one raster cell, while when P is a road or a community, it can be represented by a raster polyline or polygon. The input time interval T is the required evacuation time for the residents or firefighters at P, and it can be estimated using evacuation traffic simulation.

Cova et al. (2005) used trigger modeling to create trigger buffers for a fire crew's location, and another study conducted by Anguelova, Stow, Kaiser, Dennison, and Cova (2010) applied trigger modeling in pedestrian evacuation scenarios in wildland areas. These studies have demonstrated the potential of trigger modeling for small geographic scale scenarios. Dennison et al. (2007) performed trigger modeling at the community level using historic maximum wind-speeds to show how trigger modeling can be used for strategic community-level evacuation planning.

The shape of trigger buffer depends on fuels, wind, and topography (Dennison et al., 2007), and a study by Larsen et al. (2011) used varied wind speed and direction to create nested, dynamic trigger buffers for a community using the 2003 Cedar Fire as a scenario. Fryer et al. (2013) used varied wind speed, wind direction, and fuel moisture to create a series of trigger buffers for firefighting crew escape routes using travel times calculated for different modes. It should be noted that the size and shape of trigger buffers can be affected by fuel moisture, wind speed and wind direction (Fryer et al., 2013), and this should be taken into account.

2.2. Fire spread modeling

Fire behavior is determined by the fire environment, which includes topography, fuel, weather and the fire itself (Pyne, Andrews, & Laven, 1996, p. 48). Computerized modeling of wildfire spread has a long history (Rothermel, 1983), and fire spread models developed in the past few decades can be categorized into physical, semi-physical and empirical models (Sullivan, 2009a, 2009b). The Rothermel fire spread model (Rothermel, 1972), a semi-physical model based on energy conservation principles and calibrated with empirical data, has been widely used in various fire modeling systems such as BEHAVE (Andrews, 1986), FlamMap (Finney, 2006), and FarSite (Finney, 1998). The elliptical fire shape model proposed by Van Wagner (1969) models fire spread rates for head fire, flank fire, and back fire using an elliptical shape and has enjoyed great popularity in fire simulation. After fire behavior parameters are derived from fire spread models, fire growth models are utilized to propagate the fire across the landscape. The minimum fire travel time algorithm is used to propagate fire in FlamMap (Finney, 2002), while an algorithm based on Huygens' principle is used in FarSite (Finney, 1998). Other fire propagation models include Delaunay triangulation and shortest path algorithms (Stepanov & Smith, 2012), and Cellular Automata (CA)-based models (Clarke, Brass, & Riggan, 1994). Recently developed fire models have begun to include complex interactions between fire and weather by coupling an atmospheric prediction model with a fire spread model (Clark, Coen, & Latham, 2004; Coen, 2005; Coen et al., 2013).

The past few decades have witnessed the application of fire-spread modeling in various fields, such as wildlife habitat preservation (Ager, Finney, Kerns, & Maffei, 2007) and wildfire risk evaluation (Carmel, Paz, Jahashan, & Shoshany, 2009). However, research on using fire-spread modeling in wildfire evacuation is scarce. Post-event studies of wildfire evacuations have revealed the significant value of fire progression in understanding evacuation timing (Kim et al., 2006), and in this regard, fire-spread modeling has a great potential in improving situational awareness and facilitating decision making in wildfire evacuations when it is integrated with evacuation modeling.

2.3. Evacuation modeling and planning

Evacuation is defined as the process of moving people from risk areas to safer areas and can decrease the loss of life and property when a natural or technological hazard becomes a threat to residents (Lindell, 2013). However, it was not until the mid-twentieth century that evacuation became a research topic (Quarantelli, 1954). In the U.S., the Three-Mile Island nuclear incident in the 1970s attracted significant attention from research domain and became a milestone for modern evacuation studies (Cutter & Barnes, 1982). Numerous studies have been conducted on emergency evacuations in the past few decades and can be categorized into two types: behavioral and engineering studies (Murray-Tuite & Wolshon, 2013). Behavioral studies focus on public response and decision making (e.g., risk perception, evacuation decision making, and departure times) during emergency evacuations and on relevant socio-economic or psychological factors that influence behavior (Dash & Gladwin, 2007; Lindell & Perry, 1992, 2003). The engineering perspective focuses on transportation modeling and simulation techniques, and evacuation traffic simulation has enjoyed great popularity in the past few decades (Sheffi, Mahmassani, & Powell, 1982; Southworth, 1991). A growing trend in this field is to combine the social science and engineering perspectives in an interdisciplinary direction (Murray-Tuite & Wolshon, 2013; Trainor, Murray-Tuite, Edara, Fallah-Fini, & Triantis, 2012).

Behavioral studies conducted on wildfire evacuation reveal that ICs and evacuees have different concerns during anticipation, warning, displacement, return and recovery phases (Cohn, Carroll, & Kumagai, 2006). Specifically, the ICs are concerned about evacuation timing—when to impose evacuation orders (Cohn et al., 2006), which is an important leverage point in the evacuation process. Warning compliance refers to the percentage of residents who choose to evacuate after they are given an evacuation warning and relies on people's perception of the risk (Lindell et al., 2006). Previous research revealed that evacuation warnings have a significant effect on evacuation timing (Sorensen, 1991), and thus determining the timing of warnings is an important problem in evacuation planning.

Cova and Church (1997) used nodes and arcs to represent the transportation network and evaluate spatial evacuation vulnerability to wildfire using the critical cluster model (CCM) in Santa Barbara, California. It should be noted that this line of research quantifies the imbalance and contradiction between the rapid residential development in the WUI and the insufficient capacity of the transport infrastructure for evacuations and can be used to enlighten future community planning (Cova, 2005). The past several years have witnessed the application of microscopic traffic simulations to estimate evacuation travel times and test the effectiveness of neighborhood wildfire evacuation plans (Cova & Johnson, 2002; Wolshon & Marchive III, 2007). These studies use population data to generate evacuation travel demand and perform traffic simulations but do not take into account the progression of wildfire and its impact on evacuation timing. Post-event studies on wildfire evacuations have revealed that fire progression determines the timing of evacuation orders issued for the threatened residents (Kim et al., 2006). In this regard, incorporating fire progression into modeling and simulation becomes a necessity if we are to address the critical questions of who should be evacuated and when.

Risk areas refer to the geographic areas threatened by a natural or technological hazard (Lindell, 2013), and risk area delineation has attracted a significant amount of research attention in the past few years (Arlikatti, Lindell, Prater, & Zhang, 2006; Zhang, Prater, & Lindell, 2004). Staged evacuation is defined as the evacuation practice in which the risk area is divided into evacuation warning zones, and these zones are evacuated in a progressive manner (Chen & Zhan, 2008). The strength of staged evacuation strategy over simultaneous evacuation lies in that it can relieve traffic congestion and reduce total evacuation time when the evacuation travel demand significantly exceeds the capacity of the transportation network (Chen & Zhan, 2008). Another advantage of staged evacuation is that it can minimize the disruption of non-threatened residents. It should be noted that dividing the risk area into evacuation warning zones is the premise for staged evacuation. Existing studies usually establish evacuation warning zones prior to the study using aggregate data such that they are a given (Chen & Zhan, 2008; Sorensen, Carnes, & Rogers, 1992; Southworth, 1991; Wilmot & Meduri, 2005). This top-down approach is characterized by “risk area-evacuation zone-traffic simulations” and has been the dominant paradigm in evacuation modeling and simulation in the past few years. Although evacuation zoning has been examined (Murray-Tuite & Wolshon, 2013), it is still an under-researched subfield in emergency management. With the rapid development of computing power, modeling and simulation at the individual level have become a popular trend (Bonabeau, 2002), which provides a good opportunity to research staged evacuation zoning using a bottom-up approach.

3. Methods

In general, wildfire evacuations are conducted at a relatively small geographic scale from a few households up to a few thousand. Trigger modeling has been applied at the community scale, but this work aims to perform trigger modeling at a more detailed scale to examine household-level evacuation warning timing and zoning. Fig. 1 is a conceptual representation of the proposed method. The red polygons represent fire perimeters, while the black polygons represent evacuation trigger buffers (ETBs) for houses 1 and 2 respectively. Note that the shape of the fire perimeter is skewed in the same direction as the wind, while the two ETBs are skewed in the opposite direction of the wind to offer the same amount of warning time if fire should approach from that direction (i.e., a trigger buffer is a fire travel-time isochrone).

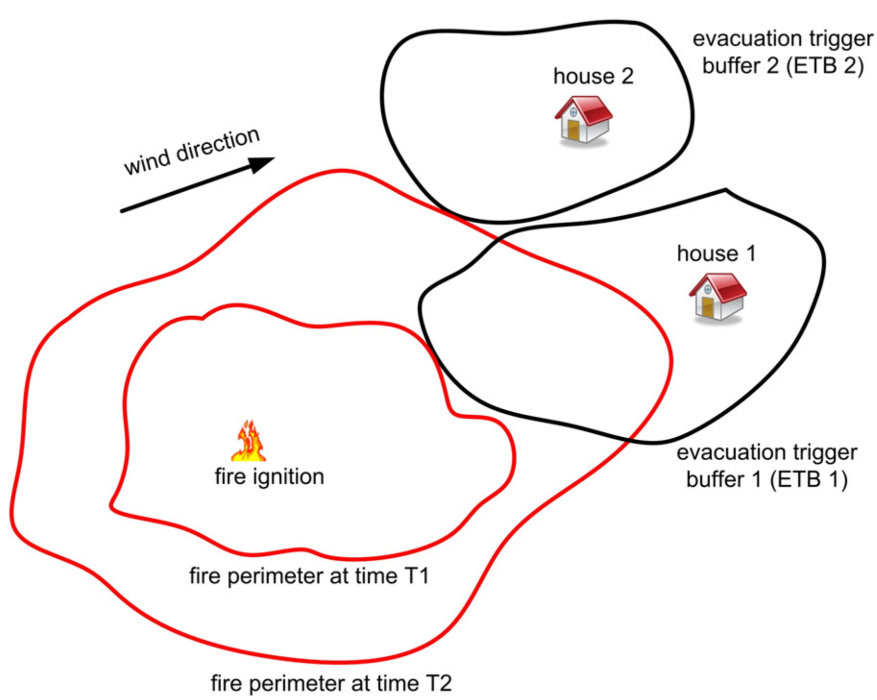

Fig. 1. A conceptual representation of the method.

The fire shown crosses the boundary of ETB 1 at time T1, so household 1 should be notified to evacuate at T1. Similarly, household 2 should be notified to evacuate at T2.

Given a series of sparsely distributed exurban households $H = \{h_1, h_2, \ldots, h_n\}$ and an estimated evacuation time for each household $ET = \{et_1, et_2, \ldots, et_n\}$, trigger modeling can be used to create ETBs $B = \{b_1, b_2, \ldots, b_n\}$ for each household with relevant wind direction, wind speed, and fuel moisture. If the fire-spread process has m time steps $T = \{t_1, t_2, \ldots, t_m\}$, and the spreading fire crosses the boundary of ETB b_i at time t_j, then household h_i should be warned to evacuate. These residents should have at least et_i before the fire reaches their residence. With the progression of the fire, the recommended evacuation departure time (REDT) for each household h_i can be derived and can be represented by $REDT = \{redt_1, redt_2, \ldots, redt_n\}$. Then, the derived evacuation departure times REDT can be used to group the households into staged evacuation warning zones $Z = \{z_1, z_2, \ldots, z_k\}$. An emergency manager could use these zones to issue staged evacuation warnings when the households are threatened by wildfire.

The proposed method is formulated into a three-step process, and the workflow of the method is shown Fig. 2. In the first step, reverse fire-spread modeling is performed using the household locations, evacuation times for households, elevation, aspect, slope, vegetation cover, wind direction, wind speed, and fuel data as the inputs. The output of the first step is a set of ETBs, which can be used as inputs in the second step—fire-spread modeling. Fire-spread modeling uses the same set of fire environment inputs, and the evacuation notifications are triggered when the fire crosses the boundary of the ETB of each household. The output of the second step is a set of REDTs for the households. In the third step, the REDTs of the households are used to divide the households into different evacuation warning zones.

3.1. Step 1: household-level trigger modeling

In the first step, trigger modeling is performed at the household level to generate the ETBs based on the estimated evacuation time. Evacuation time in this specific context refers to the time taken by a household to travel from the risk area to safety. The input time for trigger modeling is the estimated evacuation time for the target population. The inputs can be divided into two groups: one group that includes topography (elevation, slope, and aspect), vegetation (fuel and canopy cover), and weather (wind direction and speed) data that is used for fire-spread modeling, and a second group that includes household locations and estimated evacuation times.

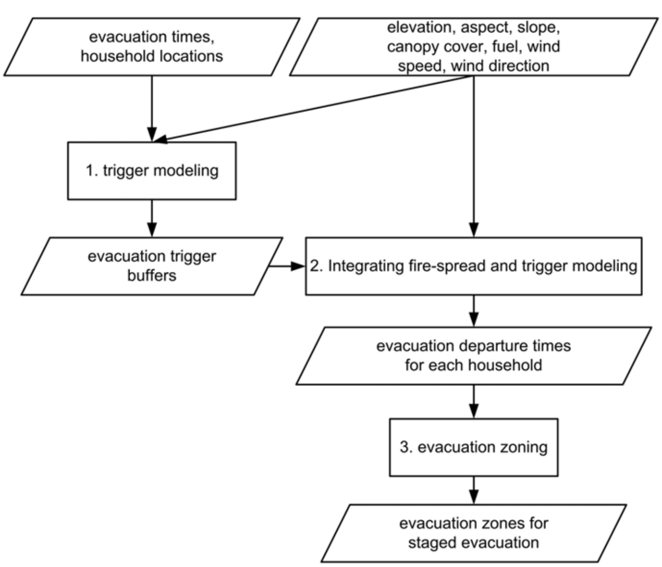

Fig. 2. Workflow of the research method.

In order to facilitate trigger modeling, the three-step process proposed by Dennison et al. (2007) is used to create ETBs for the households, as shown in Fig. 3. The first step employs a fire-spread modeling software package (FlamMap) that uses the topography, vegetation, and weather inputs to calculate fire spread rates (Finney, 2006). The second step uses the derived fire spread rates in eight directions to calculate the travel times between orthogonally and diagonally adjacent raster cells, which are then used to construct a fire travel-time network. In this network, the arcs are directional and the weight of an arc denotes the travel time from one cell to its neighbor in that specific direction. In the third step, all the arcs in the network are reversed and Dijkstra's algorithm (Dijkstra, 1959) is employed to traverse from a given cell containing a household until the accumulated travel time reaches a specified constraint time, in this case the estimated evacuation time. In this manner, a set of household-level ETBs can be derived using trigger modeling.

3.2. Step 2: integrating fire-spread with trigger modeling

After the generation of trigger buffers for the households, fire-spread modeling can be performed to trigger the evacuation warnings for households based their corresponding ETBs. When the spreading fire on the landscape reaches the boundaries of the ETBs, those households should be notified to evacuate. When ICs use triggers in practice, they need to first estimate the evacuation times needed for the threatened population before they set triggers (Cova et al., 2005).

The first step can generate an ETB $b \in B$ for each household $h \in H = \{h_1, h_2, \ldots, h_n\}$. Moreover, the spatial data used in fire spread modeling can also be used in FlamMap to generate a minimum travel time (MTT) map, which is a raster map where the value for each cell within the map represents the MTT it takes from the ignition cell to every raster cell in the landscape. The MTT algorithm produces a travel-time network that depicts the shortest path that fire might take between the ignition and each raster cell in the landscape. We should note that the MTT and Dijkstra's algorithm used in fire growth modeling and trigger modeling both calculate the shortest path in a travel-time network and thus have taken into account the worst case scenario (i.e., fire taking the most rapid path), which is of critical significance in evacuation studies because early warnings are better than late ones. The resulting MTT map can be used to trigger the evacuation of the households using their ETBs and obtain the REDT for each household.

The algorithm used for calculating the REDTs for the households is shown in Table 1. The MTT map is used to simulate the fire spread across the raster landscape. The time at the ignition starts at time 0 (in minutes), which is also used as the starting time for the simulation. In the algorithm initialization, all households are added to a set that have not been warned (or triggered) to evacuate. As the fire progresses, the algorithm will search for the ETBs that are being crossed by the fire

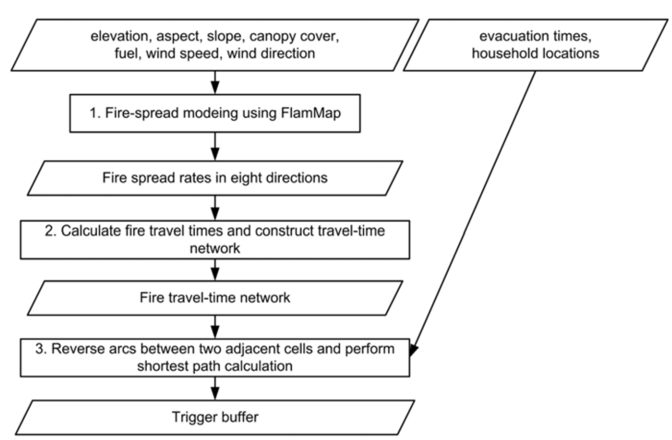

Fig. 3. Workflow of trigger modeling.

Table 1
Algorithm for calculating recommended evacuation times by integrating fire-spread with triggers.

```
tMax = getMaxTime(MTTMap)          // the maximum fire travel time (MTT map is from FlamMap)
setHousehold = getHouseholds()       // a set of households to be evacuated
triggerBuffers = getTriggerBuffers()  // get the trigger buffer for each household
mapHouseholdEvactime  = NULL       // record the household ID and its evacuation time
For t From 0 To tMax                   // iterate t from 0 to the maximum value tMax
    For cell In MTTMap                 // iterate each cell in the MTT map
        If cell == t                   // if the value of the cell is equal to t
            For household In setHousehold                    // for each household in the set
                If cell Is In triggerBuffer[household]       // if the cell is within the buffer
                    setHousehold.remove(household)           // remove household from the set
                    mapHouseholdEvactime.insert(household, t)  // add the household and its time
```

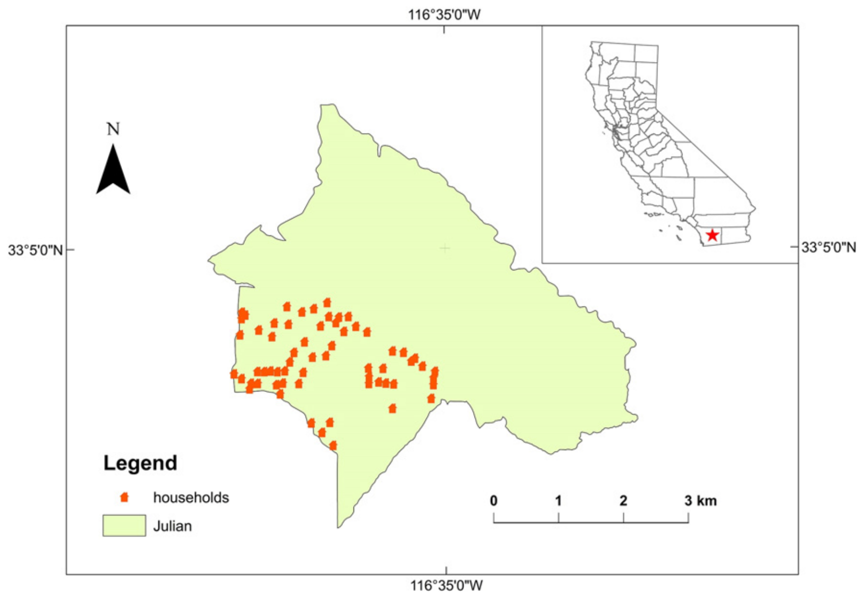

Fig. 4. Sparsely distributed households in Julian, California.

and record the household, as well as the time when fire crosses the boundary of its ETB. When a household has been triggered to evacuate, it is eliminated from the household set. The REDTs derived are relative to the fire ignition time and are also in minutes. Eventually, the REDTs for all the households are derived, which can be used to group the households into different evacuation warning zones in the next step.

3.3. Step 3: evacuation zoning

This step aims to develop bottom-up evacuation warning zones using the REDTs of the households according to above-mentioned procedures. Evacuation zoning should take into consideration both the REDTs and the spatial configuration of the households. In other words, the households with similar REDTs should be grouped into one zone, and the households in geographic proximity to each other should be included in one zone. At this point the zoning problem is transformed to a clustering problem with spatial constraints—the REDTs can be used as attributes and the household locations can be used to measure spatial closeness. Assunção, Neves, Câmara, and da Costa Freitas (2006) put forward the Spatial "K" luster Analysis by Tree Edge Removal (SKATER) algorithm to cluster spatial features by partitioning a minimum spanning tree (MST) constructed using the features, which has been proved to be effective in clustering spatial features efficiently. Thus, the SKATER algorithm can be used to partition the households into different evacuation warning zones based on their departure times as well as their spatial configuration.

When given a set of features, the SKATER algorithm requires that a connectivity graph be constructed using contiguous or proximal relationships. In this context, each node in the graph represents a household, and the value of edge between two features denotes the dissimilarity of REDTs. In the context of household evacuation zoning, the households are point features and proximity measurements between two households can be used to construct the connectivity graph. For example, K Nearest Neighbors (KNN) method can be used to define proximity based on the Euclidean distance between households. After the construction of connectivity graph, the SKATER algorithm prunes edges with high dissimilarity and uses Prim's algorithm to derive a MST, which is a spanning tree with the minimum sum of dissimilarities over all the edges. Since sub-trees can be derived by cutting the tree at suitable places, the clustering problem is transformed to an optimal graph partitioning problem. The sum of intra-cluster square deviations is used as an objective function in the optimization process,

Table 2
Scenarios for fire-spread and trigger modeling.

Scenario	Ignition	Wind direction	Wind speed (km/h)
1	West	West	16
2	West	West	32
3	Southwest	Southwest	16
4	Southwest	Southwest	32
5	South	South	16
6	South	South	32

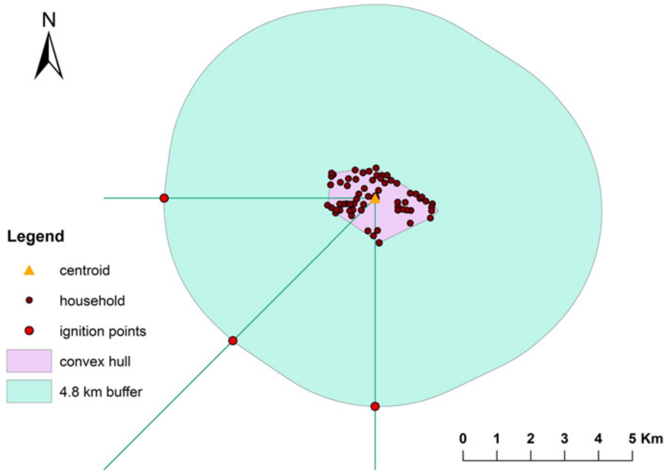

Fig. 5. Map for the case study design.

which reflects the intra-cluster homogeneity and should be minimized. It should be noted that the MST partitioning problem is NP-hard, and therefore a heuristic method is employed in SKATER to perform the tree partitioning at a relatively low computational cost (Assunção et al., 2006). After the partitioning of the MST, the households are divided into different groups, which can be used as staged evacuation warning zones.

Since topography, fuel, and weather determine fire behavior and thus can determine the size and shape of the trigger buffer generated by trigger modeling (Dennison et al, 2007), the REDTs derived in the second step may not strictly reflect the distance decay principle. For example, if the REDT of household h_1 is smaller than that of household h_2, it means h_1 should be evacuated earlier than h_2. However, h_2 may be closer to the fire front compared to h_1 because they may differ in terms of topography, fuel, and weather. This influences the shape and size of the trigger buffer and can result in inconsistency between their distances to the fire front and their REDTs. In this regard, the evacuation warning zones derived directly using clustering method based on the REDTs need to be adjusted using prominent geographic features. The purpose of adjustment is to establish evacuation warning zones that are easily identifiable by the threatened residents and can be conveniently and effectively communicated to the public by ICs in issuing actual warnings. Common geographic features used to establish evacuation zone boundaries include roads, neighborhoods and other prominent physiographic (rivers) and cultural features (landmarks). Zip codes, or other administrative zones, can also be used to construct

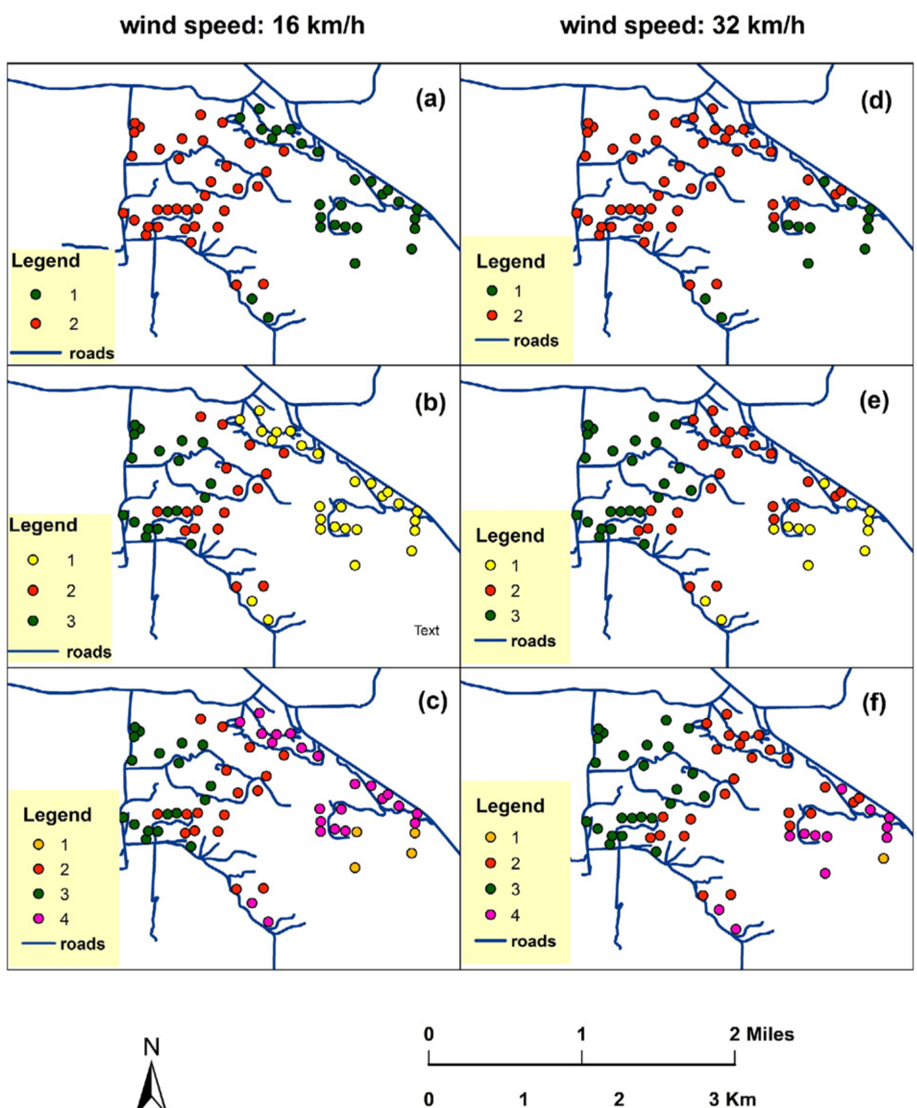

Fig. 6. Group analysis for scenarios 1 and 2.

evacuation warning zones when a hazard threatens a large geographic area, but they are relatively rare in wildfire evacuations because most are performed for smaller areas. Finally, it should be noted that the results of this step are a series of delineated evacuation warning zones with REDT for each zone, which can be used to issue warnings to threatened residents and facilitate staged evacuation.

4. Case study

Flammable vegetation types, seasonal drought, and Santa Ana winds have made the fire-prone communities in southern California extremely vulnerable to devastating wildfires (Westerling, Cayan, Brown, Hall, & Riddle, 2004). Wildfires have caused significant losses in life and property in the past few decades in this area (Rogers, 2005). The devastating 1991 Tunnel Fire in Oakland/Berkeley cost 2475 homes and 25 lives, and the 2003 Cedar Fire in San Diego caused the loss of 2232 homes and 14 lives (Rogers, 2005). Public safety in these fire-prone communities in southern California has attracted a significant amount of attention in the past few years (Cova, 2005; Stephens et al., 2009). In the case study, Julian, a census-designated place (CDP) in San Diego County, California, is our study site. As noted by Dennison et al. (2007), Julian is relatively isolated from the metropolitan areas and is surrounded by large areas of fuels, making it a good case study for wildfire evacuation studies. A total number of 62 sparsely distributed households located in the southwest portion of Julian were selected, and the map for the distribution of these households is shown in Fig. 4. The household locations were derived by calculating the centroids of the residential parcels in Julian using the 2010 parcel data downloaded from the GIS agency of San Diego County—SanGIS. Other vector road network and Julian boundary data were also obtained from SanGIS. Python and the ArcGIS Python library ArcPy were used to transform household location data into raster cells. The raster data were at 30 m resolution and the study area contains 500 × 500 raster cells. A 2003 fuel map at 30 m resolution from the Fire and Resource Assessment Program (FRAP) at California Department of Forestry and Fire Protection was used as the fuel data. The compiled fuel data use the 13 Anderson (1982) fuel models and include 11 flammable fuel types and 3 unburnable fuel classes. The 30 m resolution digital elevation model (DEM) data obtained from the United States Geological Survey (USGS) was used to calculate aspect and slope data using the GIS software package ArcGIS.

Different software packages and programming languages were used to implement the proposed method as a loosely coupled system (Brown, Riolo, Robinson, North, & Rand, 2005). It was assumed that 1 h is sufficient for each household to evacuate to a safe area, and thus the input time for trigger modeling was set to 1 h. The wildfire spread modeling software package FlamMap was used to perform wildfire spread modeling and get the maximum spread rates, maximum spread direction, elliptical parameters for calculating directional fire spread, and MTT map. The programming language C++ was used to create ETBs for each household in the first step and simulate the "fire triggers evacuation" process in the second step because it has good computational efficiency and its object-oriented programming (OOP) characteristics can favor the reusability of the code in the future. Since the SKATER clustering algorithm has been implemented in ArcGIS, ArcGIS was used to cluster the households into different groups based on their spatial locations and REDTs. Finally, Python was used to adjust the derived groups based on road segments to get the final evacuation warning zones, and ArcGIS was used to map the zones constructed using the proposed method.

In order to better understand the characteristics of the proposed method, different fire ignition points and varying wind speeds were used for fire-spread and trigger modeling. Specifically, 3 ignition points located 3 miles away from the centroid of the households were used, and 2 wind speeds (16 and 32 km/h) were used for each ignition point. In total, 6 scenarios were used to evaluate the proposed method, as shown in Table 2. Wind directions were set from the ignition point toward the households, which can denote the worst case scenario in terms of the risk imposed by the fire to the households. The map in Fig. 5 illustrates the experiment design. The centroid of the households was calculated, and a 4.8 km (3 miles) buffer was created around the

Table 3
Results of group analysis.

Scenario (number of groups)	Group ID	Count	Mean (min)	Std. Dev.	Min (min)	Max (min)
1 (2)	1	27	307	43	255	458
	2	35	206	37	127	277
1 (3)	1	27	307	43	255	458
	2	17	236	18	216	277
	3	18	176	25	127	208
1 (4)	1	4	387	41	361	458
	2	17	236	18	216	277
	3	18	176	25	127	208
	4	23	293	24	255	340
2 (2)	1	13	111	18	94	166
	2	49	72	12	49	91
2 (3)	1	13	111	18	94	166
	2	25	82	6	73	91
	3	24	61	7	49	71
2 (4)	1	1	166	0	166	166
	2	25	82	6	73	91
	3	24	61	7	49	71
	4	12	106	8	94	118
3 (2)	1	25	386	48	336	522
	2	37	285	34	225	356
3 (3)	1	4	480	29	452	522
	2	37	285	34	225	356
	3	21	368	23	336	429
3 (4)	1	4	480	29	452	522
	2	15	319	17	285	356
	3	21	368	23	336	429
	4	22	263	22	225	302
4 (2)	1	6	153	23	130	190
	2	56	98	12	75	121
4 (3)	1	6	153	23	130	190
	2	31	89	7	75	99
	3	25	109	7	98	121
4 (4)	1	2	185	6	179	190
	2	31	89	7	75	99
	3	25	109	7	98	121
	4	4	138	6	130	147
5 (2)	1	5	1243	47	1174	1293
	2	57	1066	38	944	1157
5 (3)	1	5	1243	47	1174	1293
	2	10	1005	24	944	1027
	3	47	1079	25	1045	1157
5 (4)	1	5	1243	47	1174	1293
	2	10	1005	24	944	1027
	3	14	1102	18	1082	1157
	4	33	1069	21	1045	1126
6 (2)	1	9	406	24	384	455
	2	53	352	13	310	378
6 (3)	1	9	406	24	384	455
	2	21	364	5	358	378
	3	32	344	10	310	359
6 (4)	1	6	391	10	384	414
	2	21	364	5	358	378
	3	32	344	10	310	359
	4	3	434	15	418	455

Table 4
The number of households by road segment.

Road name	Number of households
6th Street	12
Van Duesan Road	11
Old Cuyamaca Rd	9
Slumbering Oaks Trl	8
Pine Hills Rd	4
Deer Lake Park Rd segment 1 (north)	14
Deer Lake Park Rd segment 2 (south)	4
Total number of households	62

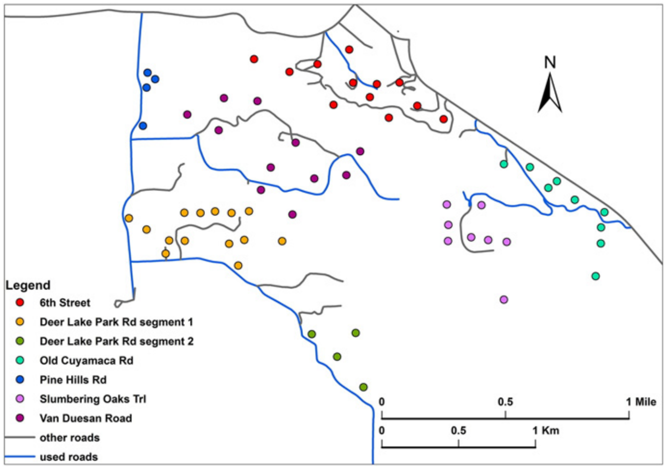

Fig. 7. Households grouped by road segments.

convex hull of the households using ArcGIS. The three ignition points were placed on the boundary of the buffer to the west, southwest, and south of the centroid.

The results of the 6 scenarios were derived using the proposed method, and Fig. 6 shows the clustering results for scenarios 1 and 2 using the group analysis tool in ArcGIS. Specifically, KNN was used as the spatial constraints and 8 neighbor households were used to determine the group one household will fall in. The number of groups was set as 2, 3, and 4 respectively for each scenario, and the results for the group analysis are listed in Table 3. The geographic scale of the study area is relatively small, thus we can use road segments as the building blocks for evacuation warning zones, which is common in exurban wildfire evacuations. From the overlaid road network, we can note that the households are naturally clustered by road segments, and using road segments to adjust the zones will make issuing emergency warnings more convenient. Based on the structure of the road network and the spatial configuration of the households, six roads with names were chosen and one road with the name “Deer Lake Park Rd” was split into two parts because the households along it fall into two natural clusters. Table 4 gives the seven clusters of households grouped by their closest road segment, and the spatial configuration of the grouped households is shown in Fig. 7. Then these road-segment household groups were used to adjust the results of the group analysis—voting was performed within each road-segment group, and the group is assigned with the most popular evacuation group ID of the households. The final adjusted evacuation warning zones for the six scenarios are

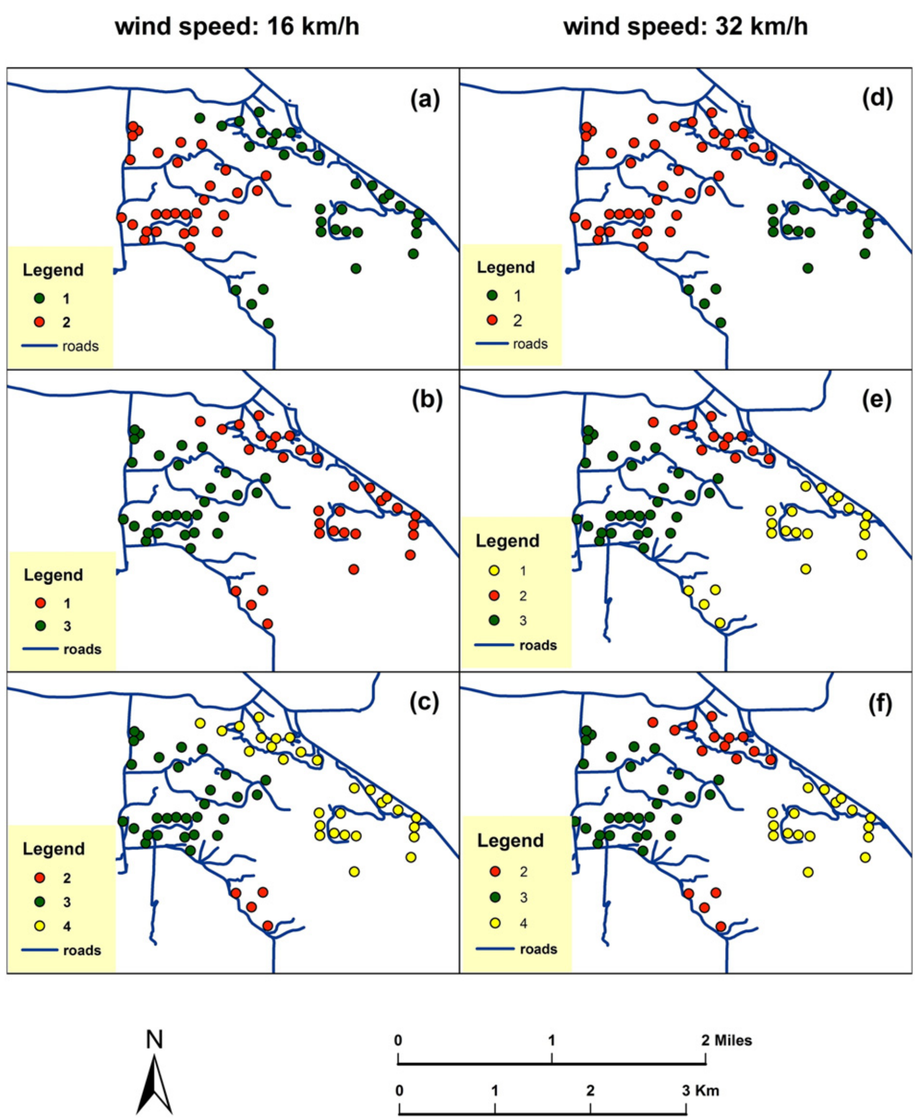

Fig. 8. Adjusted zones using road segments for scenarios 1 and 2.

shown in Figs. 8–10. After adjusting the zones, heterogeneity is eliminated within each zone and the zones become homogenous. The final adjusted results also demonstrate that the spatial configuration of evacuation warning zones can reflect the spread direction of the fire. For example, the zones in Fig. 8 are arranged from the west to the east, which corresponds to the wind direction in scenarios 1 and 2; the zones in Fig. 9 are arranged from the southwest to the northeast; and the zones in Fig. 10 are arranged from the south to the north. Thus, wind direction can influence the spatial configuration of the zones.

5. Discussion and conclusion

Wildfire evacuation is a complex spatio-temporal process, which involves the progression of the fire and the evacuation of the at-risk population to safe areas. In order make sound warning decisions, ICs need to take into account many factors during evacuation, e.g., the direction and speed of fire progression, the population at risk, estimated evacuation traffic demand, and shelter selection. The complexity of the evacuation process can overwhelm ICs and poses significant problems for effective decision making (Drews, Musters, Siebeneck, & Cova, 2014). Post-event studies on fire progression and the timing of protective action recommendations during wildfire evacuations can help improve our understanding of the evacuation process and provide guidance for future evacuations (Kim et al., 2006). In this regard, simulations can be performed to help increase situational awareness and facilitate decision making during wildfire evacuations. This work presents a method that employs fire-spread modeling and household-level trigger modeling to tackle wildfire evacuation warning timing and staged zoning from the IC's perspective. Several implications from this study are summarized as follows.

First, this study demonstrates that household-level wildfire evacuation trigger modeling is technically feasible. However, this finer-grain modeling and simulation costs significantly more computationally, and the necessity of performing modeling and simulation at the finer level should be determined before any endeavors are conducted. The value of performing trigger modeling at the household level is twofold: first, for those isolated households in rural areas, household trigger modeling can be used to facilitate emergency warning at a very detailed level. Second, when household-level triggers are integrated with fire-spread, ICs can develop a better understanding of timing evacuation warnings and managing travel demand. This work focuses on the second implication and demonstrates how the integration of household trigger modeling and fire-spread modeling can facilitate evacuation warnings and staged zoning. However, the first implication is equally important and has great potential in evacuation warning practice. With modern warning technologies like the reverse 911 system,

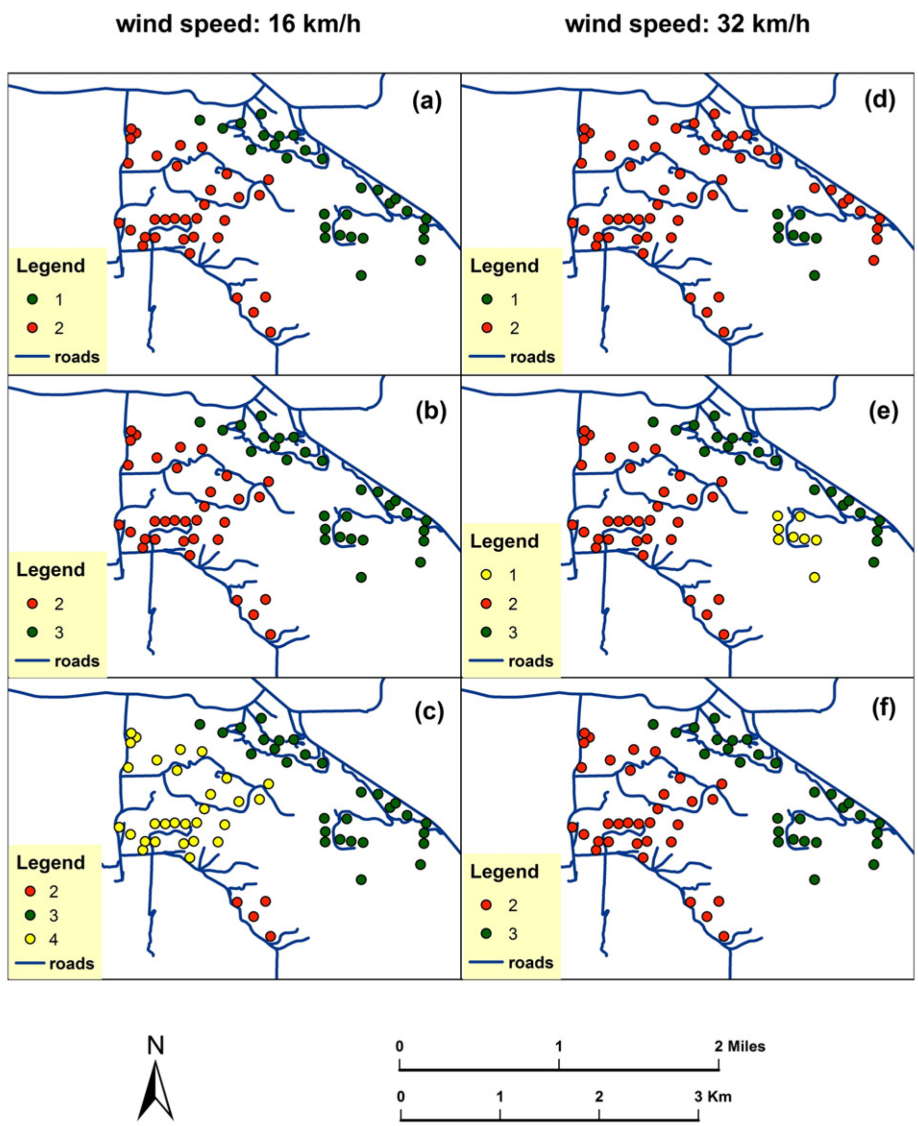

Fig. 9. Adjusted zones using road segments for scenarios 3 and 4.

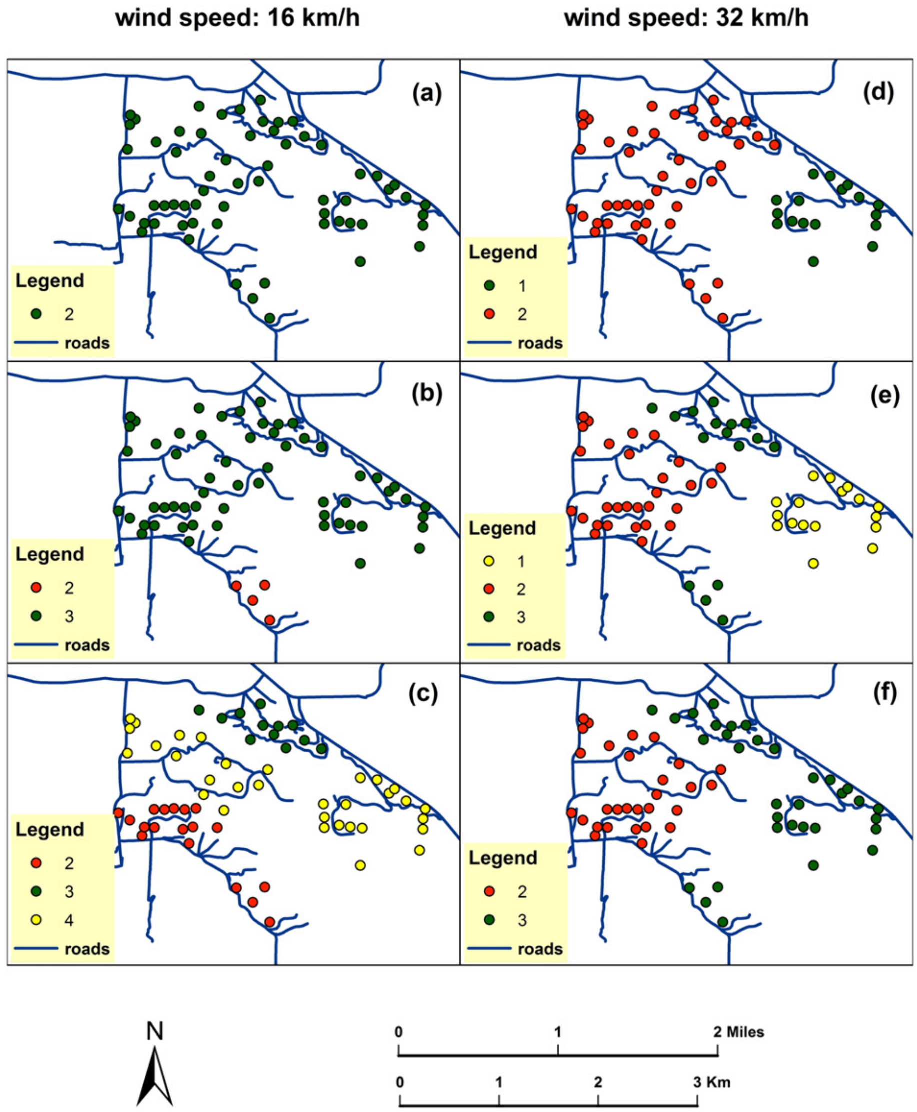

Fig. 10. Adjusted zones using road segments for scenarios 5 and 6.

household-level warning has become popular (Strawderman, Salehi, Babski-Reeves, Thornton-Neaves, & Cosby, 2012). Household-level trigger modeling is a means of controlling evacuation timing based on the MTT it will take for the fire to reach a specific household. Estimating the REDTs for sparsely distributed households in the WUI holds promise to improve emergency notification and warning at the household level, thereby improving public safety while minimizing the disruption of households that are not at risk. Future work could focus on using WebGIS to implement the trigger modeling on the server side, while using the most recent mobile computing to provide relevant emergency warning and notification at the client side (web or mobile client). This has been called “geo-targeted warnings” and it represents a significant research challenge in issuing public warnings to people with location-based devices like cell phones (Aloudat, Michael, Chen, & Al-Debei, 2014; National Research Council, 2013). Moreover, modern sensor web technologies have capabilities to retrieve data from sensors and process the data in a near real-time manner (Chen, Di, Yu, & Gong, 2010). These sensor web technologies can be used to detect fire progress in wildfire evacuations and have great potential in facilitating decision making when they are integrated with trigger modeling.

Second, integrating fire-spread and trigger modeling is a central contribution of this paper. This work uses a loosely coupled strategy to build the system. For example, the software package FlamMap is used to perform fire spread modeling, and ArcGIS is employed to accomplish group analysis and construct evacuation warning zones. This loosely coupled strategy has limitations when it comes to sensitivity analysis and will bring inconvenience to decision makers in wildfire evacuation, and more efforts should be devoted to building a tightly coupled system so as to facilitate the use of the method. Specifically, relevant open source libraries can be borrowed to couple the systems at the source code level, which could bring great convenience to decision making in wildfire evacuations.

Third, this work examines building wildfire evacuation warning zones by using a risk-based, bottom-up approach that integrates fire-spread and household-level wildfire trigger modeling, which proves to be applicable to staged evacuation planning. The geographic scales of evacuations vary with different hazard agents. For example, hurricane evacuations are usually performed at the country, state, or regional level, while wildfire evacuations are generally conducted at the community scale. The geographic scale of hazard agents determines the size of the risk area and the population at risk, which will eventually influence the size of evacuation warning zones. This study illustrates the use of road segments in delineating evacuation warning zones at the finer scale. The strength of using road segments lies in that people have great familiarity with the road names around them, which will significantly facilitate people's perception of the risk area during the warning process. Traditionally, the ICs will estimate fire progress and then divide the risk area into evacuation warning zones using prominent geographic features. In this top-town method, the determination of the order of the evacuation warning zones is determined by the spatial configuration of the zones relative to the fire, and the staged evacuation warnings are sent to the zones merely based on the ICs' situational awareness. Taking the evacuation scenario in the case study as an example, the ICs can delineate the zones using road segments and send out warnings accordingly, but they cannot specify when to send warnings to each zone. The proposed method can generate evacuation warning zones with their corresponding REDTs, and the zones are aggregated and constructed based on the computation of the REDT for each household. Thus, the ICs can not only delineate the zones using prominent features, but also specify the REDT for each zone and recommend staged evacuation warnings accordingly. Thus, the proposed method makes a contribution to existing methods.

Lastly, the assumptions used for fire propagation and trigger modeling should be taken into account. The MTT and Dijkstra's algorithm are employed for fire propagation modeling and trigger modeling, and they use the same data structure and both calculate the shortest path in a fire travel-time network. Fire propagation models can have different implications for different contexts. In the context of wildfire evacuation, the implication of using shortest path algorithms in a fire travel-time network is that fire propagates in the fastest manner in the landscape, which ensures that worst-case scenarios are considered in evacuation planning (i.e., the case with the least time available to take protective action). Fire travel times in modeling fire-spread have significant implications because the speed of fire propagation directly influences evacuation timing. If fire growth from shortest path algorithms is faster than reality, the generated REDTs will have smaller values and the households will be evacuated earlier than they should be, which could result in unnecessary disruption. Conversely, if fire propagates slower than reality, late evacuation could occur and the households will be placed in danger during evacuation (Handmer & Tibbits, 2005). Thus, the accuracy of fire propagation models should be taken into consideration. Finney (2002) compared fire-perimeter growth using MTT with that from FarSite simulations, and the results indicate that the two methods can produce identical fire-growth expansions. Future work can use other fire propagation methods in the proposed method and compare their results with that of shortest path algorithms. Another assumption taken in our trigger modeling is that 1 h is sufficient for the households to safely evacuate. Although traffic congestions in exurban areas during wildfire evacuation is less likely to happen than in larger regional evacuations (e.g., hurricanes), poor design of the evacuation route systems may still result in the residents' inability to evacuate (Cova, Theobald, Norman III, & Siebeneck, 2013). For example, road closures caused by the fire can influence households' evacuation route choice and their evacuation times. As a result, traffic simulation could be performed in future work to further examine this assumption.

This study integrates fire-spread with trigger modeling and presents a novel simulation-based, bottom-up approach to establishing staged wildfire evacuation warning zones and warnings. This work also provides a road map for integrating different systems and can shed light on how to use simulation-based methods for wildfire evacuation decision making. Trigger modeling is highly sensitive to environmental factors and the evacuation zoning process is also sensitive to clustering methods. Thus, sensitivity analysis needs to be conducted in future work to evaluate how sensitive the proposed method is when input variables vary so as to help develop a better understanding of it. Simulation-based sensitivity analysis has enjoyed great popularity in spatial modeling and simulation in the past few years (Crosetto, Tarantola, & Saltelli, 2000) and can be used to perform sensitivity analysis for the proposed method. We should note that a tightly coupled system needs to be implemented before hundreds of thousands of simulations can be run for sensitivity analysis. Moreover, since fire-spread and trigger modeling are computationally intensive, modern parallel computing techniques will be employed to accomplish simulation-based sensitivity analysis. Finally, the principles for evacuation warning zone establishment still remain unclear at this moment due to the scarcity of research on evacuation zoning. These endeavors will perfect the proposed method and help develop a better understanding of wildfire evacuation warning timing and zoning.

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