Integrating fire-spread and household-level trigger modeling to stage wildfire evacuation warnings

Dapeng. Li[1], Thomas. J. Cova[1], Philip. E. Dennison[1]

[1]Department of Geography, University of Utah, 260 S. Central Campus Dr., Rm. 270, Salt Lake City, UT 84112-9155, USA.
Telephone: (+1)8015816419
Email: dapeng.li@utah.edu, cova@geog.utah.edu, dennison@geog.utah.edu

1. Introduction

Wildfire evacuation trigger points are agreed-upon prominent geographic features (e.g., ridges, rivers, and roads) used in wildfire evacuation practices, and when a fire crosses these features, an evacuation is recommended for the communities or firefighter crew in the path of the fire (Cook, 2003; Cova et al., 2005). Spatial modeling of wildfire evacuation triggers has used fire-spread modeling and Geographic Information Systems (GIS) to calculate evacuation trigger buffers (ETBs) around a location with a specified amount of warning time as the input (Cova et al., 2005; Dennison et al., 2007). Sorensen (1991) points out that evacuation warnings have a significant effect on evacuation timing. This work explores the potential uses of fire-spread and household-level wildfire evacuation trigger modeling in establishing staged evacuation warning zones.

2. Methods

Fire-spread and trigger modelling are integrated to simulate how triggers are used to trigger the evacuation of households. A conceptual representation of the process is given in fig. 1. The red point represents the fire ignition point, the red polygon represent fire perimeters, and the black polygon represents ETBs generated from trigger modeling for the household. Trigger modeling uses *t* (available time for evacuation) to create an ETB around the household. The input time *t* should be derived by estimating the time needed by the household to evacuate to safety. When fire reaches the boundary of the ETB at time *T*, the household should be recommended to evacuate and will have t for its evacuation. *T* is defined as the recommended evacuation departure time (REDT) for the household, which can be used by the incident commanders (ICs) to issue staged warnings to households at risk.

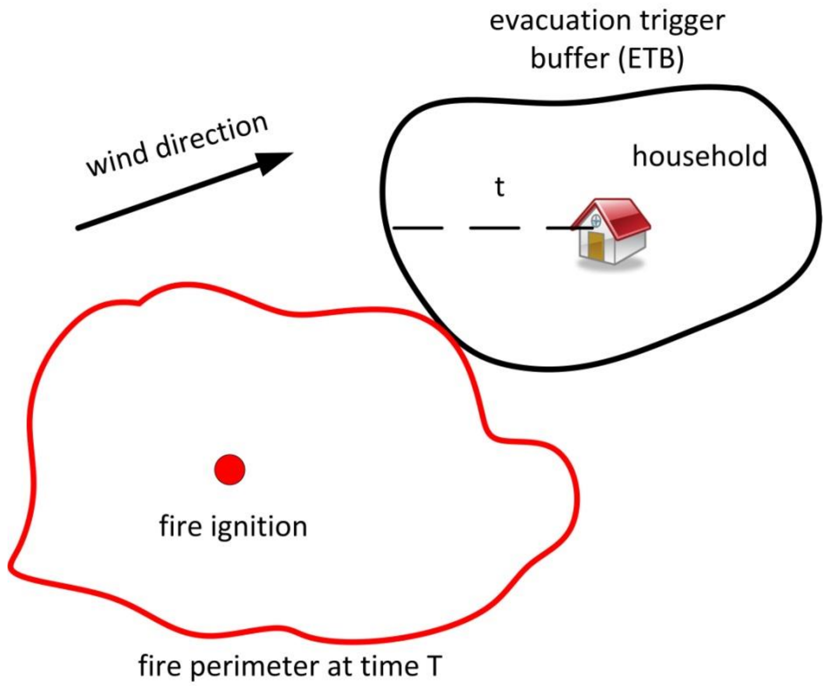

Figure 1. A conceptual representation of the method

The workflow of the proposed method is shown in fig. 2. The method consists of three steps. In the first step, trigger modelling is performed at the household level. Household locations, estimated evacuation times, weather conditions, environmental data, and topographic data are used as the inputs for trigger modeling. Fire-spread modelling is used to calculate fire spread rates. Then, fire spread rates in eight directions are used to calculate the travel times and construct a fire travel-time network. All the arcs in the network are reversed to model fire-spread backwards, and the Dijkstra's algorithm (Dijkstra, 1959) is employed to traverse from a given household cell until the accumulated travel time reaches a specified threshold (i.e., the boundary where the input warning time is reached).

In the second step, fire-spread and trigger modelling are integrated to derive REDT for each household. FlamMap is used to generate a minimum travel time (MTT) map, which is a raster map with each cell denoting the time the fire reaches it. The start time for fire ignition is set to 0, and when the fire reaches the boundary of the ETB of a household, the specific time is recorded as the REDT for that household. Thus, the REDTs for all households under study can be calculated.

The third step divides the households into staged evacuation warning zones based on their REDTs as well as their locations. Cluster analysis is performed by using REDT as the attributive constraint and using K Nearest Neighbors (KNN) as the spatial constraint. The Spatial "K"luster Analysis by Tree Edge Removal (SKATER) algorithm divides spatial features into clusters by partitioning a minimum spanning tree (MST) constructed using the features and its effectiveness in clustering spatial features has been proved (Assunção et al., 2006). The SKATER algorithm is used to divide the households into several groups. However, the clusters derived using the SKATER algorithm are not associated with easily communicated geographic units, which makes it inconvenient for the ICs to evacuation warnings. Thus, geographic features (i.e., roads, zip code zones) are used to adjust the groups and establish evacuation warnings zones that can be easily communicated to the public.

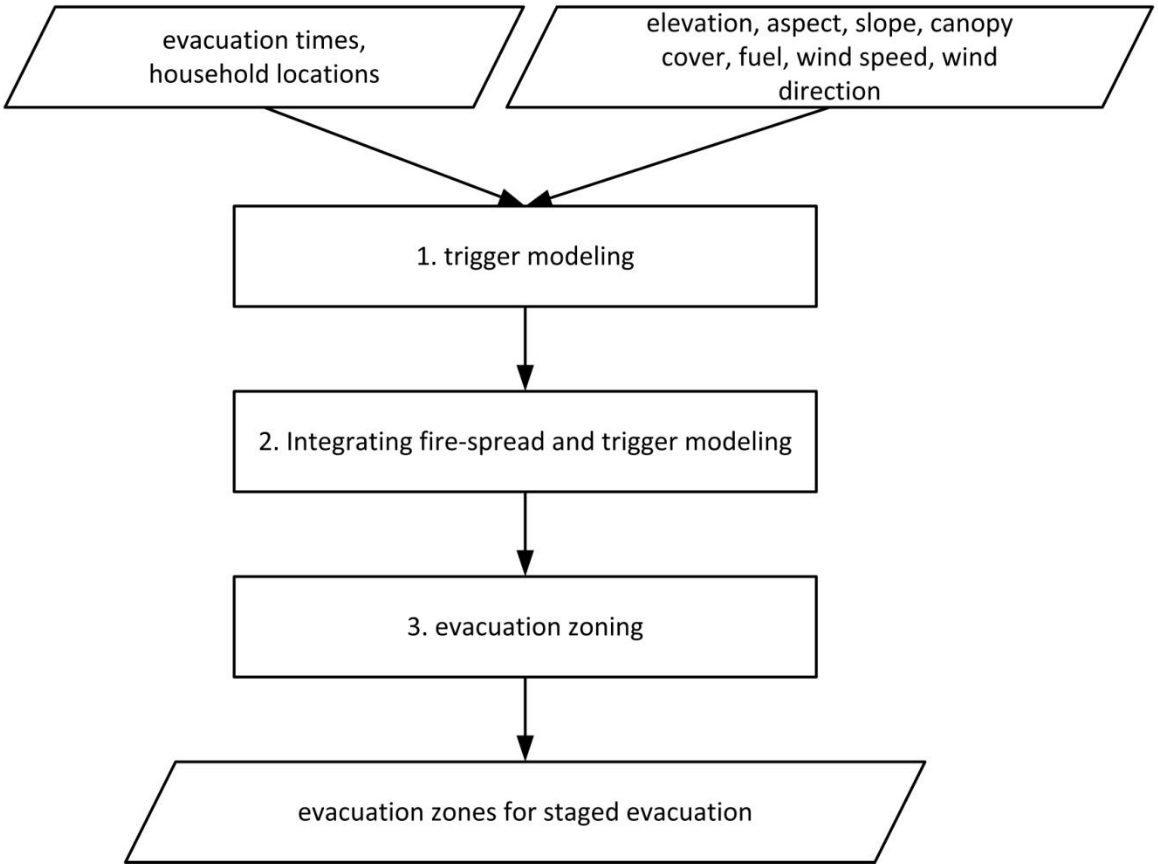

Figure 2. Workflow of the research method

3. Case study

In the case study, Julian, California, is chosen as our study site. All vector data were from the GIS Agency of San Diego County—SanGIS, and the household locations were derived by calculating the centroids of the residential parcels using the 2010 parcel data. The sparsely distributed households are shown in fig. 3. The raster data were at 30 m resolution, and there are 500 × 500 raster cells in the study area. A 2003 fuel map from California Department of Forestry and Fire Protection was used as the fuel data. The 13 Anderson (1982) fuel models were used for the fuel data. The digital elevation model (DEM) data from the United States Geological Survey (USGS) was used to calculate aspect and slope.

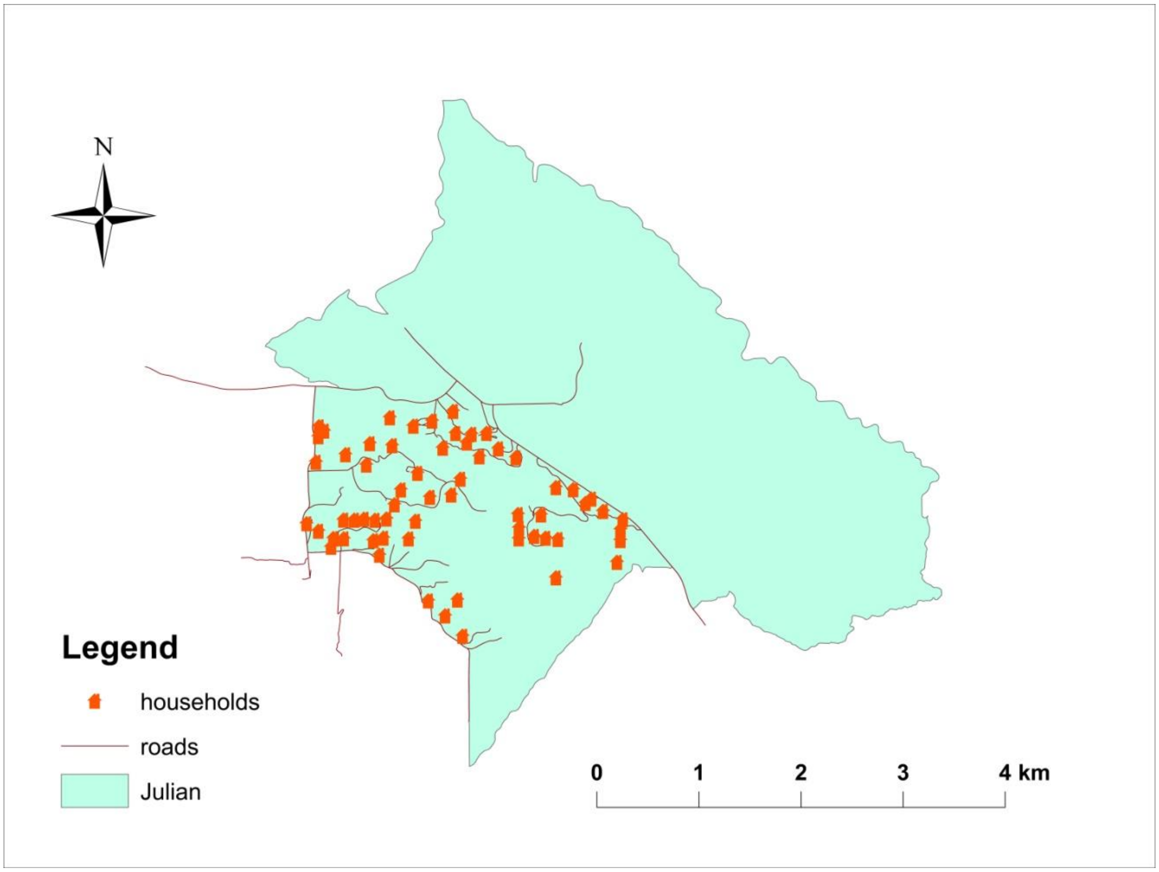

Figure 3. Sparsely distributed households in Julian

The case study design is illustrated in fig. 4. The ignition point is set at 4.8 km to the west of the households. The wind direction is west, and its magnitude is set to the highest recorded wind speed or worst-case scenario. Two scenarios are given using different wind speeds (16 km/h for scenario 1and 32 km/h for scenario 2). We assumed that 1 hour will be enough for all the 62 sparsely distributed households to evacuate and created 1 hour ETBs for these households. The households were divided into 4 groups in group analysis, and the results are listed in table 1. For each group, the minimum REDT denotes the first household to be triggered to evacuate and can be used as the worst-case warning time for that group.

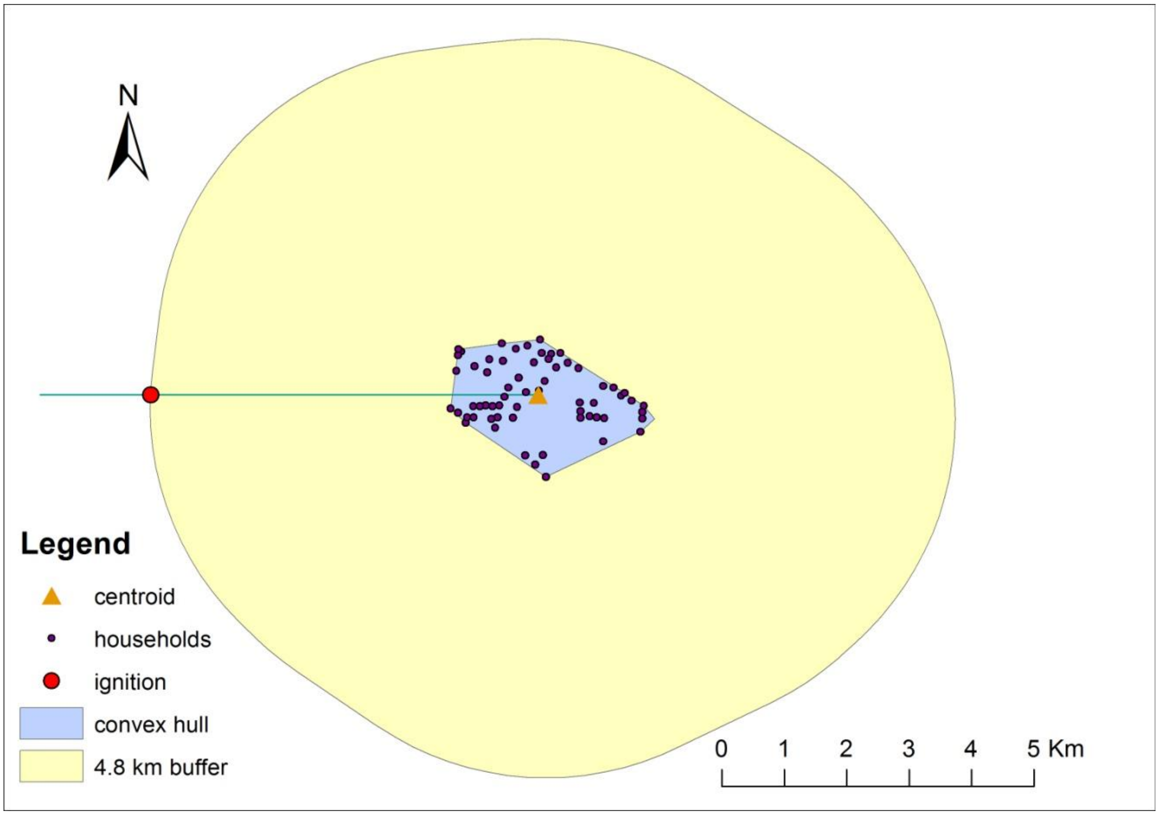

Figure 4. Case study design

Scenario	Group ID	Count	Mean (min)	Std. Dev.	Min (min)	Max (min)
1	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	1	1	166	0	166	166
	2	25	82	6	73	91
	3	24	61	7	49	71
	4	12	106	8	94	118

Table 1. Results of group analysis

Households that belong to one road segment fall into different groups in the left column of fig. 5, which is impractical in real-world evacuation warnings. To address this issue, the households were adjusted and regrouped based on road segments. Within each road-segment group, voting was performed and the group is assigned with the most popular evacuation group ID of the households. The final adjusted evacuation warning zones are shown in the right column of fig. 5. The households in the adjusted zone can be associated with a road segment, which makes it more convenient for the ICs to issue warnings to those households and can also facilitate communication during evacuations.

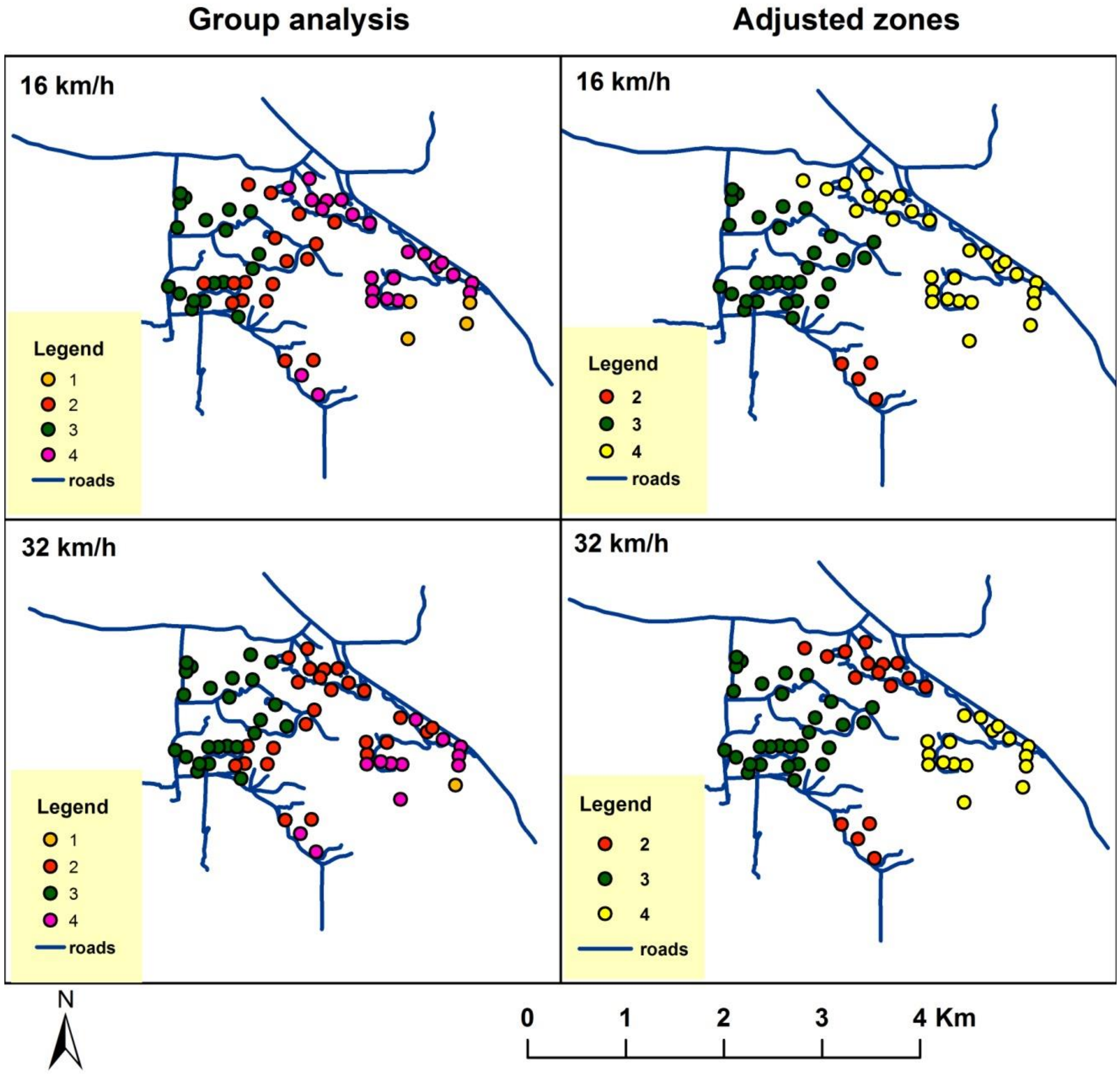

Figure 5. Results of the group analysis and adjusted zones for the two scenarios

4. Discussion and conclusions

In conclusion, this study integrates fire-spread with household-level trigger modeling and presents a novel bottom-up approach to establishing staged wildfire evacuation warning zones. The integration of fire-spread and trigger modeling can shed light on using simulation-based approach to facilitate wildfire evacuation decision making. The proposed method is implemented as a loosely coupled system. Future work can focus on building a tightly coupled system so as to perform simulation-based sensitivity analysis. Moreover, the assumption used in our case study is that 1 hour will be enough to evacuate the households. Traffic simulation can be used to estimate the evacuation times for the households in future work.

5. Acknowledgements

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