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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.

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