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Identification of firefighter safety zones using lidar

Philip E. Dennison*, Gregory K. Fryer, Thomas J. Cova

Department of Geography and Center for Natural and Technological Hazards, University of Utah, 260 S Central Campus Dr., Salt Lake City, UT 84112, USA

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ABSTRACT

Safety zones protect wildland firefighters from dangerous heat exposure, and are separated from fuels by a safe separation distance (SSD) derived from flame height. In this study, we describe a model for automated identification of safety zones using decision rules based on lidar-measured vegetation height, flame height, and terrain slope. Inputs included lidar and orthoimage data collected over a study area in the southern Sierra Nevada, USA. Safety zones were required to be large enough to shelter 20 firefighters and two vehicles, and distance to the closest road was measured to determine ease of access. Safety zones comprised less than 0.5% of the study area at 4 m flame height (16 m SSD). As flame height increased, the number and size of safety zones decreased. This model provides a flexible framework for identification of safety zones, which should assist firefighters and reduce potential for injury and loss of life.

1. Introduction

Unanticipated fire behavior can place firefighters at risk of injury or death due to exposure to intense heat produced by fuel combustion (Alexander et al., 2012). Entrapment and burnover fatalities occur in situations where firefighters are unable to reach an adequate safety zone protected from fire. Establishing safety zones is essential for reducing risk of firefighter injury and fatality, since safety zones provide a buffer between personnel and the fire (Beighley, 1995). Firefighters are regularly trained to identify safety zones, and escape routes to safety zones, in advance of engaging in fire suppression activities (Gleason, 1991; National Wildfire Coordinating Group, 2014).

A safety zone is separated from fuels by a safe separation distance (SSD) needed to reduce radiative and convective heating to noninjurous levels (Butler, 2014). The size of a safety zone is determined based on the number of personnel and equipment requiring protection, and the area required for each (Butler and Forthofer, 2002). An idealized representation using a circular clearing places the safety zone at the center, with the SSD extending in all directions between the safety zone and fuels (Fig. 1).

Radiative energy transfer models have provided guidelines for SSD based on flame height or flame length, but have made multiple simplifying assumptions including flat terrain, uniform flame temperature and/or emissivity, and lack of convective heat transfer (Butler, 2014). Flame height is measured in the vertical dimension, while flame length may be longer due to tilting of the flame by wind and slope. Based on a maximum heat threshold of 7 kWm^{-2} for firefighters wearing protective clothing, Butler and Cohen (1998) modeled the relationship between flame height and SSD. They proposed a guideline that SSD should exceed a minimum of four times flame height to provide a distance safe from heat exposure. Butler and Forthofer (2002) used an improved radiative energy transfer model to account for a curved flame sheet tilted toward the safety zone with a vertical temperature gradient. This improved model, along with measurements from experimental crown fires (Butler and Cohen, 2000), maintained the four-times-flame height guidance. Rossi et al. (2011) demonstrated that minimum SSDs from flame fronts are dependent on modeled flame temperature, with a cooler assumed temperature producing distances in the 2–3 times flame length range and a hotter assumed temperature producing distances up to 10 times flame length. The BehavePlus fire modeling system (Andrews, 2009) has incorporated guidelines from Butler and Cohen (1998) to provide a SAFETY module for calculating minimum SSD from fire. Flame length calculated from a surface fire model (Albini, 1976; Byram, 1959) is assumed to represent worst case flame height. The National Wildfire Coordinating Group (NWCG) uses a four times flame height guideline for SSD, but notes that safety zones downwind or upslope from fire may require a larger SSD (National Wildfire Coordinating Group, 2014).

Safety zones are typically determined on-site using minimum safety zone size and SSD requirements. Firefighter perception of

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* Corresponding author. Room 270. Tel.: +1 801 585 1805.
E-mail address: dennison@geog.utah.edu (P.E. Dennison).

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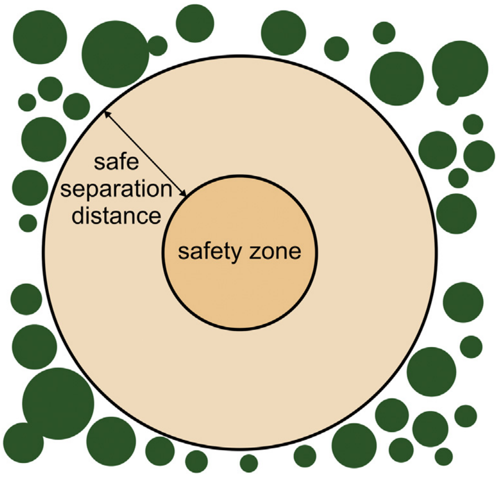

Fig. 1. A safety zone determined using a safe separation distance from the closest trees, possessing an area large enough to contain the protected personnel and equipment. After Butler and Forthofer (2010).

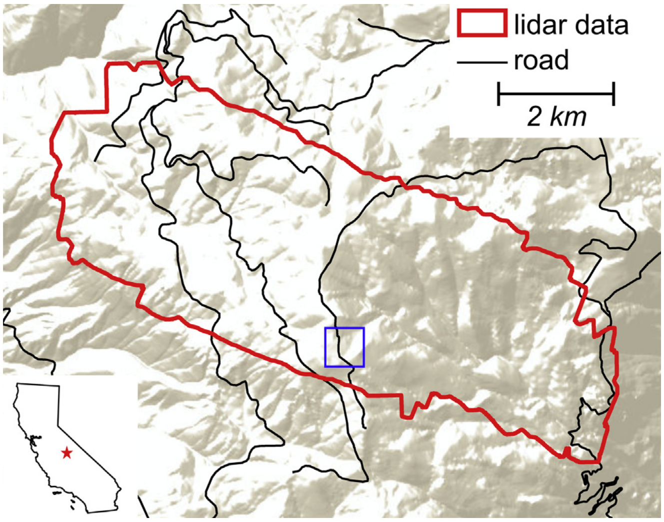

Fig. 2. Study area in Sierra National Forest, California, USA. The square indicates the subset area shown in Fig. 3 and Figs. 8–10.

SSD in given conditions may be flawed; Steele (2000) found that firefighters shown a fuel photograph series had widely ranging estimates of minimum SSD. Detailed information on the geographic distribution of vegetation, provided by high resolution remote sensing, may permit automated identification of safety zones over large areas well in advance of wildfire occurrence. In this paper, we demonstrate a spatial model capable of determining safety zones using lidar and orthoimage inputs. A series of decision rules can be used to adjust parameters such as flame height and maximum terrain slope. Outputs such as safety zone size and distance to the closest road can aid in determining whether modeled safety zones are suitable for firefighter protection. This model provides an automated means for identifying safety zones that may assist firefighter decision making and reduce risk of firefighter injury and fatality.

2. Methods

2.1. Data

A study area in Sierra National Forest, California, USA was selected based on lidar data availability (Fig. 2). Vegetation in the study area is predominantly mixed conifer forest, typically comprised of Jeffrey pine (*Pinus jeffreyi*), ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), and white fir (*Abies concolor*). Lodgepole pine (*Pinus contorta*) and red fir (*A. magnifica*) dominate at higher elevation. Meadows with herbaceous vegetation and shrub cover are widely dispersed.

Airborne lidar uses laser pulses to measure the range between the aircraft and the Earth's surface. Multiple returns from the same pulse can be recorded to determine the elevation of both the vegetation canopy and ground surface. Discrete return lidar data were collected over a 22 km^2 area capturing part of the Southern Sierra Critical Zone Observatory in August 2010 by the National Center for Airborne Laser Mapping (Anderson et al., 2012). The data were collected with an average point density of approximately 11.7 points per m^2. The point cloud was processed to 1 m gridded products made available through the OpenTopography Project. A "first return" digital surface model (DSM) captures the highest elevation of the points within each grid cell (Fig. 3c). A corresponding 1 m "bare earth" digital terrain model (DTM) (Fig. 3b) is created by interpolating the lowest elevation returns in the point cloud (Guo et al., 2010). For vegetated surfaces, the first return DSM represents the absolute elevation of the upper vegetation canopy (Clark et al., 2004; Lefsky et al., 2002). The bare earth DTM was subtracted from the first return DSM to provide vegetation height. Slope over a 15 m by 15 m window was calculated using the bare earth DTM (Fig. 3d). Mean slope within the study area was 15°. Color infrared digital imagery was acquired over the study area by the National Agriculture Imagery Program (NAIP) in summer 2010. These data are orthorectified to create 1 m spatial resolution composites with near infrared (NIR), red, green, and blue bands (Fig. 3a). Nearest neighbor resampling was used to align the orthoimagery to the lidar gridded data.

2.2. Safety zone requirements

A transect across the lidar subset in Fig. 3 demonstrates how the first return DSM and bare earth DTM capture gaps between vegetation canopies that can potentially be used as safety zones (Fig. 4). Vegetation heights exceeding a threshold can be buffered by an SSD determined by flame height. Once the SSD is accounted for, the resulting safety zone must be large enough to shelter both personnel and equipment (Fig. 1). As the number of firefighters and vehicles change, the minimum safety zone size will also change. The BehavePlus fire modeling system provides guidelines for the minimum area required by both personnel and heavy equipment (Andrews, 2009). Approximately five square meters (50 square feet) is recommended for each firefighter to have space to deploy a fire shelter, which if becomes necessary, would make the safety zone a "deployment zone". Approximately 28 square meters (300 square feet) is given as an average area needed for heavy equipment (Andrews, 2009). Examples of heavy equipment include trucks, dozers, and engines. For this study, we assumed a crew of 20 firefighters accompanied by two pieces of heavy equipment. Using these assumptions, any safety zone was required to contain a minimum of 156 m^2. This should be regarded as the minimum size of a safety zone, with no safety margin applied. Safety zones larger than this minimum would provide additional protection.

2.3. Safety zone modeling

Decision trees were used to determine whether each 1 m grid cell was suitable as a part of a safety zone. Simplified decision trees illustrating this process are shown in Fig. 5. An initial decision tree splits cells into "buffered cell" and "unbuffered cell" categories (Fig. 5a). Buffered cells are considered to be tall fuels that are likely to produce tall flame heights. These cells are buffered by a distance of four times the expected maximum flame height based on NWCG guidelines (National Wildfire Coordinating Group, 2014), and cannot be used as part of a safety zone. A second decision tree splits the unbuffered cells into "safe cell" and "unsafe cell" categories (Fig. 5b). The primary decision rule is whether the distance to the closest buffered fuel cell is less than or greater than four times the expected maximum flame height (Fig. 5b). Additional criteria, such as slope and minimum safety zone size, can be used to further refine safety zones.

Decision trees were implemented in the Interactive Data Language (IDL), version 8.2 (Exelis Visual Information Solutions, Boulder, Colorado, USA). The coregistered first return DSM, bare earth DTM, terrain slope, and orthoimage data were read into memory and used to calculate vegetation height and normalized difference vegetation index (NDVI). A more complex rule set was implemented to identify safety zones for the study area (Table 1). All decision points were determined empirically, but are easily adjustable based on expert knowledge. For the first decision tree, the vegetation height grid was used as described above. A vegetation height threshold of 1 m was used to separate buffered cells containing tree and tall shrub fuels from unbuffered cells containing low or no fuels. Shorter fuels in the 0.2–1 m range were excluded from safety zones in a step described below, but were not buffered. In some clearings, we found that single, isolated trees were classified as buffered cells and resulted in reduced safety zone size. A potential safety zone containing a small number of hazardous trees may be made safe by felling those trees. To increase safety zone size in situations where site fuel treatment may be possible, a second decision rule was created to reduce the number of buffered cells assigned to isolated trees (Table 1). A 25 m kernel was applied to the