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Assessing Potential Safety Zone Suitability using the Safe Separation Distance Evaluator (SSDE)

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Abstract

Safety zones are fundamental tools that can be used by wildland firefighters to avoid injury or fatality when engaging in wildland fire operations. The National Wildfire Coordinating Group (NWCG) recommends that a safety zone be defined as a pre-planned area of sufficient size and suitable location that is expected to prevent injury to fire personnel from known hazards without using fire shelters. Currently, safety zones are primarily designated by fireline personnel as part of daily fire management operations. Though critical to safety zone assessment, the effectiveness of this approach is inherently limited by the individual's ability to accurately and consistently interpret vegetation conditions, topography, burning conditions and spatial characteristics of potential safety zones (e.g., area and geometry of a forest clearing). Regardless, effective safety zones provide safe separation distance (SSD) from surrounding flames, ensuring that the surrounding heat cannot cause burn injury. We introduce a new online tool for mapping SSD based on vegetation height, terrain, wind speed, and burning conditions: the Safe Separation Distance Evaluator (SSDE). The new tool allows users to draw a potential safety zone polygon and estimate SSD and the extent to which that safety zone polygon may be suitable, given the local landscape, weather, and fire conditions. The SSDE tools calculates separation distance based on vegetation height, wind and slope adjustment factors and burning conditions. Fuels layers are imported for LANDFIRE Existing Vegetation Height. Slope is calculated from the Shuttle Radar Topography Mission (STRM) digital elevation model. Winds are derived from the local fire weather forecast. Burning conditions are based on fuel moisture, relative humidity, and temperature. The Safe Separation Distance Evaluator (SSDE) algorithm is built and applied in Google Earth Engine (GEE), a cloud-based platform for processing and analyzing GIS and remotely sensed data, using JavaScript application programming interface. SSDE is a tool that can provide valuable safety information to wildland fire personnel who are charged with the critical responsibility of protecting the public and landscapes from increasingly intense and frequent fires in a changing climate.

1. Introduction

Wildland firefighters are tasked with a wide variety of fire management duties, many of which place them in close proximity to flames. One of the primary tasks is the removal of fuels and construction of containment lines to limit the potential damage to lives, property, and other critical resources (Wei, 2019; Silva, 2020; Connor, 2017). Particularly when engaged in a direct attack, whereby firefighters may be working within a few meters or less of that flaming zone, the potential risk for safety incidents is elevated (Cheney, 2001). Sudden or unexpected changes in fire behaviour can have devastating effects to vulnerable fireline personnel on the ground (Page, 2017). Events such as the Yarnell Hill fire in 2013, which claimed the lives of 19 firefighters and the South Canyon fire, which resulted in 14 firefighter fatalities, demonstrate the tragedy that can occur in the wildland fire profession (Arizona State Forestry Division, 2022; Butler, 1998; Alexander, 2015). Beyond these well-known, high-fatality events, there is an additional and significant background level of mortality that occurs among on-duty wildland firefighters (Butler, 2017). The causes of death are varied, and include heart attacks, vehicular and aircraft accidents, falling trees, and smoke inhalation, to name a few. Between 1990 and 2020, there were 525 documented wildland firefighter fatalities in the United States (National Interagency Fire Centre, Wildfire Today). The causes of fatalities vary greatly (Figure 1), with nearly one fifth (19%) of which were due to burnovers or entrapments. This category is the direct result of fatal exposure to excessive heat, fire, and/or smoke. Burnover results from fire rapidly overtaking firefighting personnel before they can move to a safe area, and entrapment indicates that firefighters' ability to move to a safe area is compromised (National Wildfire Coordinating Group, 2017). As wildland fires increase in frequency, extent, and intensity, wildland firefighters may be put at heightened risk while working in the increasingly complex fire environment (Abatzoglou, 2016; Abatzoglou, 2021; Dennison, 2014; Balch, 2017; Westerling, 2016).

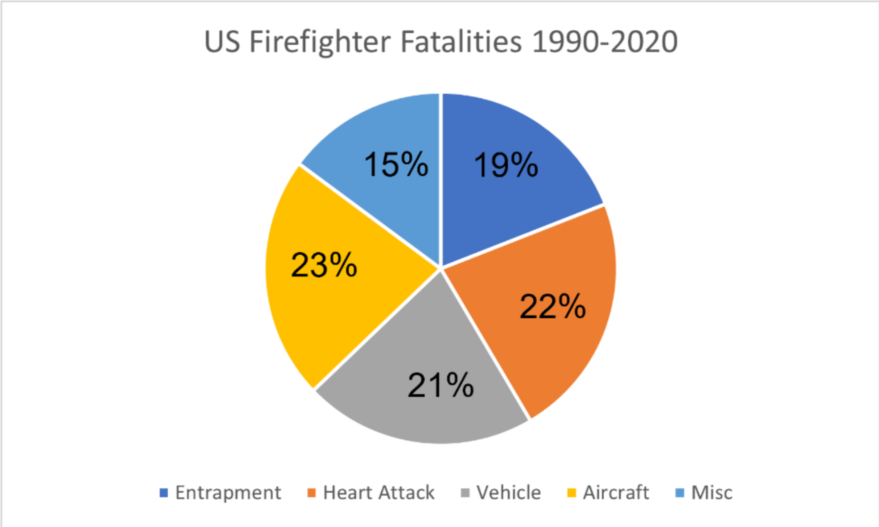

Figure 1- Firefighter fatalities by category from 1990-2020. Total wildland fire fatalities during that time span were 525.

Gleason (1991) proposed a system of interdependent safety measure to reduce firefighter risk of burnover and entrapment: lookouts, communications, escape routes, and safety zones (LCES). Safety zones are a critical component of this system, essentially areas large enough to allow firefighters to escape the harmful effects of fire (Beighley, 1995). Safety zones must be large enough to hold firefighting personnel and equipment and should provide a safe separation distance (SSD) between vegetation and these assets (Figure 2). The SSD must be large enough that heat from the wildfire is reduced to the point that a fire shelter is not necessary to prevent firefighter injury.

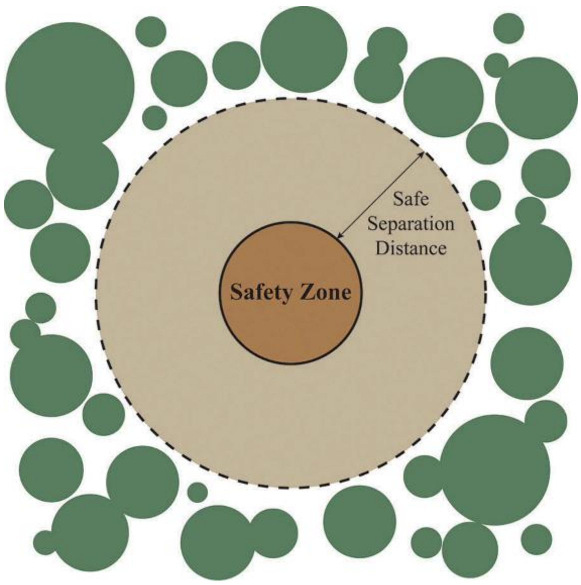

Figure 2 – Basic safety zone example diagram depicting Safe Separation Distance (SSD)

The current NWCG guideline for estimating SSD comes from Butler and Cohen (1998a), who determined, based on radiant heat modelling, that SSD should be equal to or greater than four times flame height. This guideline assumes flat terrain and does not account for convective heat transfer, which can strongly contribute to firefighter heat exposure (Butler, 2014). Although this guideline has since been widely adopted (National Wildfire Coordinating Group, 2022), the research that underlies it is based solely on one heat transfer mechanism: radiation. Heat transfer by convection is also a major—sometimes dominant—force, particularly in the presence of steep slopes and high winds (Dupuy, 2011; Frankman, 2013; Parsons, 2014). In the presence of such convective heat, particularly if a fire crew is upslope and/or downwind of flames, SSD will increase (Page, 2017, Butler, 2014). Thus, the four times flame height rule is likely insufficient in these conditions. Recent work by Butler et al. (Butler, 2017) has sought to update this guideline with the inclusion of a "slope-wind factor", which adds a multiplicative term to the SSD equation to account for the effects of convective heat transfer (Page, 2017, Butler, 2014; Parsons, 2014; Page, 2018, Campbell, 2022). In addition, given that safety zones should be designated prior to, rather than during, the presence of flames, the four times flame height rule requires firefighters to predict how tall the flames might eventually be, which is a challenging endeavour. Accordingly, the newly proposed guidelines assume that, in a crown fire, flame height is approximately equal to twice the vegetation height (Campbell, 2022). As a result, the new SSD equation is defined as:

$$\mathbf{SSD = 8 \times VH \times \Delta,}$$

where VH is vegetation height and Δ is the slope-wind factor. Butler recently defined these slope-wind factors seen in Table 1, based not only on slope and wind speeds, but also on the burning conditions, as dictated by fuel conditions (e.g., moisture) and weather (e.g., relative humidity) (Campbell, 2022).

Table 1. Slope-wind factors (Δ) from Butler, coloured on a scale from blue (low Δ) to while (moderate Δ) to red (high Δ) (Campbell, 2022).

		Slope					
		Flat (0–7.5%)	Low (7.6–22.5%)	Moderate (22.6–40%)	Steep (>40%)		
Wind Speed	Light (0–4.5 m/s)	0.8	1	1	2	Low	Burning Condition
		1	1	1.5	2	Moderate	
		1	1.5	1.5	3	Extreme	
	Moderate (4.6–8.9 m/s)	1.5	2	3	4	Low	
		2	2	4	6	Moderate	
		2	2.5	5	6	Extreme	
	High (>8.9 m/s)	2.5	3	4	6	Low	
		3	3	5	7	Moderate	
		3	4	5	10	Extreme	

Although guidelines for use on the ground are valuable, they still require the firefighters themselves to make the calculation of SSD on the ground while engaged in other fire management activities. This requires the ability to accurately estimate vegetation height and terrain slope and anticipate wind speed and fire intensity. Moreover, even if these difficult interpretations and predictions can be made, an even more challenging endeavour is to identify an area on the ground cleared of vegetation that provides the calculated SSD in all directions.

To resolve these limitations and improve wildland firefighter safety, we introduce a new, interactive, web-based, open-access mapping tool for estimating SSD and evaluating potential safety zone effectiveness through geospatial analysis. The Safe Separation Distance Evaluator (SSDE) tool uses LANDFIRE Existing Vegetation Height data, which is both nationally available in the contiguous US and is updated every few years. Additionally, instead of only assessing SSD-driven suitability on clearings that already exist, this tool allows users to draw their own safety zone polygon to evaluate the potential suitability of a safety zone in any environment (Figure 3). The SSDE algorithm is built and applied in Google Earth Engine (GEE), a cloud-based platform for processing and analyzing GIS and remotely sensed data, using the JavaScript application programming interface (Gorelick, 2017).

2. Methods

2.1. Algorithm Description

The Safe Separation Distance Evaluator (SSDE) algorithm is built and applied in Google Earth Engine (GEE), a cloud-based platform for processing and analyzing GIS and remotely sensed data, using the JavaScript application programming interface (Campbell, 2022). GEE was selected a for few reasons: (1) it enables the production of user-facing applications that can be widely accessed by anyone with an internet connection; (2) it hosts an immense catalog of geospatial data, including datasets necessary for the analysis of SZ suitability; (3) its cloud computing capabilities provide for rapid execution of complex geospatial functions, allowing users to quickly assess SZ suitability.

SSDE evaluates SSD through the analysis of proportional SSD (pSSD) within potential SZ polygons (Figure 3). pSSD quantifies the extent to which a potential SZ polygon provides SSD from surrounding vegetation/flames, considering the average per pixel SSD contained within a series of segments (or clusters of contiguous pixels) around the SZ polygon. Measured in percent, a pSSD of 100% or greater for a given pixel would mean that, factoring in vegetation height surrounding the polygon, slope, wind speed, and burn condition, the pixel's location should provide sufficient SSD, should fire personnel opt to use this location as a SZ. Conversely, a pixel with a pSSD of less than 100% would indicate that firefighters located within that pixel may risk injury from burning vegetation outside the boundary of the polygon.

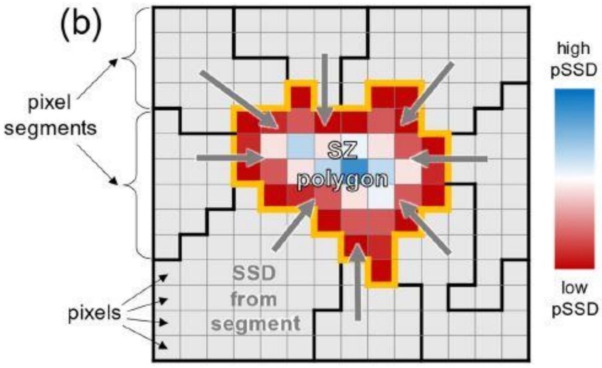

Figure 3: Conceptual depiction of that SSDE calculates SSD within a safety zone (SZ) polygon.

To calculate pSSD at the SZ polygon level, the user can define a potential SZ using the polygon drawing tools in SSDE, guided by the conditions both within the polygon and surrounding the polygon. The best SZs are those that contain no flammable material within, naturally or otherwise, so ideally this SZ polygon would be drawn in an area with low fuel loading, such as short or sparse grasses or litter. Alternatively, a SZ polygon could also be drawn in an area that has recently burned, or an area that would be targeted for fuel removal to create a SZ.

pSSD within a SZ is dependent upon the slope and vegetation height of the surrounding landscape. As discussed in the introduction, heat transfer from flames generally increases with increasing vegetation height and terrain slope. Accordingly, a SZ in the midst of steep terrain and tall vegetation will require a larger SSD than a SZ in the midst of flat terrain and short vegetation. If we assume that the SZ itself contains little or no flammable material, then the primary concern for SZ evaluation is the area surrounding the SZ. Accordingly, to calculate pSSD within the SZ polygon, slope and vegetation height need to be evaluated within a "buffer" surrounding a SZ (Campbell, 2017; Dennison, 2014).

3. Results and Discussion

The SSDE was developed in GEE and a free, open-access, web-based application can be viewed at https://firesafetygis.users.earthengine.app/view/ssde. The full publication can be viewed at https://www.mdpi.com/2571-6255/5/1/5/htm.

We envision the SSDE being of broad interest to the wildland fire community, from fire scientists to incident management personnel to wildland firefighters. Its open-access nature allows anyone to explore, examine, and interact with the concepts of SZs and SSD. Even if not used in an operational context, there is great value in being able to quickly and easily examine the conditions that define potential SZ suitability on a broad spatial scale. Wildland firefighters designate SZs on a daily basis as a part of their fire management

duties. Built into this designation process is an inherent degree of subjectivity that can result in differences in the interpretation of SZ suitability between and among crews. By using an objective tool for SZ suitability analysis that can be broadly applied in the US, fire crews across the country can increase the consistency and reliability of the SZ evaluation process. However, given that this is a web-based platform requiring an internet connection, that also does not translate well to a mobile environment, we do not envision this as a real-time decision-making tool that firefighters could use on the ground. Instead, operational use of SSDE could be at the incident command level, for daily or more frequent evaluation of potential SZs for crews working on a fire. Given the dynamic and fast-paced nature of fire management, it is essential to be able to make rapid assessments of SZ suitability, particularly as fire conditions change. For example, cross-referencing near-real time data representing the current fire perimeter with SSDE can enable the evaluation of whether or not previously burned areas can provide SSD from nearby unburned fuel. Additionally, our SZ suitability driver analysis revealed the strong influence of wind on maximum within-SZ pSSD. This highlights the need to continually re-evaluate SZ suitability not only as the fire evolves, but as local weather conditions change as well.

4. References

Abatzoglou, J.T.; Williams, A.P. Impact of Anthropogenic Climate Change on Wildfire across Western US Forests. Proc. Natl. Acad. Sci. USA 2016, 113, 11770–11775.

Abatzoglou, J.T.; Battisti, D.S.; Williams, A.P.; Hansen,W.D.; Harvey, B.J.; Kolden, C.A. Projected Increases in Western US Forest Fire despite Growing Fuel Constraints. Commun. Earth Environ. 2021, 2, 227.

Alexander, M.E.; Taylor, S.W.; Page, W.G. Wildland firefighter safety and fire behaviour prediction on the fireline. In Proceedings of the 13th International Wildland Fire Safety Summit & 4th Human Dimensions Wildland Fire Conference, Boise, ID, USA, 20–24 April 2015; pp. 20–24.

Arizona State Forestry Division. Yarnell Hill Fire: Serious Accident Investigation Report. 2013. Available online: **https://dffm.az**. gov/sites/default/files/YHR_Data_092813_0.pdf (accessed on 3 January 2022).

Balch, J.K.; Bradley, B.A.; Abatzoglou, J.T.; Nagy, R.C.; Fusco, E.J.; Mahood, A.L. Human-Started Wildfires Expand the Fire Niche across the United States. Proc. Natl. Acad. Sci. USA 2017, 114, 2946–2951.

Beighley, M., 1995. Beyond the safety zone: creating a margin of safety. Fire Management Notes, 55 (4), 22–24.

Butler, B.W.; Bartlette, R.A.; Bradshaw, L.S.; Cohen, J.D.; Andrews, P.L.; Putnam, T.; Mangan, R.J. Fire Behaviour Associated with the 1994 South Canyon Fire on Storm King Mountain, Colorado; Research Paper RMRS-RP-9; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Ogden, UT, USA, 1998; 82p.

Butler, B.W., 2014. Wildland firefighter safety zones: a review of past science and summary of future needs. International Journal of Wildland Fire, 23, 295–308. doi:10.1071/WF13021

Butler, C.; Marsh, S.; Domitrovich, J.W.; Helmkamp, J.Wildland Firefighter Deaths in the United States: A Comparison of Existing Surveillance Systems. J. Occup. Environ. Hyg. 2017, 14, 258–270.

Campbell, Michael J., Philip E. Dennison, and Bret W. Butler. "Safe separation distance score: a new metric for evaluating wildland firefighter safety zones using lidar." International Journal of Geographical Information Science 31.7 (2017): 1448-1466.

Campbell, Michael J., Philip E. Dennison, Matthew P. Thompson, and Bret W. Butler. "Assessing potential safety zone suitability using a new online mapping tool." *Fire* 5, no. 1 (2022): 5.

Cheney, P.; Gould, J.; McCaw, L. The Dead-Man Zone—A Neglected Area of Firefighter Safety. Aust. For. 2001, 64, 45–50.

Connor, C.D.O.; Calkin, D.E.; Thompson, M.P. An Empirical Machine Learning Method for Predicting Potential Fire Control Locations for Pre-Fire Planning and Operational Fire Management. Int. J. Wildland Fire 2017, 26, 587–597.

Dennison, P.E.; Brewer, S.C.; Arnold, J.D.; Moritz, M.A. Large Wildfire Trends in the Western United States, 1984–2011. Geophys. Res. Lett. 2014, 41, 2928–2933.

Dennison, Philip E., Gregory K. Fryer, and Thomas J. Cova. "Identification of firefighter safety zones using lidar." Environmental Modelling & Software 59 (2014): 91-97.

Dupuy, J.-L.; Maréchal, J. Slope Effect on Laboratory Fire Spread: Contribution of Radiation and Convection to Fuel Bed Preheating. Int. J. Wildland Fire 2011, 20, 289–307.

Frankman, D.; Webb, B.W.; Butler, B.W.; Jimenez, D.; Forthofer, J.M.; Sopko, P.; Shannon, K.S.; Hiers, J.K.; Ottmar, R.D. Measurements of Convective and Radiative Heating in Wildland Fires. Int. J. Wildland Fire 2013, 22, 157–167.

Gorelick, N.; Hancher, M.; Dixon, M.; Ilyushchenko, S.; Thau, D.; Moore, R. Google Earth Engine: Planetary-Scale Geospatial Analysis for Everyone. Remote Sens. Environ. 2017, 202, 18–27.

National Wildfire Coordinating Group Glossary A-Z|NWCG. Available online: https://www.nwcg.gov/glossary/a-z (accessed on 17 February 2017).

National Wildfire Coordinating Group. Incident Response Pocket Guide. 2014. Available online: https://www.nwcg.gov/sites/default/files/publications/pms461.pdf (accessed on 3 January 2022).

Page,W.G.; Butler, B.W. An Empirically Based Approach to Defining Wildland Firefighter Safety and Survival Zone Separation Distances. Int. J. Wildland Fire 2017, 26, 655–667.

Page, W.G.; Butler, B.W. Fuel and Topographic Influences on Wildland Firefighter Burnover Fatalities in Southern California. Int. J. Wildland Fire 2018, 27, 141–154.

Parsons, R.; Butler, B.; Mell,W. "Ruddy" Safety Zones and Convective Heat: Numerical Simulation of Potential Burn Injury from Heat Sources Influenced by Slopes and Winds; Imprensa da Universidade de Coimbra: Coimbra, Portugal, 2014; ISBN 978-989-26-0884-6.

Silva, F.R.Y.; O'Connor, C.D.; Thompson, M.P.; Martínez, J.R.M.; Calkin, D.E. Modelling Suppression Difficulty: Current and Future Applications. Int. J. Wildland Fire 2020, 29, 739–751.

Wei, Y.; Thompson, M.P.; Scott, J.H.; O'Connor, C.D.; Dunn, C.J. Designing Operationally Relevant Daily Large Fire Containment Strategies Using Risk Assessment Results. Forests 2019, 10, 311. [CrossRef]

Westerling, A.L. Increasing Western US Forest Wildfire Activity: Sensitivity to Changes in the Timing of Spring. Phil. Trans. R. Soc. B 2016, 371, 20150178.