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Community-level risk assessment of structure vulnerability to WUI fire conditions in the 2017 Tubbs Fire

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Abstract

This study presents a risk analysis for structures in the wildland-urban interface (WUI) using fragility curves. Reconstruction modelling using the model ELMFIRE is conducted to reproduce exposure conditions for the 2017 Northern California Tubbs Fire as a case study. The reconstruction simulates the distribution of embers, expanding the ability of fire reconstruction to represent conditions during the fire event which are not represented by the flaming fire front. Results from the Tubbs Fire simulation are used to provide exposure conditions to investigate the relationship between exposure conditions, structure and community characteristics, and the damage sustained by a structure in the fire event. A methodology using fragility curves to estimate the probability of destruction, used for risk analysis in other disaster fields, is modified and developed here for application to wildland-urban interface fires. Results of the fragility analysis find that increased ember exposure increases the likelihood of damage or destruction. Relatively low levels of ember exposure still result in relatively high likelihoods of destruction, highlighting the importance of ember spread. Current models cannot simulate structure-to-structure fire spread; additional limitations are highlighted for future work.

1. Introduction

In the last decade, large wildland fires threatening communities, called wildland-urban interface (WUI) fires, have become increasingly frequent and severe, causing increasing damage and destruction to structures. For example, fifteen of California's twenty most destructive wildland fires (measured in terms of homes destroyed) have occurred from September 2015 onward (CAL FIRE, 2022), with the most destructive, the 2018 Camp Fire, destroying over 18,000 structures. Globally, in the last five years alone, major destructive fires have occurred in Australia (2020), Chile (2019), Greece (2021), and Portugal (2017), to name a few. The increase in destructive WUI fires is anticipated to continue, due to the combined effects of climate change and increasing development in the WUI, the area where structures and wildland fuels interface or intermix.

Current mitigation strategies to protect homes from wildfire vary extensively and, for the most part, have little quantitative data supporting their effectiveness. One approach to addressing effectiveness of mitigation efforts is to investigate the risk to structures from wildfire. Risk can be defined, generally, as the product of hazard and vulnerability (Scott et al., 2013). Hazard consists of the probability of a given exposure level being achieved, and vulnerability consists of the susceptibility of a structure to a given exposure level. Current hazard and risk assessment of wildland fires focuses primarily on fire risk at a landscape scale, used for land and resource management (Scott et al., 2013). Despite the importance of fire exposure from the wildland, risk assessment at

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the community scale has neglected to include the conditions to which a structure was or may have been exposed (Alexandre et al., 2016; Syphard & Keely, 2019), primarily because such information has been out of reach.

An objective of the present work is to develop a quantitative wildfire risk assessment framework, applicable to structures and communities in the WUI that can inform pre-disaster community design and emergency planning and support strategic operations that ensure fire and life safety during a wildfire. The methods detailed herein include leveraging reconstruction wildland fire modelling and statistical analysis to connect hazard exposure conditions and urban vulnerability characteristics to the amount of damage a structure or community experiences. As a preliminary case study, we investigate the 2017 Tubbs Fire in California, the second most destructive fire in California history. This fire directly exposed over 8,000 structures in a period of under six hours, thus providing a large database of structure information. This work addresses a major gap in current WUI risk assessment which has, to-date, not included ember exposure, a key cause of fire ignition in WUI fires.

2. Methods

2.1. Fire Hazard Modelling

The Tubbs Fire ignited at 9:45 PM local time on 8 October 2017 (CAL FIRE, 2017). The area of the fire is characterized by a combination of grass, shrubs, understory, and timber litter fuels, such as herbaceous grasses and shrubs, and live oaks (Coen et al., 2018). Due to severe south-westerly foehn winds, the fire spread over 19 km in the 5 hrs following ignition, reaching the city of Santa Rosa in the early morning of 9 October 2017. Before containment, the fire burned 36,807 acres, destroyed 5,636 structures, and caused 22 fatalities (CAL FIRE, 2022).

An operational fire model that could be used in real time during a fire event, ELMFIRE (Eulerian Level Set Method of Fire Spread) (Lautenberger, 2013, 2019a, 2019b), was chosen to model the Tubbs fire. While it has many of the same limitations as other semi-empirical models, it is used here for its relatively fast computational run time, its ability to simulate ember deposition of multiple embers (a feature not available in other models), and its implementation of Monte Carlo analysis techniques (Lautenberger, 2017) to address the stochasticity and uncertainty of physical phenomena inherent in simulating wildland fires.

2.1.1. Model Inputs

ELMFIRE requires geospatial inputs which describe the vegetation in the simulation domain (represented as a fuel model (Scott & Burgan, 2005)), environmental conditions (i.e., fuel moisture content, weather, winds), and topographical information. Fuel and topographical data were downloaded from LANDFIRE at a resolution of 30 m (Rollins, 2009). One of the difficulties of applying wildland fire modelling methods to WUI areas is that there are differing physical scales and processes involved in fire ignition and spread across wildland fuels versus structural or urban fuels. Fuel models used in wildland fire modelling assume that urban areas are non-burnable. Despite the problems inherent in this assumption, there are no current operational models available to describe the spread of fire in WUI areas.

Weather and winds were modelled using the Weather Research and Forecasting (WRF) model, a mesoscale numerical weather prediction model. The WRF model for the Tubbs fire was initialized based on meteorological conditions at the start of the fire. The computational resolution of the WRF model was down-sampled in the fire model domain to match the limiting resolution of the fuels (30 m). In total, the model simulated 7 hours of the fire with a temporal resolution ranging from 1-15 s.

2.1.2. Model Outputs

Fire spreads into the WUI via radiation, direct flame contact, and ember exposure. Thus, key quantitative outputs from fire modelling that are subsequently used as hazard intensity metrics for risk analysis include flame length and ember count. Flame length is linearly related to fireline intensity (kW/m) by Byram's Equation (Byram, 1959), and, while the fire model does not directly output radiation, flame length is used to represent the impact of the main fire front on ignition and fire spread. Ember count is the number of embers ignited per grid cell over the course of the fire simulation.

2.2. Structure Dataset

2.2.1. Vulnerability Characteristics

Data on pre- and post-fire structure characteristics and post-fire structure damage is available for the Tubbs Fire (and many other fires) through damage inspection (DINS) reports produced by California's Department of Forestry and Fire Protection. The DINS data is obtained as a geospatial vector file with point geometry representing the location of structures. Since the defensible space around a structure is known to heavily influence its vulnerability to fire (Valachovic et al., 2021), the dataset geometry is converted so that structures are represented by polygons using a building footprints database published by Microsoft (2018). This allows for calculation of additional attributes such as minimum structure-to-structure distance and vegetation-to-structure distance (or defensible space), the latter using LiDAR data for vegetation. These two characteristics of structural vulnerability were included in the risk analysis to understand the impact of community layout on structure ignition, as structure-to-structure spread is known to be a driver of fire spread in the WUI. Year built of the structure was also included, as it influences the materials and methods of construction due to changes in building code requirements.

2.2.2. Damage States

Each structure in the DINS dataset is assigned one of six damage states ranging from "No Damage", to some percentage indicating the level of partial damage, to "Destroyed". These damage states are a key component to the risk analysis described below. Although a small selection of undamaged structures is recorded, the DINS reports preferentially include damaged and destroyed structures. Yet to draw conclusions about the relationship between structure damage level and fire exposure, it is necessary to include structures that survived the fire, as well as those that were destroyed. Therefore, this dataset has been supplemented to include structures that were likely to have been exposed to fire or embers, as assumed by their location compared against fire modelling outputs. These structures are assumed to have incurred no damage, given their omission from the DINS report. Finally, since a low number of partially damaged structures were recorded, the analysis considers only three overall damage levels (as shown in Figure 1): no damage (DS0), some damage (DS1); and destroyed (DS2). This combination is consistent with previous work that has looked at home destruction (Penman et al., 2015).

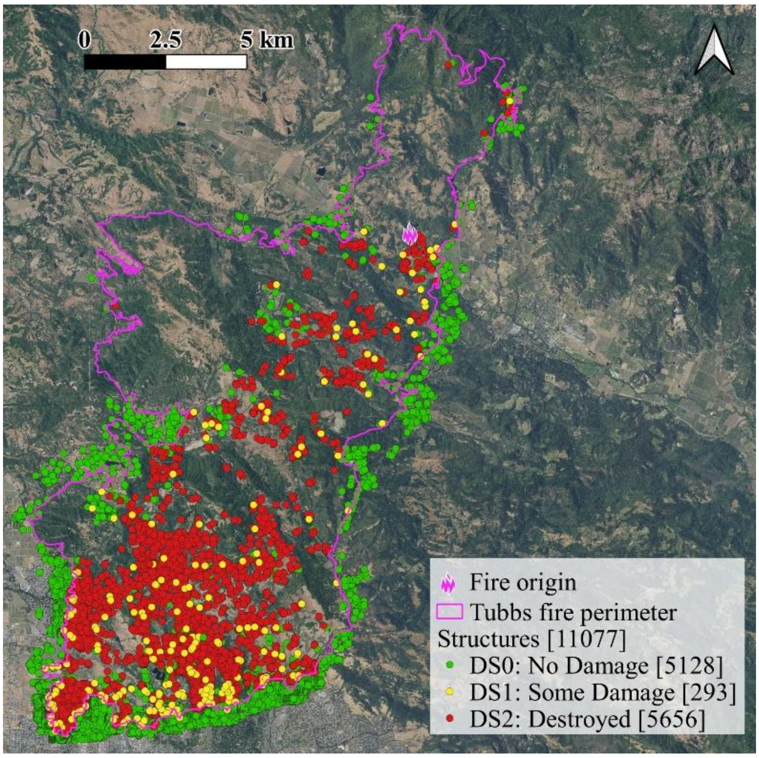

Figure 1- Tubbs fire perimeter outlined in pink with the ignition location indicated by a yellow star. The red dots indicate the location of structures that were destroyed in the Tubbs fire, the yellow dots indicated those that incurred partial damage, and the green dots are structures that were undamaged.

2.3. Risk Analysis Framework

We explore a risk analysis framework, following Rossetto et al. (2014), that incorporates fire hazard intensity metrics, structure vulnerability data, and structure loss inventory. Fragility curves, which are used in damage and loss models for flood and hurricane events, such as HAZUS (FEMA, 2001), represent a probability of exceeding a certain damage state given a level of intensity. The fragility curves are fitted using a generalized linear model with the explanatory variable considered to be the intensity measure (ember density) as well as the year built, defensible space, and the distance to the nearest structure. Other measures of intensity such as the flame length and additional structure and community characteristics can be incorporated and will be presented in future work. The response variable is modelled using a binomial probability density function.

The analysis of probability can be applied on a general level to all structures or by splitting the structures into different building classes. These building classes may be characterized by certain structure features (such as the presence/absence of combustible roofing) that could cause a structure to react differently from another structure under identical exposure conditions. The goodness-of-fit of the model is assessed using the *p*-value and the confidence interval. These metrics are used to determine the appropriate explanatory variables to include, the best link function, and to develop the building classes for significance. Initial results using all structures are presented here. The effect of building classes will be explored in further work.

3. Results and Discussion

To understand the relationship between exposure and damage, fragility curves with all structures for each intensity measure were produced. Figure 2 shows the fragility curve for all structures as a function of the number of embers ignited in a given cell. The probability shown in Figure 2 also incorporates the correlated influence of structure year built, defensible space as measured by vegetation distance via LiDAR, and the distance to the nearest structure. Here DS1 includes both partially damaged and destroyed structures, as the fragility curve represents an exceedance rather than an equivalence. In other words, the line representing DS1 indicates the probability that a structure surpasses the no-damage threshold at a given intensity level. The probability of both damage and destruction increases as the intensity measure increases. Structures require only low ember exposure to reach damaged and destroyed states (i.e., a single ember per cell is often sufficient). For high ember loads, probability of destruction of nearly all structures increases steeply.

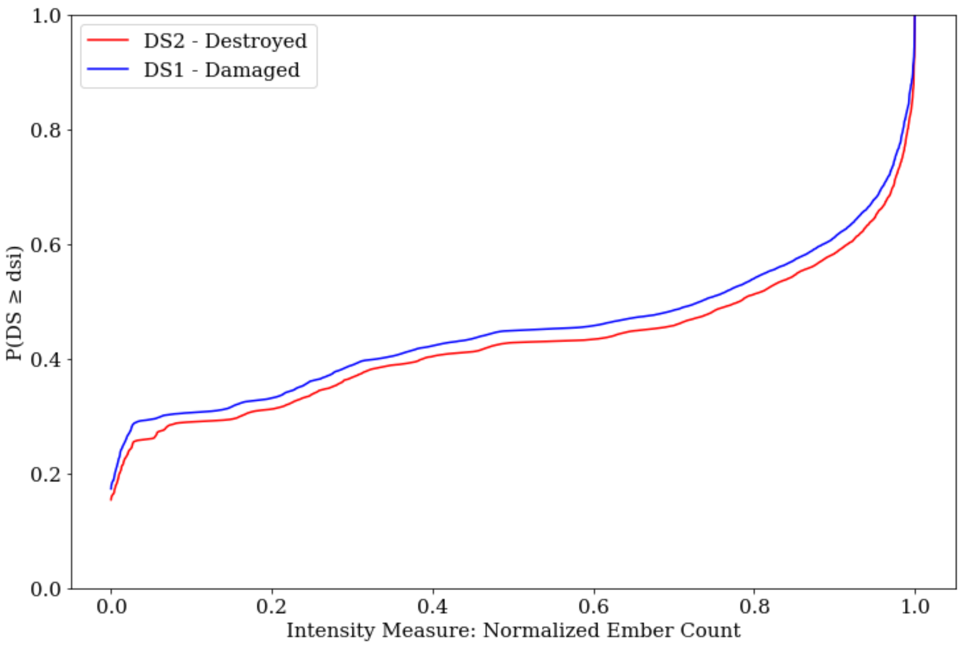

Figure 2- Fragility curve representing probability that the damage state of a structure exceeds either DS1 or DS2 as a function of a normalized ember count, which represents higher or lower numbers of embers ignited in a given cell. Ember count, year built of the structure, defensible space, and structure-to-structure distance are considered as explanatory variables.

The initial results of the fragility curve analysis show a clear relationship between exposure and destruction. Similar trends, not shown here, are found when considering flame length in the explanatory variables, though flame length is found to have a weaker correlation than embers with probability of damage or destruction. Overall, far fewer structures are exposed to flames than to embers, highlighting how critical it is to include embers in our models and in our risk analyses. While previous work (Duff & Penman, 2021) highlights that ember and fire exposure are both important in determining structure damage, the present work elucidates the relationship between ember exposure and destruction across a range of intensity conditions.

4. Conclusions and Future Work

This work shows a strong correlation between ember exposure and destruction, consistent with reports that embers are responsible for the majority of home ignitions (Mell et al., 2010). Future work will assess how local features, such as topography and fuels, compare to using embers for risk assessment. Further work should consider additional mechanisms of exposure, such as structure-to-structure spread (and the best way to capture that information). Similarly, this study focused on specific fire and structure characteristics expected to have an impact on risk, based on the literature; however, additional features may be relevant. Structure and community characteristics (defensible space, distance to nearest structure, year built of a structure) were considered individually here; however, another study has found that some characteristics are only significant when combined with others (Duff & Penman, 2021). Future work should consider interactions between features.

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6. References

Alexandre, P. M., Stewart, S. I., Keuler, N. S., Clayton, M. K., Mockrin, M. H., Bar-Massada, A., Syphard, A. D., & Radeloff, V. C. (2016). Factors related to building loss due to wildfires in the conterminous United States. *Ecological Applications; Ecol Appl, 26*(7), 2323-2338. https://doi.org/10.1002/eap.1376

Byram, George M. (1959). Combustion of forest fuels. Pages 61-89 In: Davis, K. P., editor. Forest fire: control and use. New York, NY: McGraw-Hill.

CAL FIRE. (2022, January 13). Top 20 most destructive California wildfires. California Department of Forestry and Fire Protection. Retrieved March 22, 2022, from https://www.fire.ca.gov/media/t1rdhizr/top20_destruction.pdf

CAL FIRE. (2017, October). Tubbs fire (Central LNU Complex). California Department of Forestry and Fire Protection. Retrieved March 23, 2022, from https://www.fire.ca.gov/incidents/2017/10/8/tubbs-fire-central-lnu-complex

Coen, J., Schroeder, W., & Quayle, B. (2018). The Generation and Forecast of Extreme Winds during the Origin and Progression of the 2017 Tubbs Fire. *Atmosphere, 9*(12), 462. https://doi.org/10.3390/atmos9120462

Duff, T. J., & Penman, T. D. (2021). Determining the likelihood of asset destruction during wildfires: Modelling house destruction with fire simulator outputs and local-scale landscape properties. *Safety Science*, *139*, 105196. https://doi.org/10.1016/j.ssci.2021.105196

Federal Emergency Management Agency (FEMA), 2001. Hazus99 Technical Manual. Service Release 2. (Washington, D.C., FEMA).

Lautenberger, C. (2019a). ELMFIRE – Eulerian level set model of fire spread technical reference. Technical report, Reax Engineering.

Lautenberger, C. (2019b). ELMFIRE – Eulerian level set model of fire spread users' guide. Technical report, Reax Engineering.

Lautenberger, C. (2017). Mapping areas at elevated risk of large-scale structure loss using Monte Carlo simulation and wildland fire modeling. *Fire Safety Journal, 91*, 768-775. https://doi.org/10.1016/j.firesaf.2017.04.014

Lautenberger, C. (2013). Wildland fire modeling with an Eulerian level set method and automated calibration. *Fire Safety Journal, 62*, 289-298. https://doi.org/10.1016/j.firesaf.2013.08.014

Mell, W. E., Manzello, S. L., Maranghides, A., Butry, D., & Rehm, R. G. (2010). The wildland–urban interface fire problem – current approaches and research needs. *International Journal of Wildland Fire, 19*(2), 238-251. https://doi.org/10.1071/WF07131

Microsoft. (2018). US building footprints. Retrieved March 23, 2022, from https://github.com/Microsoft/USBuildingFootprints

Penman, T. D., Nicholson, A. E., Bradstock, R. A., Collins, L., Penman, S. H., & Price, O. F. (2015). Reducing the risk of house loss due to wildfires. *Environmental Modelling & Software: With Environment Data News, 67*, 12-25. https://doi.org/10.1016/j.envsoft.2014.12.020

Rollins, M. G. (2009). LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire, 18*(3), 235-249. https://doi.org/10.1071/WF08088

Rossetto, T., Ioannou, I., Grant, D. N., & Maqsood, T. (2014). *Guidelines for the empirical vulnerability assessment.* GEM Technical Report 2014-08 V1.0.0, 140 pp., GEM Foundation, Pavia, Italy, doi: 10.13117/ GEM.VULN-MOD.TR2014.11.

Scott, J. H., & Burgan, R. E. (2005). *Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model.* Gen. Tech. Rep. RMRS-GTR-153. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p. https://doi.org/10.2737/RMRS-GTR-153

Scott, J. H., Thompson, M. P., & Calkin, D. E. (2013). *A wildfire risk assessment framework for land and resource management.* Gen. Tech. Rep. RMRS-GTR-315. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p. https://doi.org/10.2737/RMRS-GTR-315

Syphard, A., & Keeley, J. (2019). Factors associated with structure loss in the 2013–2018 California wildfires. *Fire, 2*(3), 49-64. https://doi.org/10.3390/fire2030049

Valachovic, Y., Quarles, S., Swain, S. (2021). *Reducing the Vulnerability of Building to Wildfire: Vegetation and Landscaping Guidance.* University of California Agriculture and Natural Resources, Publication Number 8695. 12 p. DOI: 10.3733/ucanr.8695