Fire risk to structures and effectiveness of mitigation in California's Wildland-Urban interface

Michael Gollner, Ph.D.

Associate Professor and Deb Faculty Fellow
Director of the Berkeley Fire Research Lab
Vice Chair for Graduate Studies
Department of Mechanical Engineering, University of California, Berkeley

Contributors: **Maryam Zamanialaei**, Daniel San Martin, Maria Theodori, Dwi Marhaendro Jati Purnomo, Ali Tohidi, Chris Lautenberger, Yiren Qin & Arnaud Trouvé

Primary Project Support from Forest Health Grant 8GG21815

Berkeley Fire Research Lab

Presentation for the Santa Clara County Fire Safe Council Board Meeting
October 21, 2025

Fire risk to structures and effectiveness of mitigation in California's Wildland-Urban interface

nature communications

Article https://doi.org/10.1038/s41467-025-63386-2

Fire risk to structures in California's Wildland-Urban Interface

Received: 13 January 2025

Accepted: 15 August 2025

Published online: 28 August 2025

Check for updates

Maryam Zamanialaei[1], Daniel San Martin[2], Maria Theodori[1], Dwi Marhaendro Jati Purnomo[1], Ali Tohidi[3], Chris Lautenberger[4], Yiren Qin[3], Arnaud Trouvé[3] & Michael Gollner[1]

The destructive impacts of wildfires on people, property and the environment have dramatically increased, especially in the Wildland-Urban Interface (WUI) in California. In these areas structures are threatened by both approaching flames and lofted embers which spread fire into and within communities. While independent factors influencing structure fire protection are well known, their combined effects remain largely unquantified, limiting the accuracy of risk assessments and mitigation strategies. Here, we examine five major historical WUI fires—2017 Tubbs, 2017 Thomas, 2018 Camp, 2019 Kincade, and 2020 Glass Fires—utilizing machine learning (ML) analysis of on-the-ground post-fire data collection, remotely sensed data, and fire reconstruction modeling to assess patterns of structure loss and mitigation effectiveness. We show that the spacing between structures is a critical factor influencing fire risk, highlighting the importance of structure arrangement, while fire exposure, the ignition resistance (hardening) of structures, and clearing around structures (defensible space) work in combination to mediate fire risk. Utilizing an XGBoost classifier, structure survivability can be predicted to 82% accuracy. Results highlight the effectiveness of hardening and defensible space, with a hypothetical 52% reduction in losses. Our findings emphasize the need for community-level mitigation to reduce structure loss in future WUI fires.

Michael Gollner, Ph.D.

ssociate Professor and Deb Faculty Fellow
irector of the Berkeley Fire Research Lab
Vice Chair for Graduate Studies
lechanical Engineering, University of California, Berkeley

GORDON AND BETTY MOORE FOUNDATION

NSF

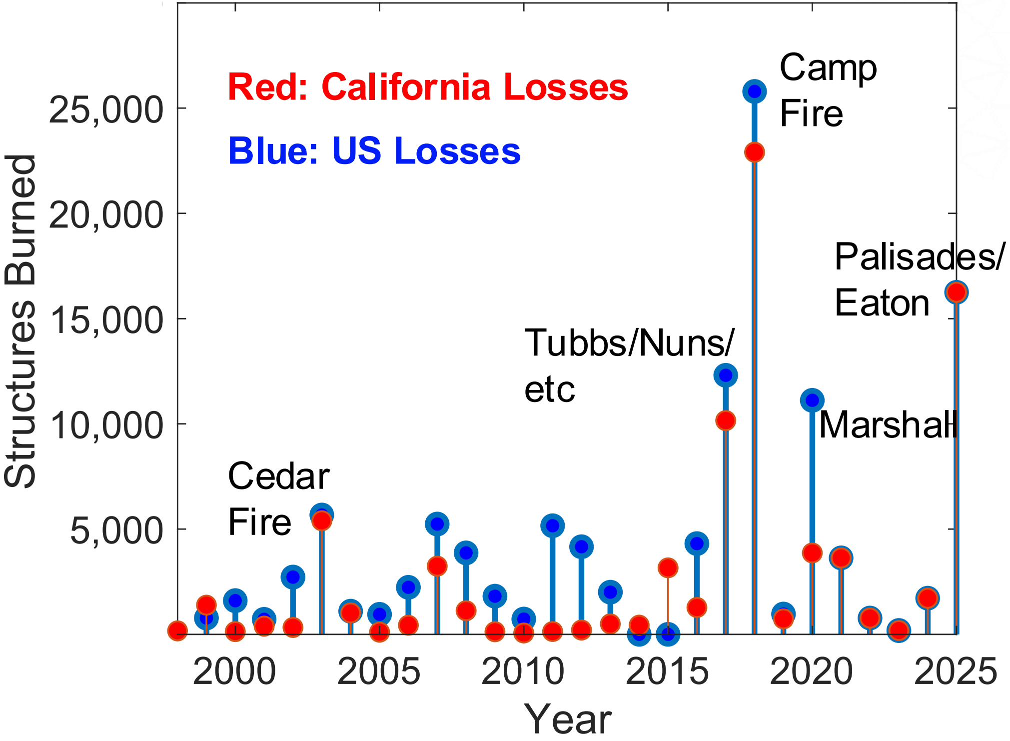
CAL FIRE

Primary Project Support from Forest Health Grant 8GG21815

Photo Credit: Melia Robbinson

Wildland-Urban Interface (WUI) Fires

Tubbs Fire / Melia Robbinson



Data: CA (CAL FIRE), US (NIFC)

Palisades Fire/Robert Gauthier/Los Angeles Times

Eaton Fire/Jeff Gritchen, Orange County Register/SCNG

Palisades Fire/Ethan Swope / AP

Camp Fire/Hector Amezcua/Sac Bee

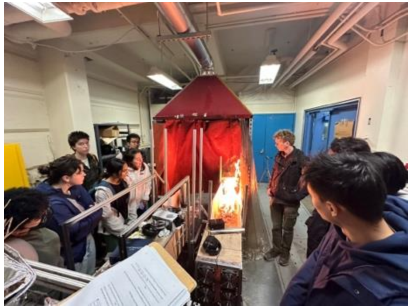

Modeling WUI Fires:
A Huge Challenge
Coffey Park
Santa Rosa, CA
Tubbs Fire

Berkeley Fire Lab Research

https://firelab.berkeley.edu

Fire Modeling

- New WUI fire spread modelling data/tools
- Risk analysis for communities
- AI and ML tools for fire



Experimental Fire Research

- WUI structure spread
- Ember generation & ignition
- Fire spread
- Ornamental vegetation

Fire Emissions & Health Effects

- WUI fire emissions
- Risk to firefighters

Fire Safety

- Spacecraft fire safety
- Li Ion Batteries
- Fire effects on solar

Saffire

SoFIE

CARNEGIE ENDOWMENT FOR INTERNATIONAL PEACE

JOINT FIRE SCIENCE PROGRAM

CALIFORNIA OFFICE OF ENERGY INFRASTRUCTURE SAFETY

CAL FIRE

NIST National Institute of Standards and Technology U.S. Department of Commerce

GORDON AND BETTY MOORE FOUNDATION

FEMA

NASA

CALIFORNIA AIR RESOURCES BOARD

BSEE Bureau of Safety and Environmental Enforcement

Pathways to Fire Spread

Radiation

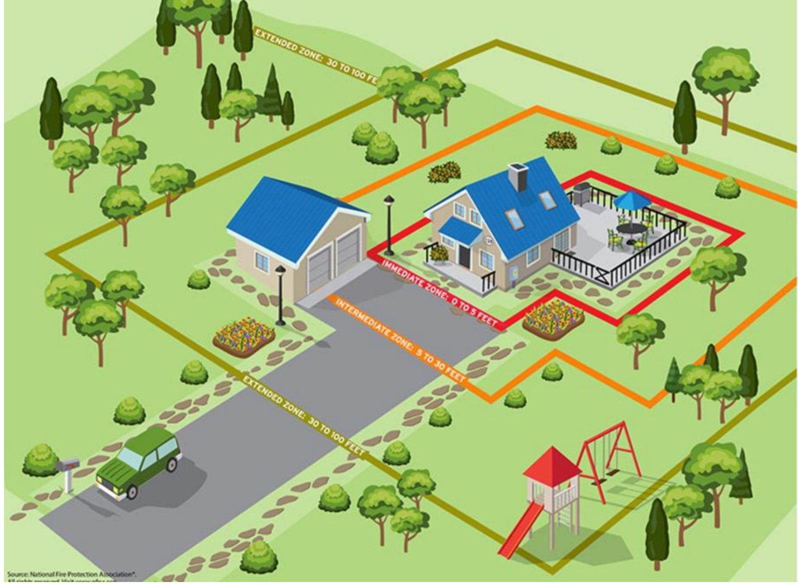
Originally thought to be responsible for most/all ignitions

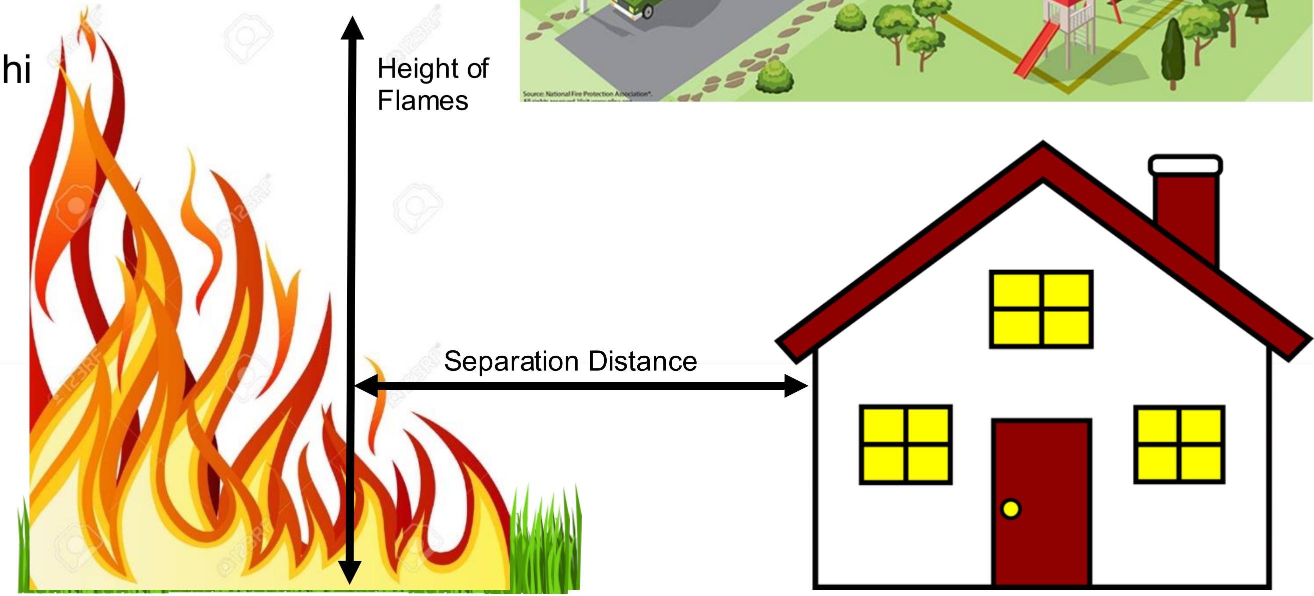
Direct Flame Contact

Smaller flames from nearby sources

Embers or Firebrands

Small burning particles whi





Caton, S. E., Hakes, R. S., Gorham, D. J., Zhou, A., & Gollner, M. J. (2017). Review of pathways for building fire spread in the wildland urban interface part I: exposure conditions. *Fire technology*, 53, 429-473.

Pathways to Fire Spread

Radiation

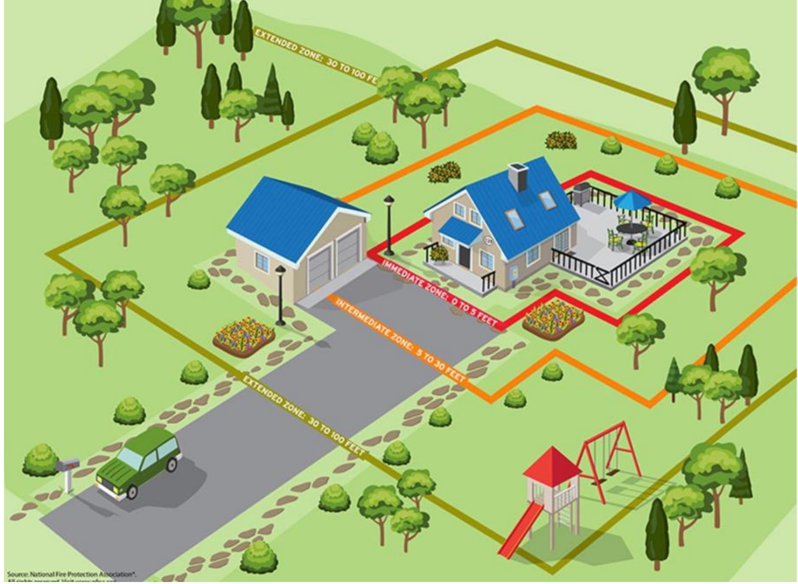
Originally thought to be responsible for most/all ignitions

Direct Flame Contact

Smaller flames from nearby sources

Embers or Firebrands

Small burning particles which cause spot ignitions



Pathways to Fire Spread

Radiation

Originally thought to be responsible for most/all ignitions

Direct Flame Contact

Smaller flames from nearby sources

Embers or Firebrands

Small burning particles which cause spot ignitions

Pathways to Fire Spread

Radiation

Originally thought to be responsible for most/all ignitions

Direct Flame Contact

Smaller flames from nearby sources

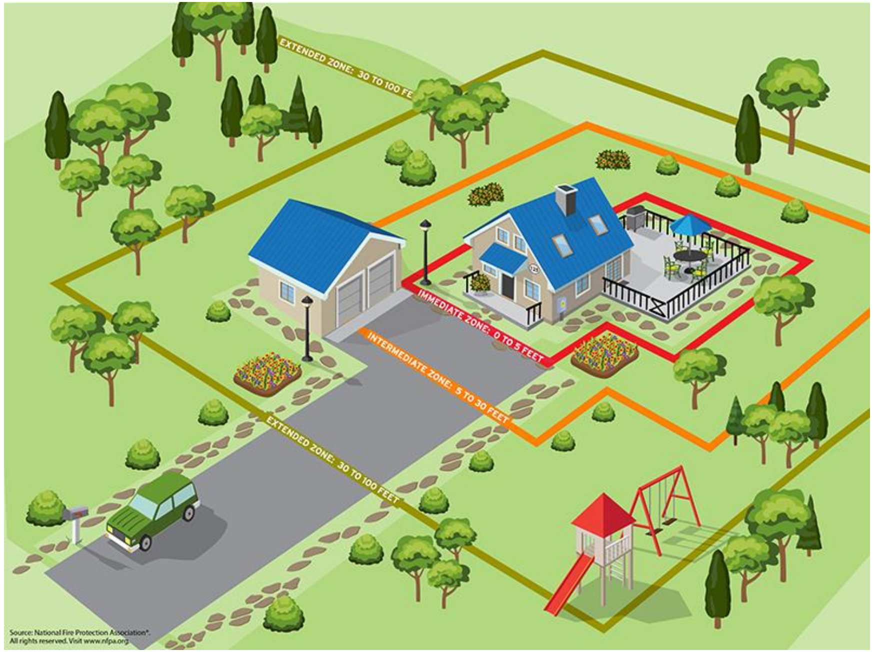
Embers or Firebrands

Small burning particles which cause spot ignitions

Nathan Trauernicht, UC Davis Fire @ Tamarack Fire

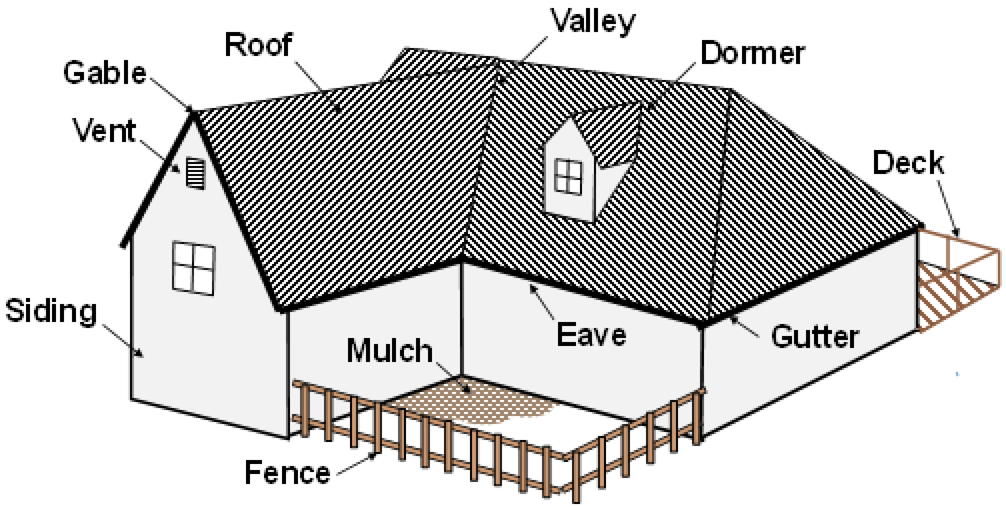
Mitigation Approaches:

Defensible Space



Reduce or clear nearby fuels

Home Hardening



Prevent ignition from small flames/embers

Berkeley Fire Research Lab

Hakes, Raquel SP, et al.." *Fire technology* 53 (2017): 475-515.
Maranghides, A., et al. (2022). *WUI Structure/parcel/community fire hazard mitigation methodology*. NIST

Data- Driven WUI Risk to Structures

- Mitigation must be applied to reduce the risk of structure losses in the future
- Need methods to relate features/exposure to losses
- Previous analyses have several drawbacks:
    - No quantitative data ranking one mitigation measure vs. another
    - Analysis of losses using only linear correlations or statistics (no interrelationships)
    - No exposure data (fire and embers) from wildland to structures

Fire Risk to Structures in California's Wildland-Urban Interface, Zamanialaei et al., Accepted for Publication, *Nature Communications*

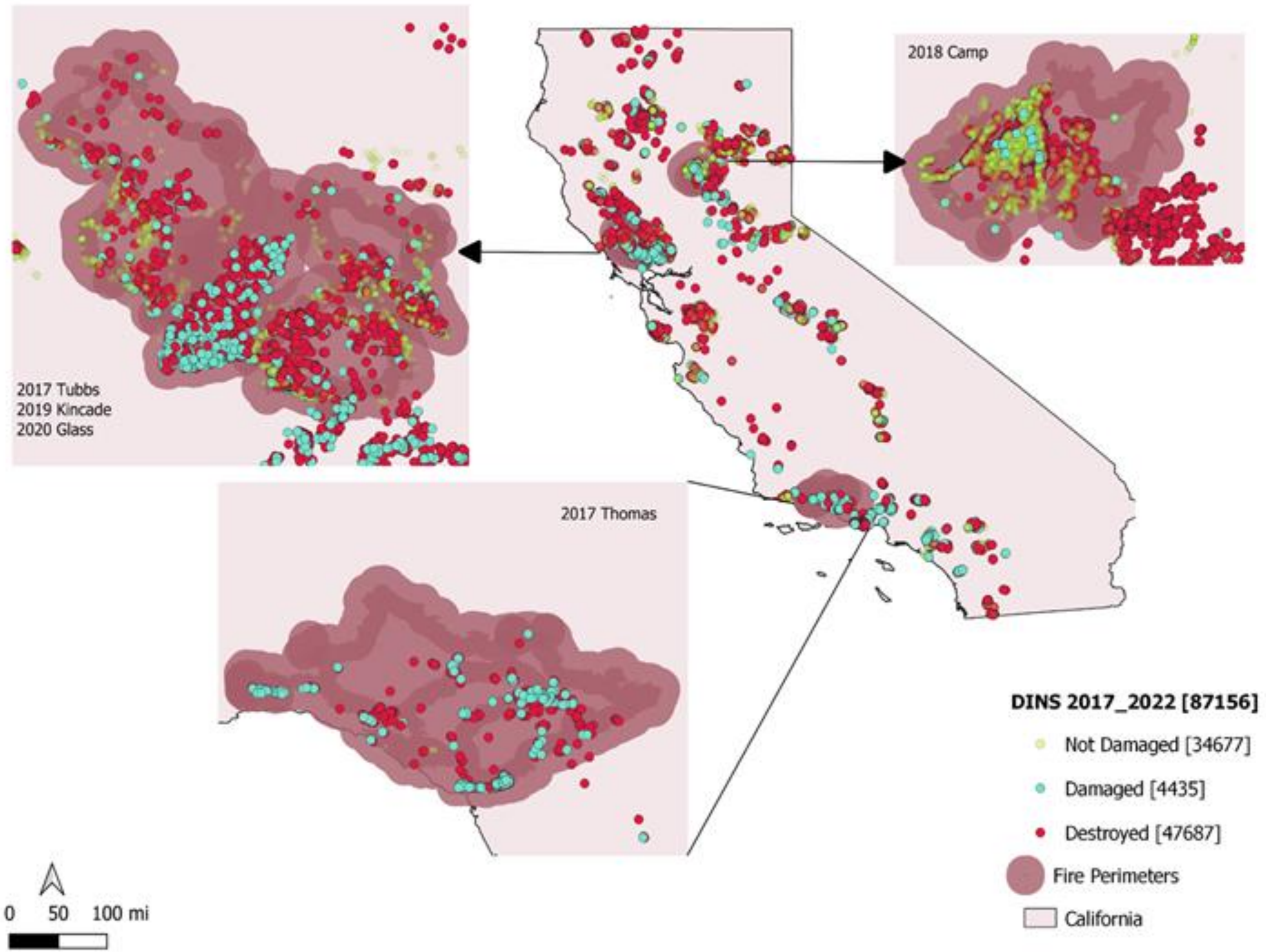
Data- Driven WUI Risk to Structures

- Create a WUI Dataset for Analysis and Model Validation:
    - Using DINS (Ground Truth), remotely sensed data and ***modeled*** exposure
- Quantify Significance of WUI Features on Structure Destruction:
    - Use SHAP Values and feature contributions
- Focus on 5 past fires in California:

WUI Fire	Acres Burned	Destroyed Structures
2017 Tubbs	36,807	5,636
2017 Thomas	281,893	1,063
2018 Camp	153,336	18,804
2019 Kincade	77,758	374
2020 Glass	67,484	1,528

CAL FIRE DINS - Damage INSpection data

WUI data:
values= 47,000
Unique data point= 45,947



Combining and processing datasets

Collected Data

DINS

- **Structure Features:** Roof, siding, windows, vent, eaves, etc.
- **Year Built**

Missing Data

Defensible Space

- **Airborne LiDAR data for Sonoma County**
  - **1 m. resolution raster for veg intensity**
- **Aerial and Street View Imagery**

Structure Separation

- **Calculated with MS Structure Footprints**

Flame and Embers

- **Generated by reconstructing past fires**
- Models run with vegetation and *limited* urban spread - extract fire intensity and ember cast

Undamaged structures

- **Adding undamaged structures for past fires (MS Footprints, OSM, Imagery)**

Validation Data

Ground Truth & RS

- **DINS**
- **MODIS , VIIRS, GOES**

Defensible Space Assessment

Zone 0: First five feet

Zone 1:Within 30 feet

Zone 2: Within 100 feet

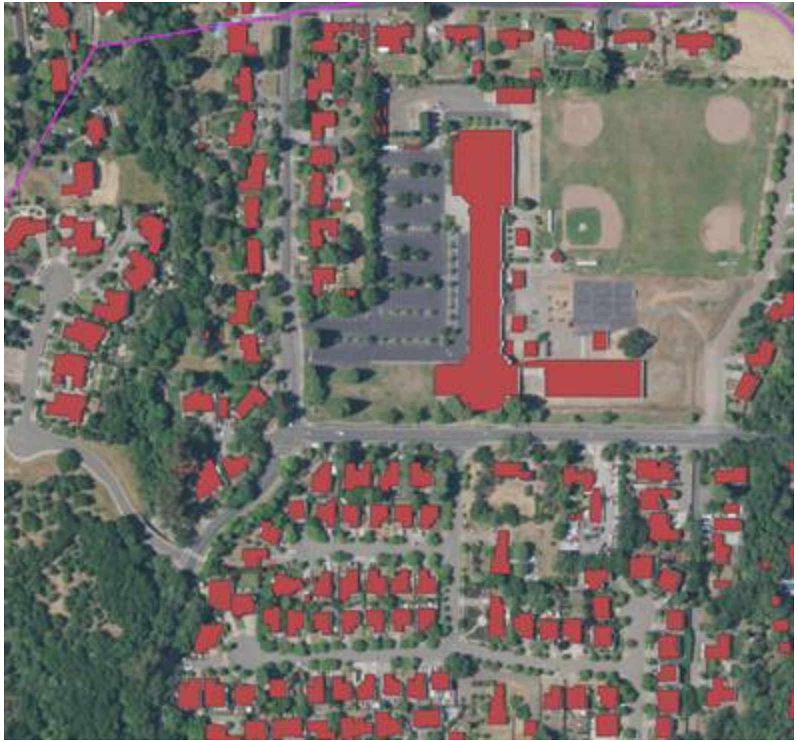
No defensible space

Zone 0 and 1 clear

Defensible space is the buffer between a structure and the surrounding area without vegetation. Used 1 m LIDAR or finer aerial
Not accounting for surface fuels

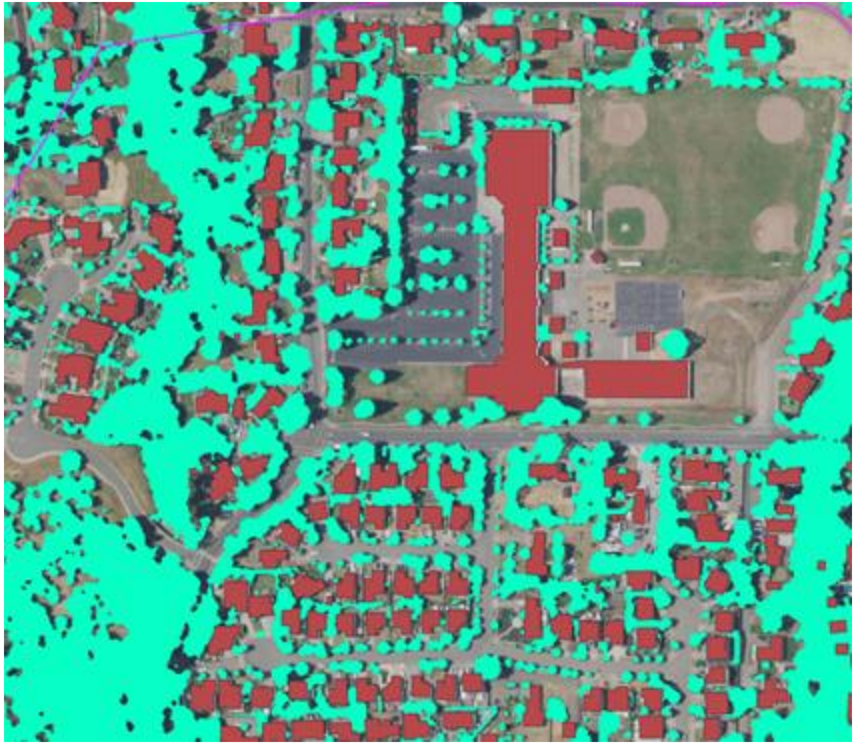
Separation Distance

Structure Separation Distance +
Unburned structures



MS Building Footprints - script analysis

Vegetation Separation Distance



LIDAR (Sonoma County)

Exposure from Fire Modeling

Current Limitations

No inclusion of exposure from neighboring structures

Underlying physics

Validation data

Input data resolution

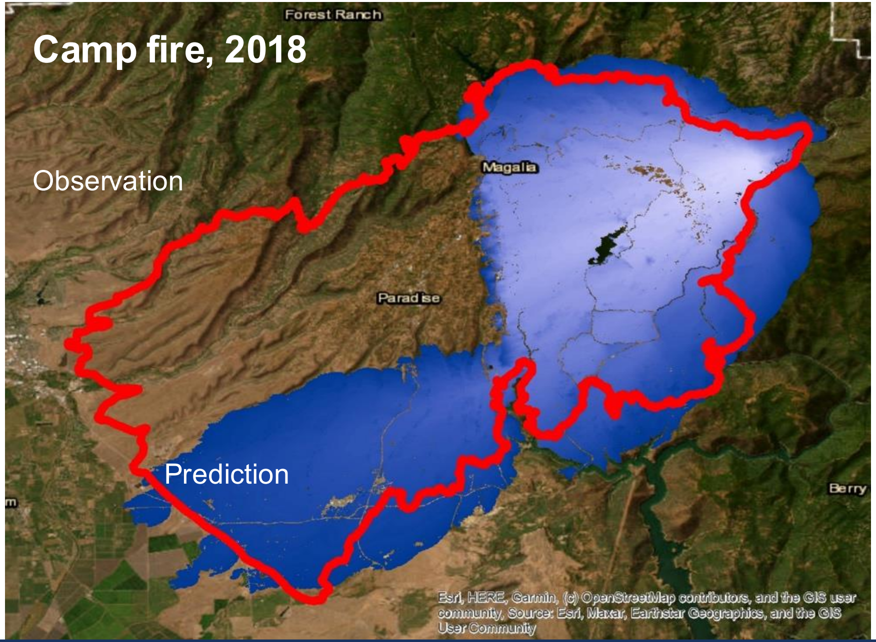
Structure-to-structure spread

Inputs
- Vegetation
- Weather
- Topography

Models
- Surface fire
- Crown fire
- Ember

Wildfire model: **ELMFIRE**

Outputs
- Spread rate
- Ember cast
- Flame length



Raquel S. P. Hakes, Sara E. Caton, Michael J. Gollner, Daniel J. Gorham, "A Review of Pathways for Building Fire Spread in the Wildland Urban Interface Part II: Response of Components and Systems and Mitigation Strategies in the United States," *Fire Technology, 53, 475–515, 2017*. doi: 10.1007/s10694-016-0601-7

Novel coupled WU-E[1] modeling framework

Wildland-**U**rban **E**xtension fire model

Geospatial inputs

- Fuels (wildland)
- Weather
- Topography

- Fuels (built)

Submodels

- Surface fire
- Crown fire
- Spotting (firebrands)

- Direct flame contact
- Radiation
- Spotting (firebrands)

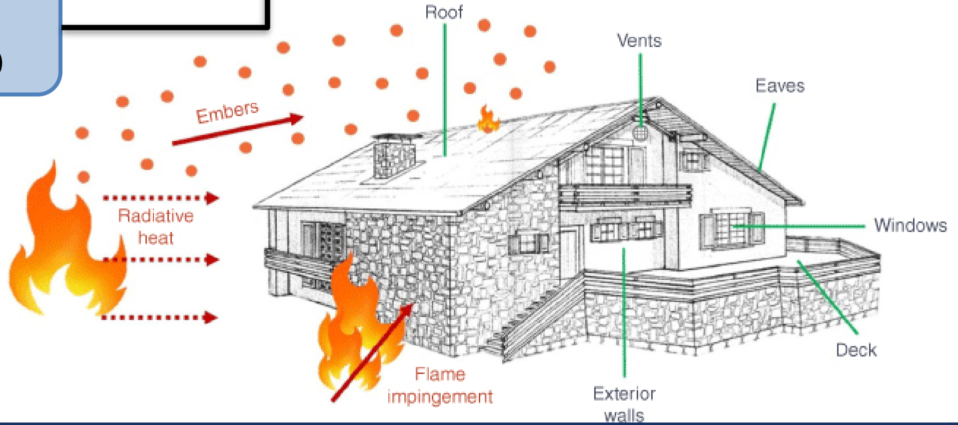
Modeling tool

Key outputs

- Rate of spread
- Heat flux
- Ember cast

Model Benefits:

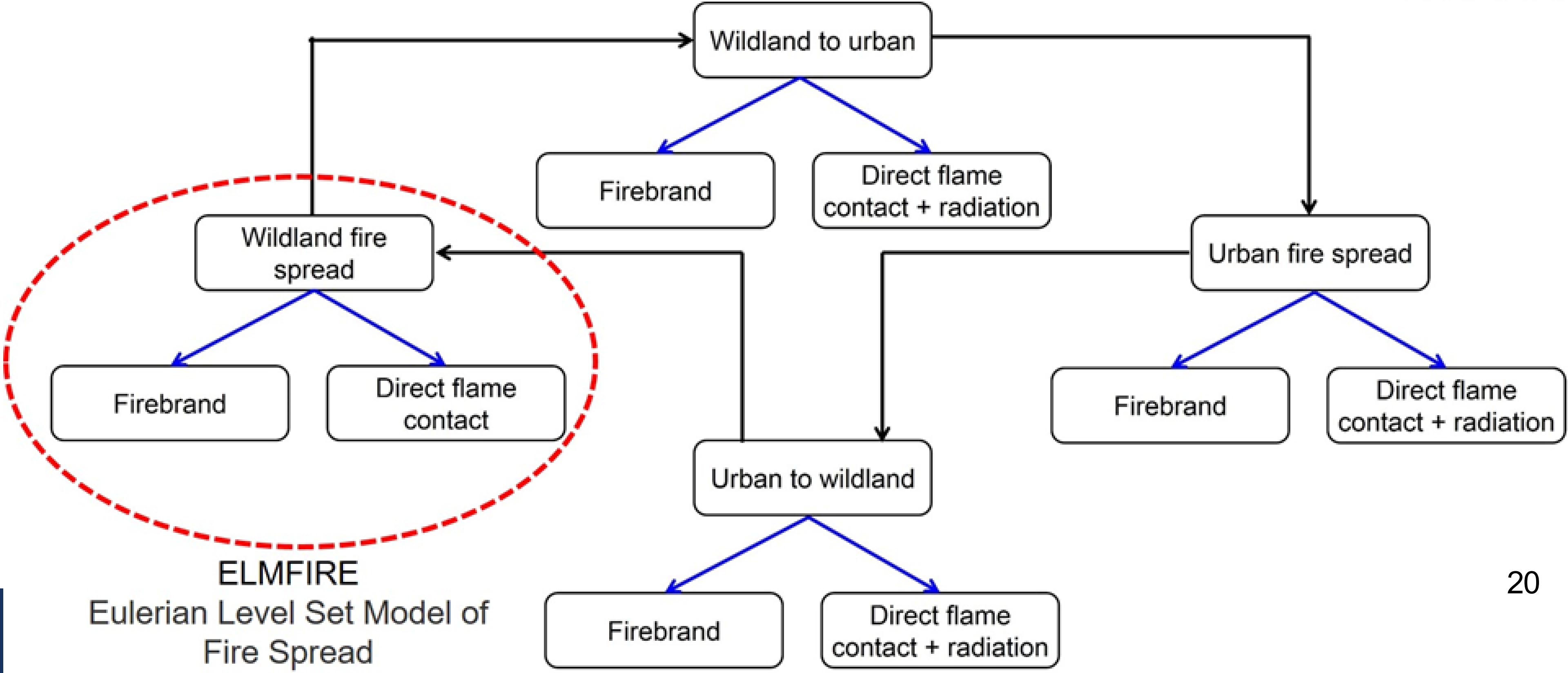
- Spreads through structures
- Incorporates effects of mitigation
- Links wildland-> structures -> wildland
- Integrates with existing management & risk frameworks



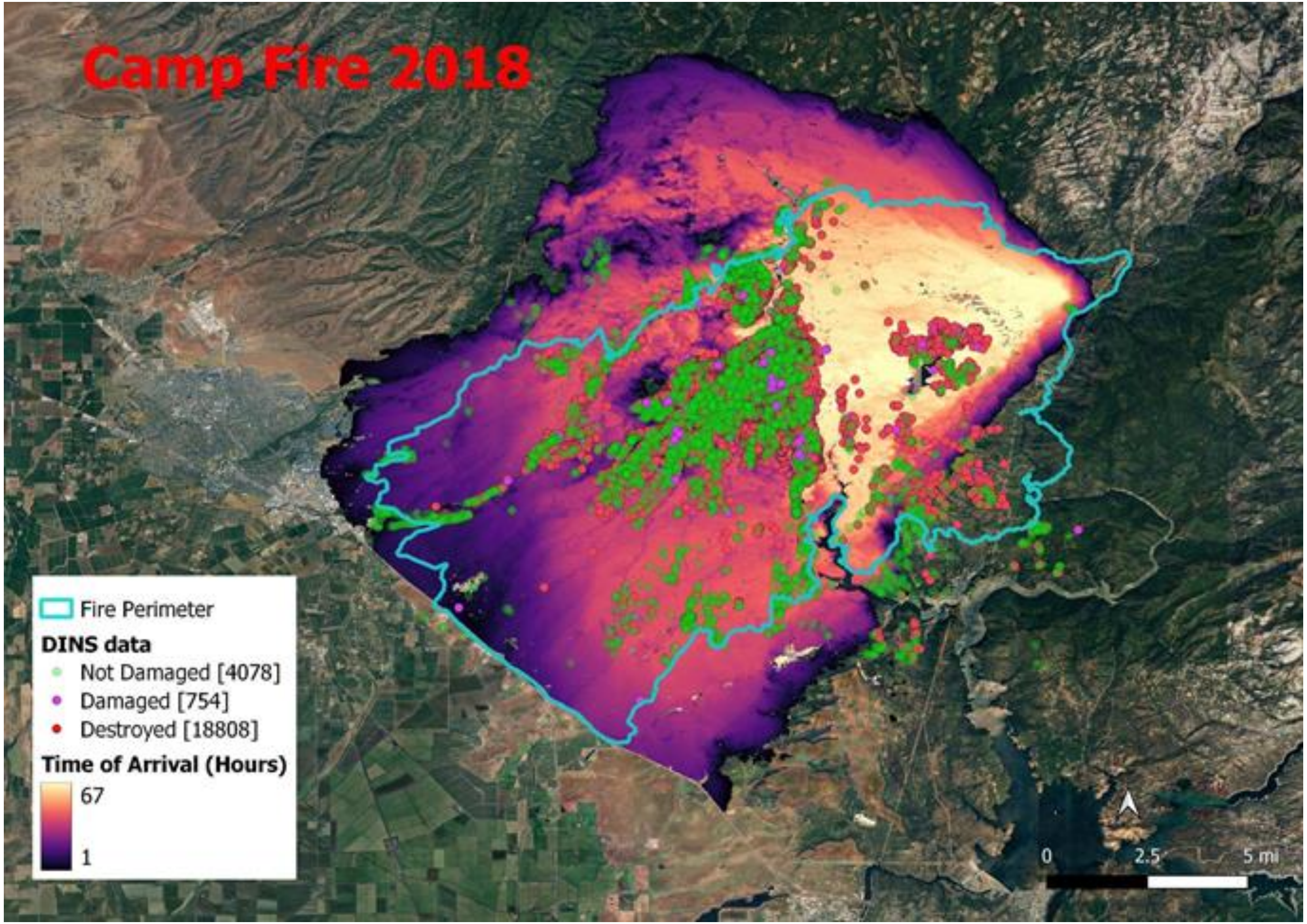
[1]Purnomo, D., et al. Reconstructing modes of destruction in wildland-urban interface fires using a semi-physical level-set model. *Proceedings of the Combustion Institute.*

Purnomo DM et al. (2024) Integrating an urban fire model into an operational wildland fire model to simulate one dimensional wildland–urban interface fires: a parametric study. International Journal of Wildland Fire 33, WF24102.doi:10.1071/WF24102

WU-E



Fire Reconstruction: Camp Fire 2018



Extracting Significance of WUI Features

- Features are inter-related so linear or statistical methods can't capture their influence

- We attempt to fit the data to a machine learning (ML) model using ***regression and classification methods*** and extract the importance of individual features.

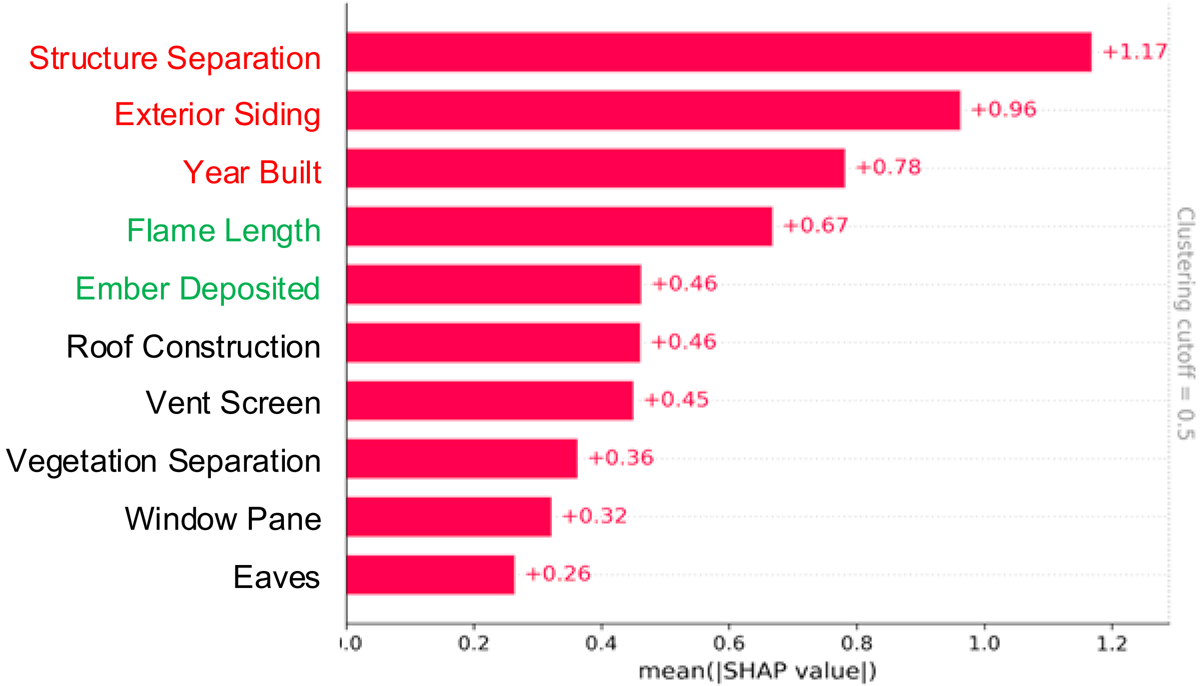
- It is important to first "clean/preprocess" the data and avoid biases, ensuring compatibility and enhancing the overall performance of the models:
  - ***Imputation*** was explored due to the presence of numerous NaN values in the dataset.
  - ***Standardized*** the numerical variables and ***Encoded*** categorical variables

Extracting Significance of WUI Features

- We explore 4 models and use the "best fit"
    - *Linear/Logistic regression*
    - *Random Forest*
    - *Gradient Boosting/ XGBoost*
    - *CatBoost*
    - **XGBoost showed better results in overall accuracy .**
- We extract feature contributions through SHAP (SHapley Additive exPlanations)
    - Interpreting machine learning models
    - Ensuring consistency and local accuracy

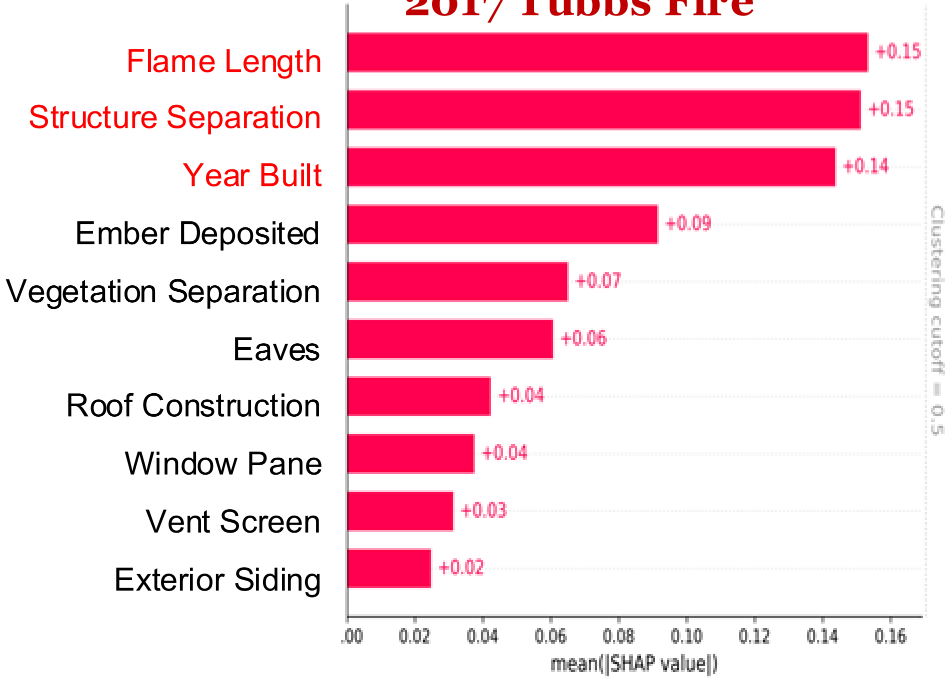
Feature Contributions Using XGBoost and SHAP Values

Stacked WUI data: 5 Past fires (2017-2022)

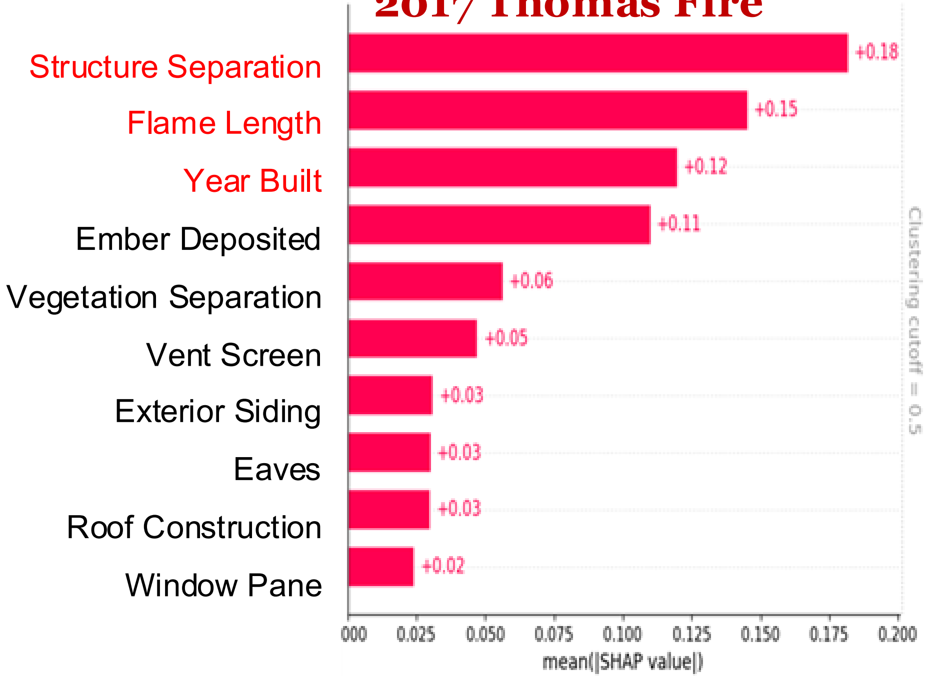


Feature Contributions Using XGBoost and SHAP Values

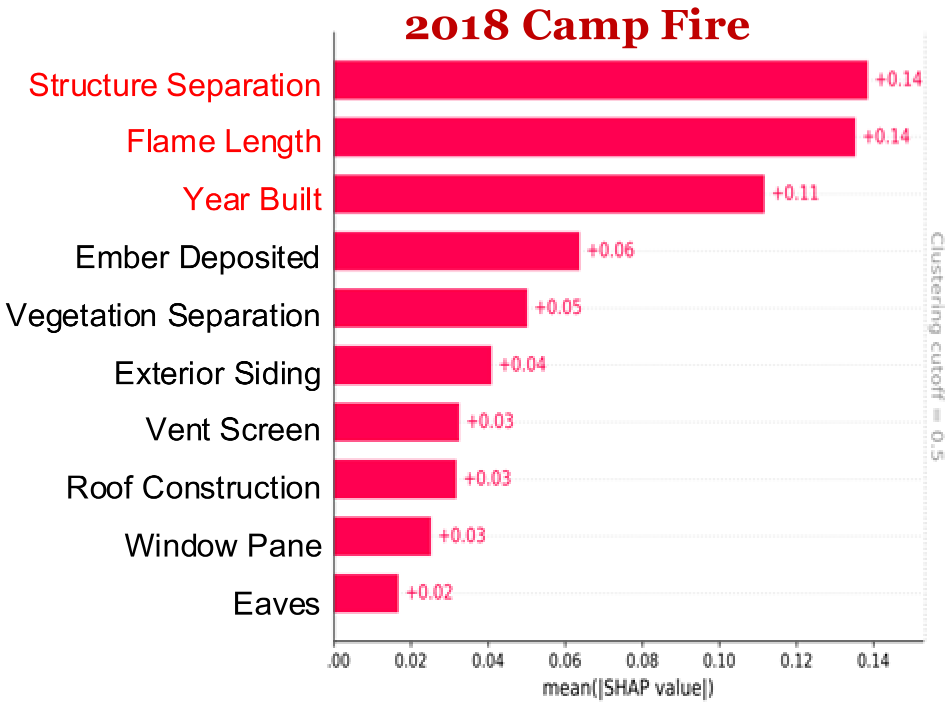
2017 Tubbs Fire

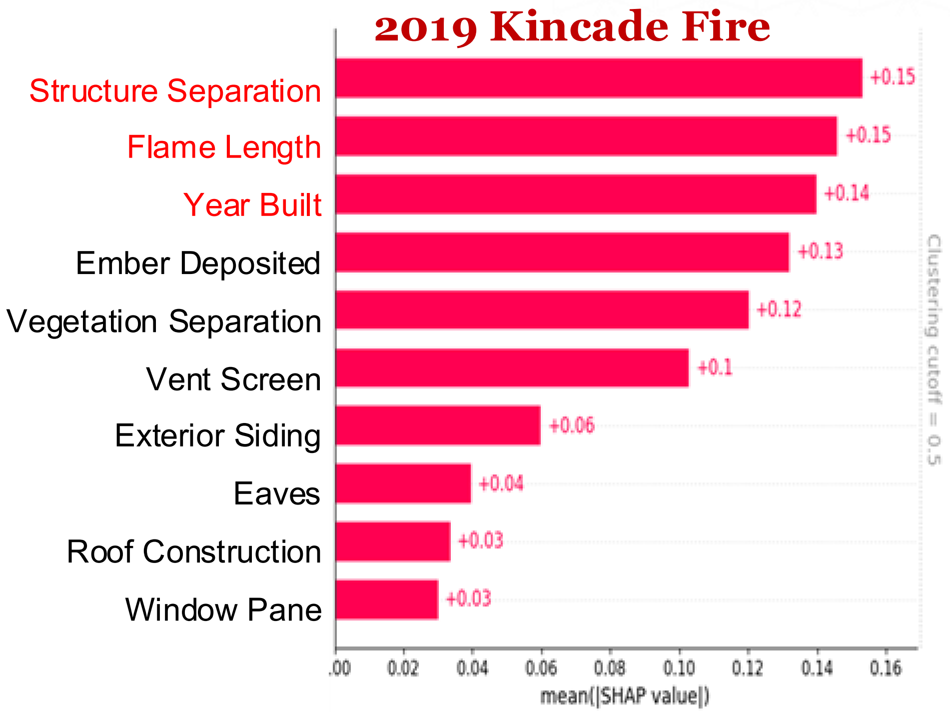


2017 Thomas Fire

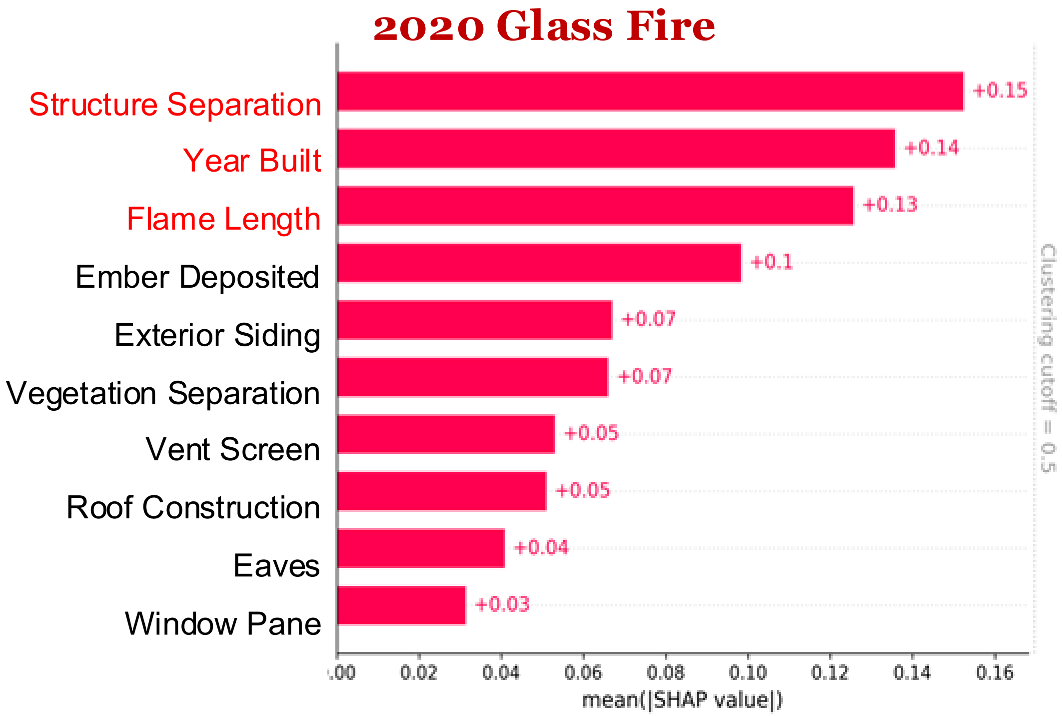


Feature Contributions Using XGBoost and SHAP Values



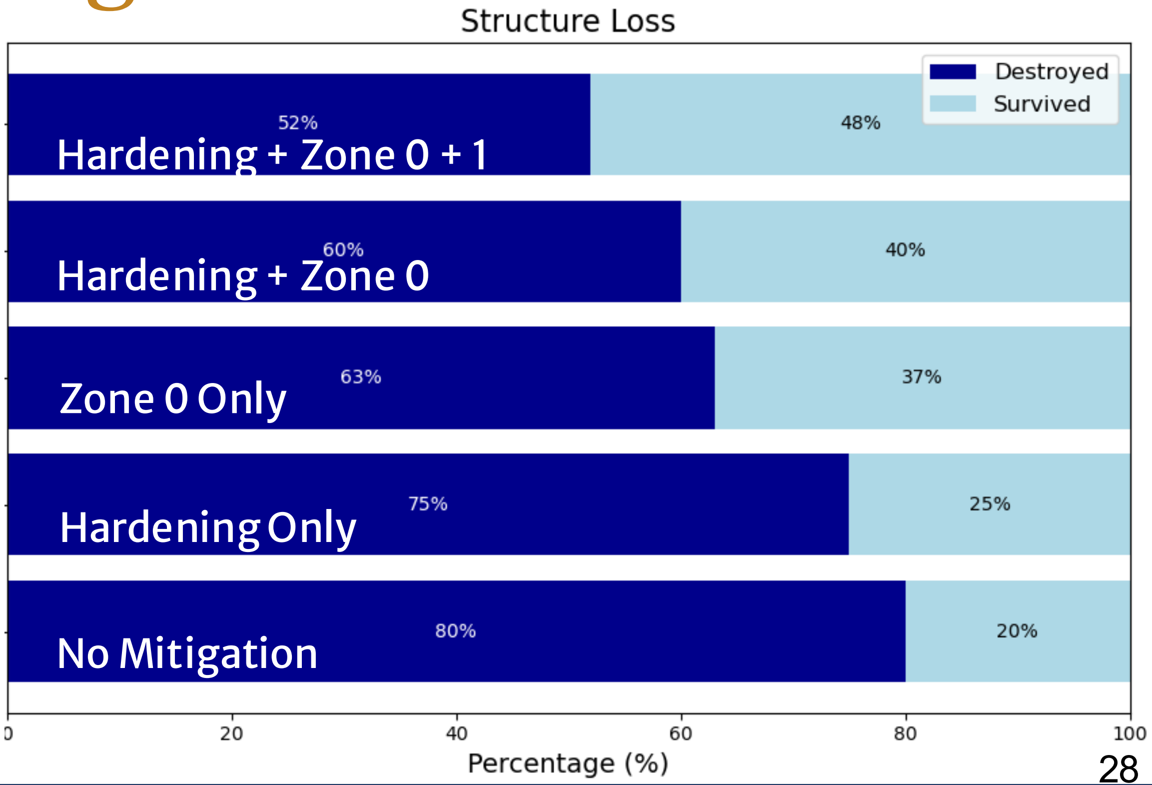


Feature Contributions Using XGBoost and SHAP Values



Influence of Mitigation Factors

- ML model can be used as a predictive tool (~82% accuracy)
- Potential influence of different mitigation strategies tested
- Probability of surviving increases with hardening + defensible space
- Even without moving (spacing) structures, can drastically cut down on losses
- Does not incorporate dynamic (spread) or suppression effects



Fire Risk to Structures in California's Wildland-Urban Interface, Zamanialaei et al., Accepted for Publication, *Nature Communications*

Conclusions

- Significant factors leading to building destruction in the WUI:
  - Structure Separation Distance
    - Fire spread in the WUI often depends on building arrangement
  - Exposure : Fire intensity and firebrands/embers
    - Flame Length critical role in determining the intensity and spread of the fire across different landscapes
    - Ember exposure key because a wide area is impacted by embers
  - Building features (vents, siding, fences, decks, etc.) – ***Home Hardening***
    - Importance varies depending on the fire and specific building construction
  - ***Defensible Space*** (Vegetation Separation Distance), ***particularly in Zone 0***, plays a crucial role in mitigation.
  - Year built: Year that primary structure in parcel was constructed (confounding parameter)
  - Data-driven ML model useful for some predictions (e.g., response function) and impacts of mitigation
- New model, **WU-E** spreads fire between structures, provides fire incident intensity outputs, flexible structural properties variations, and an adaptable physical framework for spread.

Thank you!

Work supported by Forest Health Grant 8GG21815