Fire Risk to Structures 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

Prepared for the California Fire Safe Council
County Coordinator Workshop
November 21, 2025

Primary Project Support from Forest Health Grant 8GG21815

Berkeley Fire Research Lab

Photo Credit: Melia Robbinson

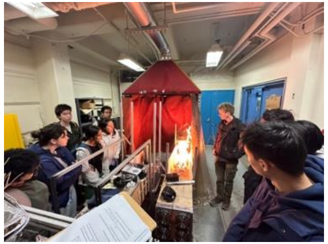
Berkeley Fire Lab Research

Fire Modeling
- New WUI fire spread modelling data/tools
- Risk analysis for communities
- Modeling to understand fire behavior
- AI and ML tools for fire

Fire Emissions & Health Effects
- Fuel/fire effects
- WUI fire emissions
- Risk to firefighters

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

Experimental Fire Research
- Structure to structure spread
- Ember generation & ignition
- Crown fire initiation
- Ornamental vegetation (zone 0)
- Laboratory & field experiments



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CALIFORNIA OFFICE OF ENERGY INFRASTRUCTURE SAFETY

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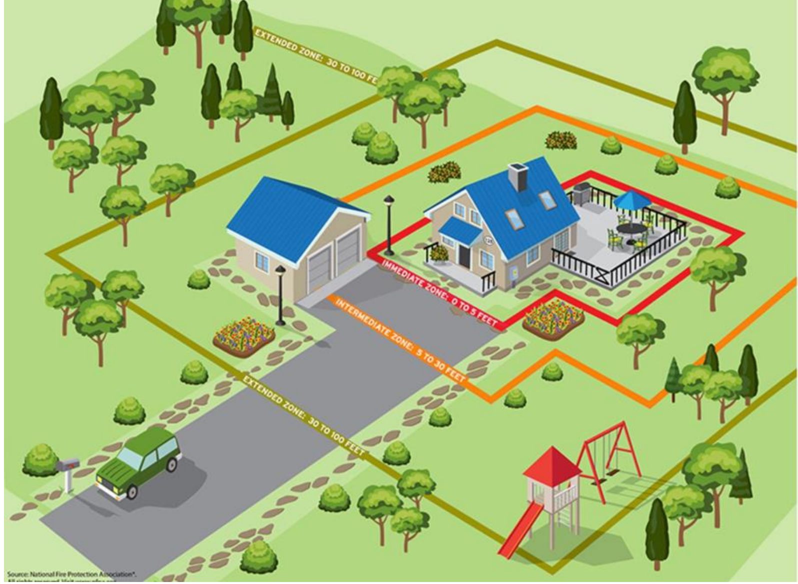
CAL FIRE · NIST National Institute of Standards and Technology U.S. Department of Commerce · GORDON AND BETTY MOORE FOUNDATION · FEMA · NASA · NSF · CALIFORNIA AIR RESOURCES BOARD · BSEE Bureau of Safety and Environmental Enforcement

Pathways to Fire Spread



Radiation

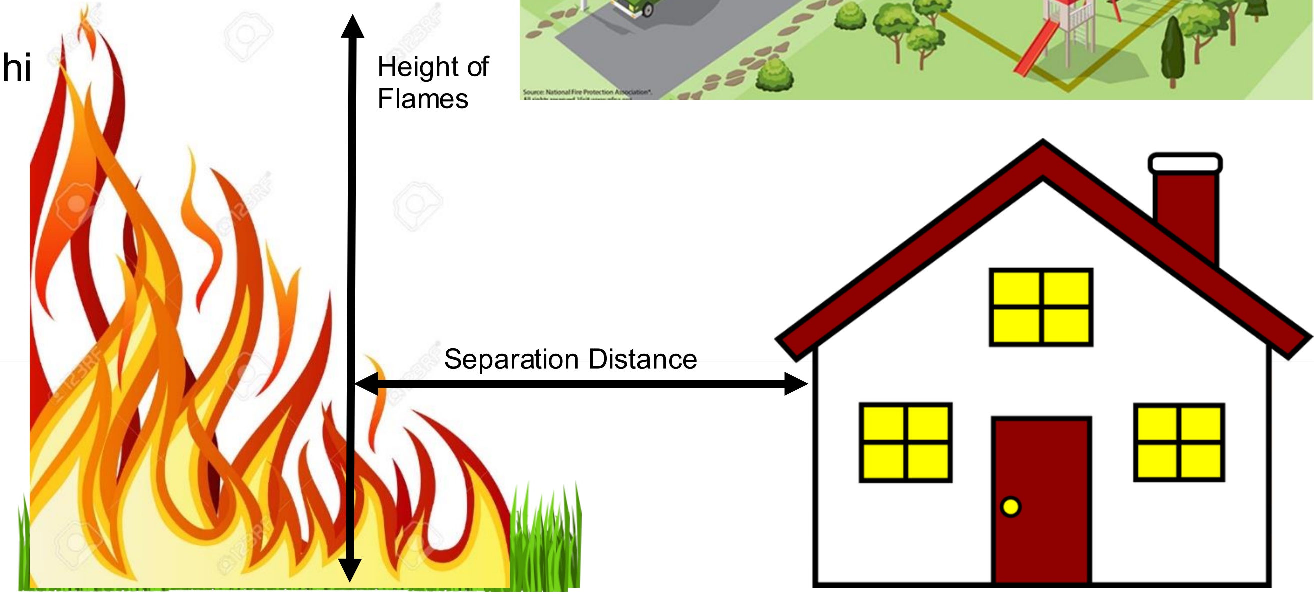
Originally thought to be responsible for most/all ignitions

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

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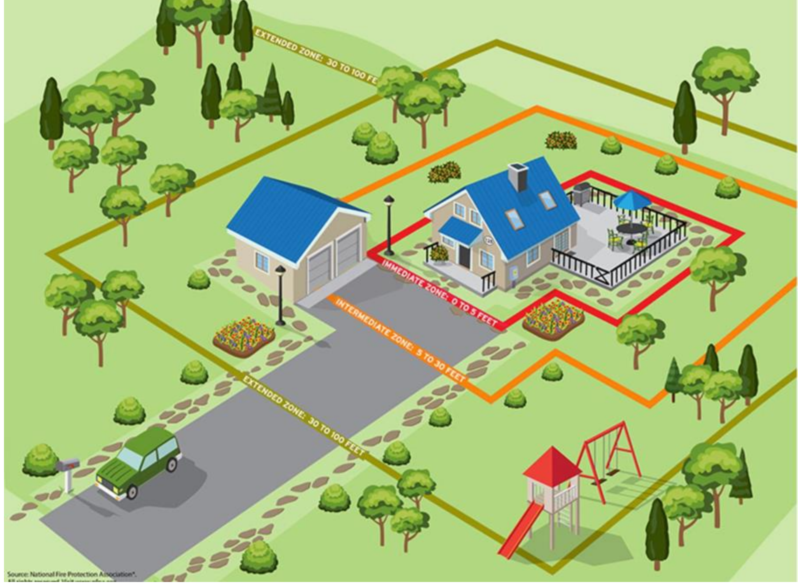
Embers or Firebrands

Small burning particles which cause spot ignitions



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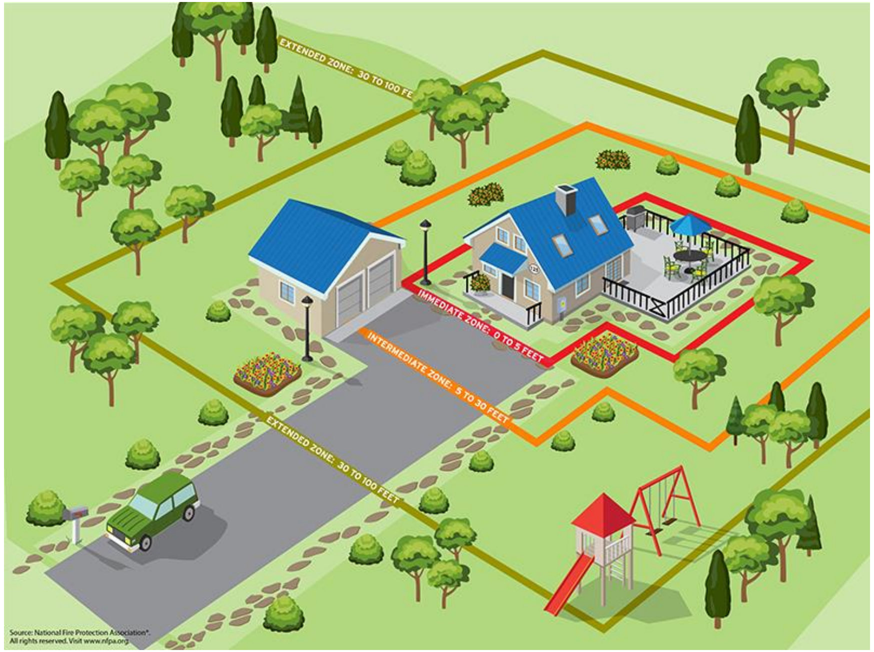
Nathan Trauernicht, UC Davis Fire @ Tamarack Fire

Mitigation Approaches:

- Remove Fuels
- Reduce Fuels
- Relocate Fuels

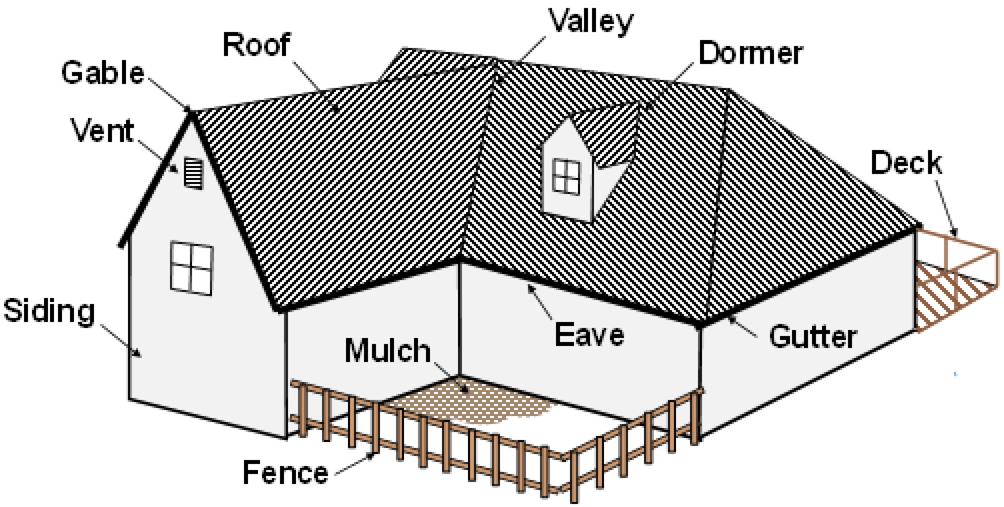
- Fire Resistant Design
- Community Design
- Ignition/Fire Spread Resistant Materials
- Active Systems

Defensible Space



Reduce or clear nearby fuels

Home Hardening



Prevent ignition from small flames/embers

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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

Part 1: 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

Zamanialaei, M., San Martin, D., Theodori, M., Purnomo, D. M. J., Tohidi, A., Lautenberger, C., ... & Gollner, M. (2025). Fire risk to structures in California's Wildland-Urban Interface. *Nature Communications*, *16*(1), 8041.

Part 1: 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

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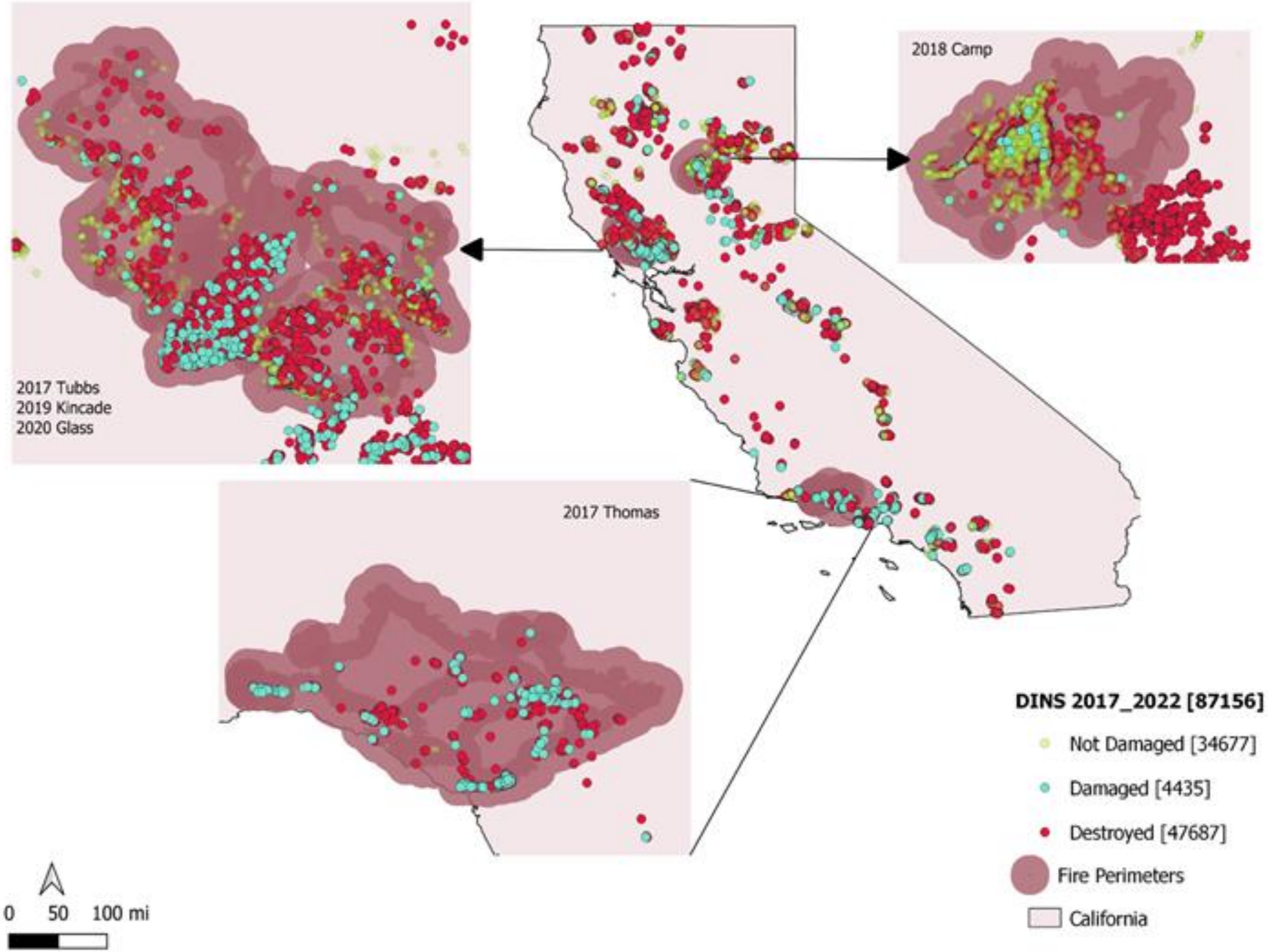
CAL FIRE DINS - Damage INSpection data

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

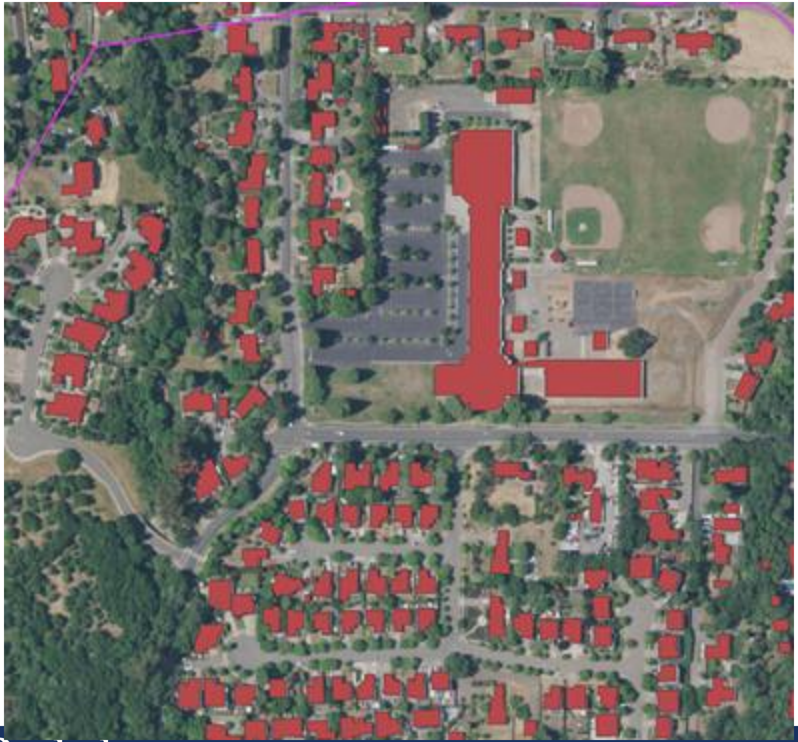
No defensible space

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

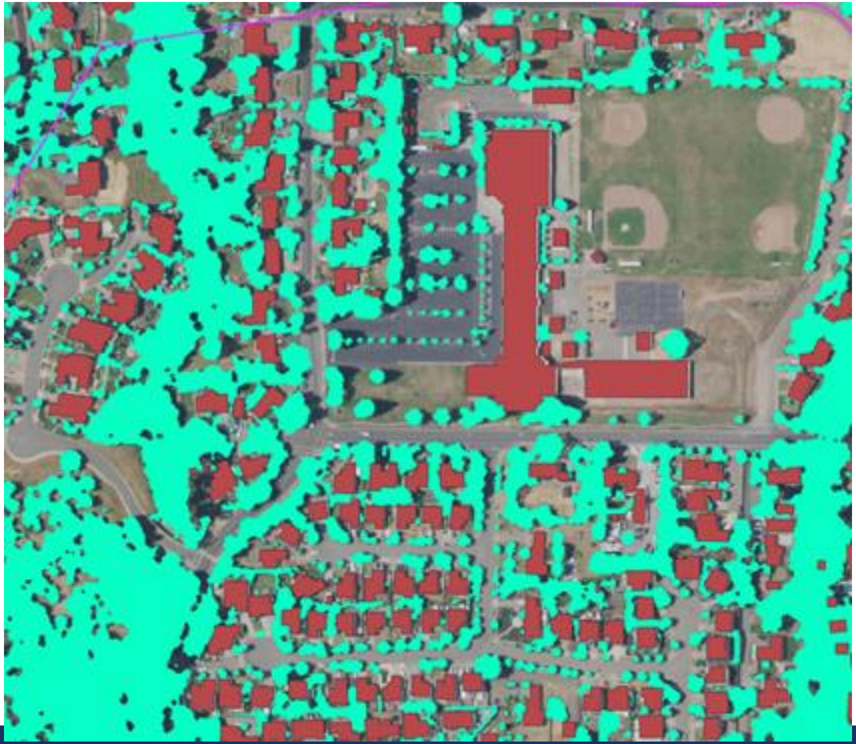
Separation Distance

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

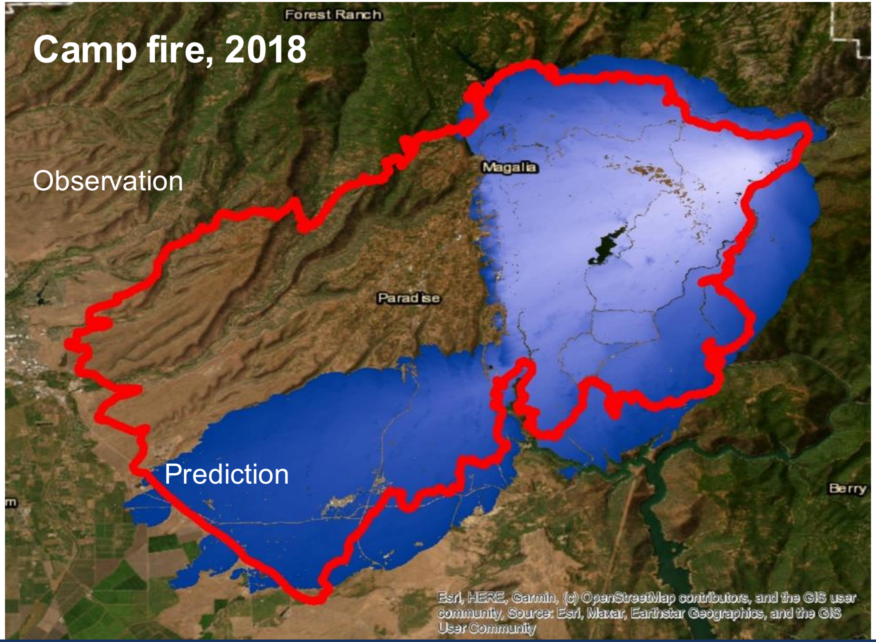
Inputs
- Vegetation
- Weather
- Topography

Models
- Surface fire
- Crown fire
- Ember

Wildfire model: **ELMFIRE**

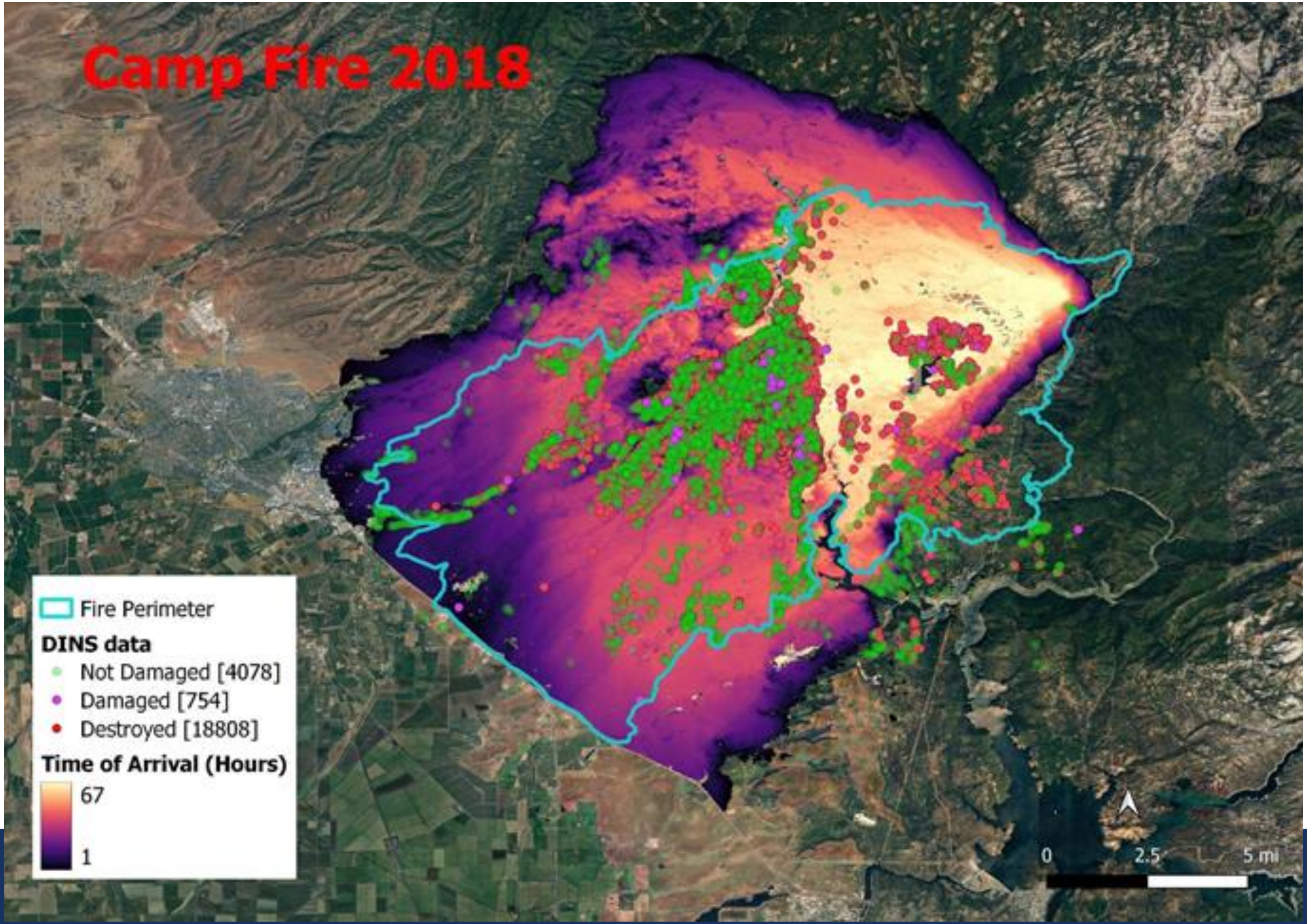
Outputs
- Spread rate
- Ember cast
- Flame length

Underlying physics | Validation data | Input data resolution | Structure-to-structure spread



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

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.

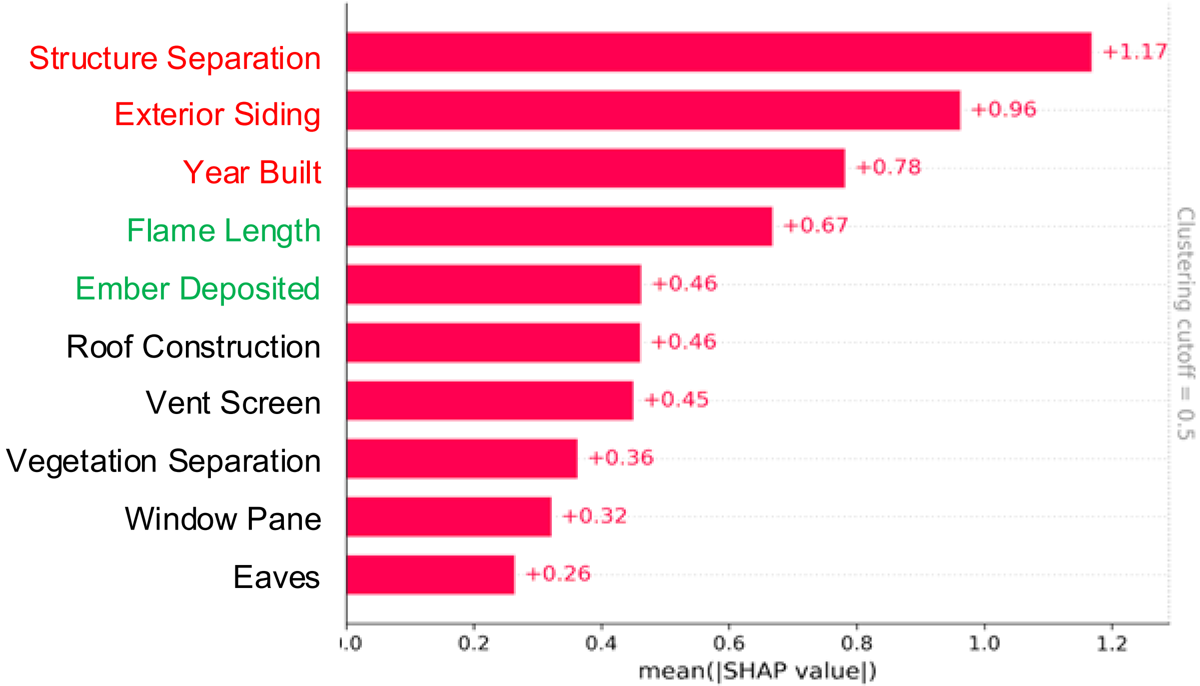
- It is important to first "clean/preprocess" the data and avoid biases, ensuring compatibility and enhancing the overall performance of the models:
  - ***Imputation*** was explored due to the presence of numerous NaN values in the dataset.
  - ***Standardized*** the numerical variables and ***Encoded***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

Extracting Significance of WUI Features

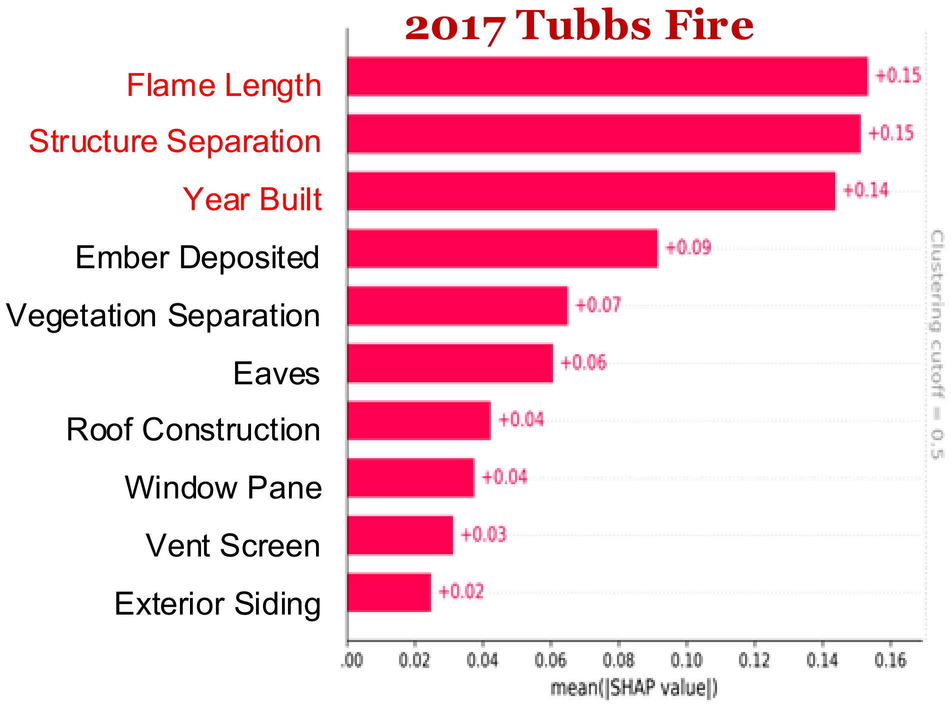
- We explore 4 models and use the "best fit"
  - *Linear/Logistic regression*
  - *Random Forest*
  - *Gradient Boosting/ XGBoost*
  - *CatBoost*
  - **XGBoost showed better results in overall accuracy .**
- We extract feature contributions through SHAP (SHapley Additive exPlanations)
  - Interpreting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

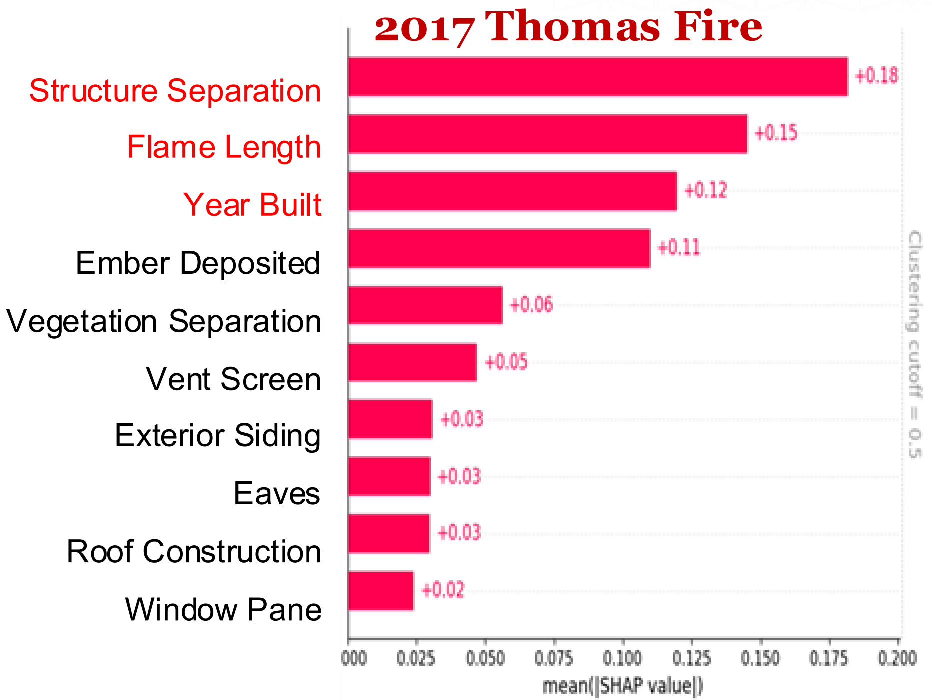
Feature Contributions Using XGBoost and SHAP Values

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



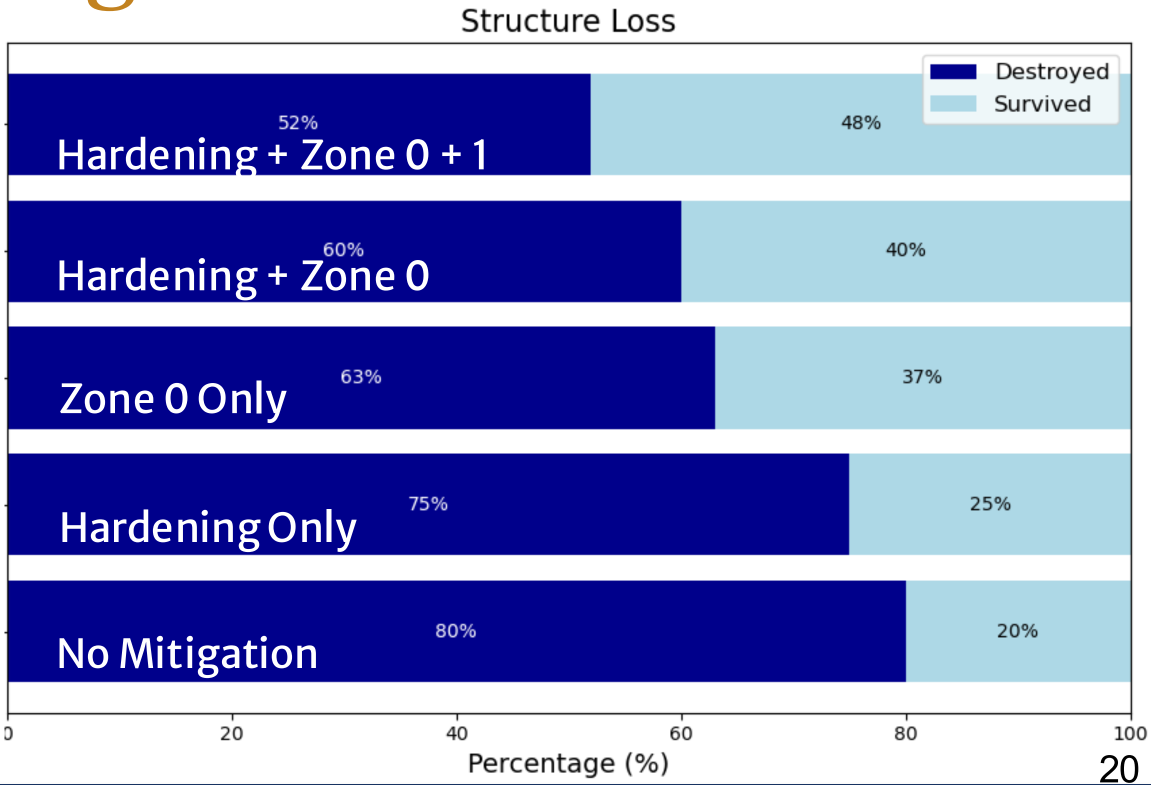
Feature Contributions Using XGBoost and SHAP Values





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



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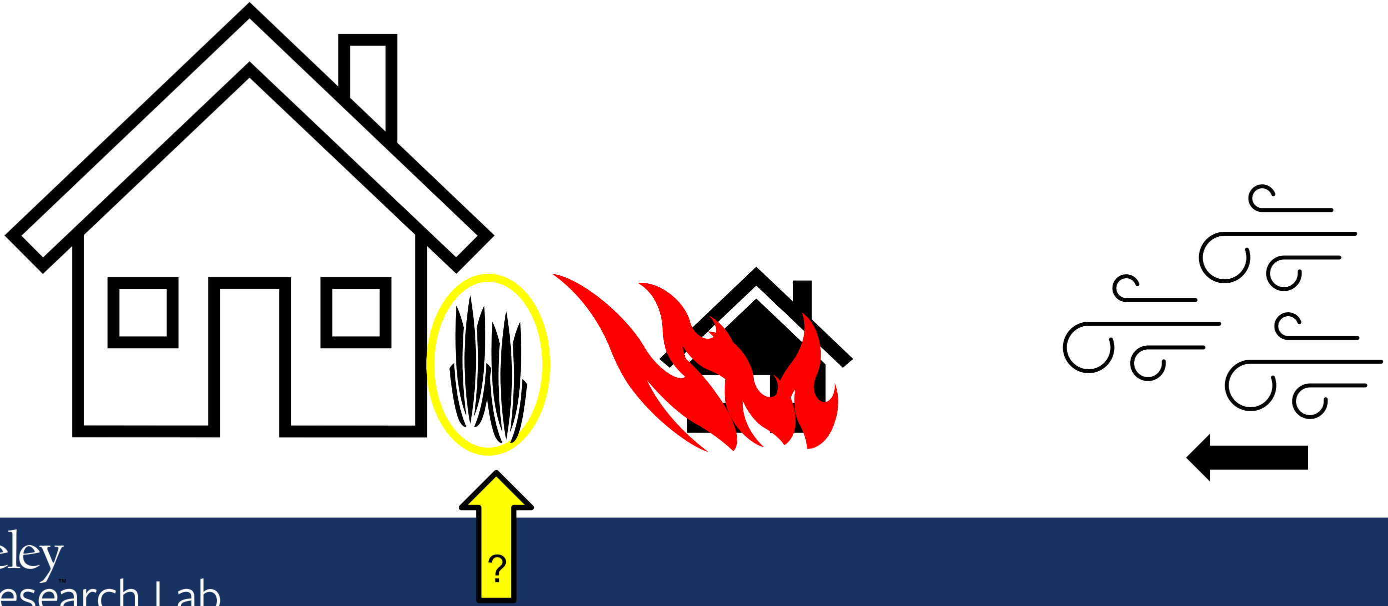
Conclusions

- 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

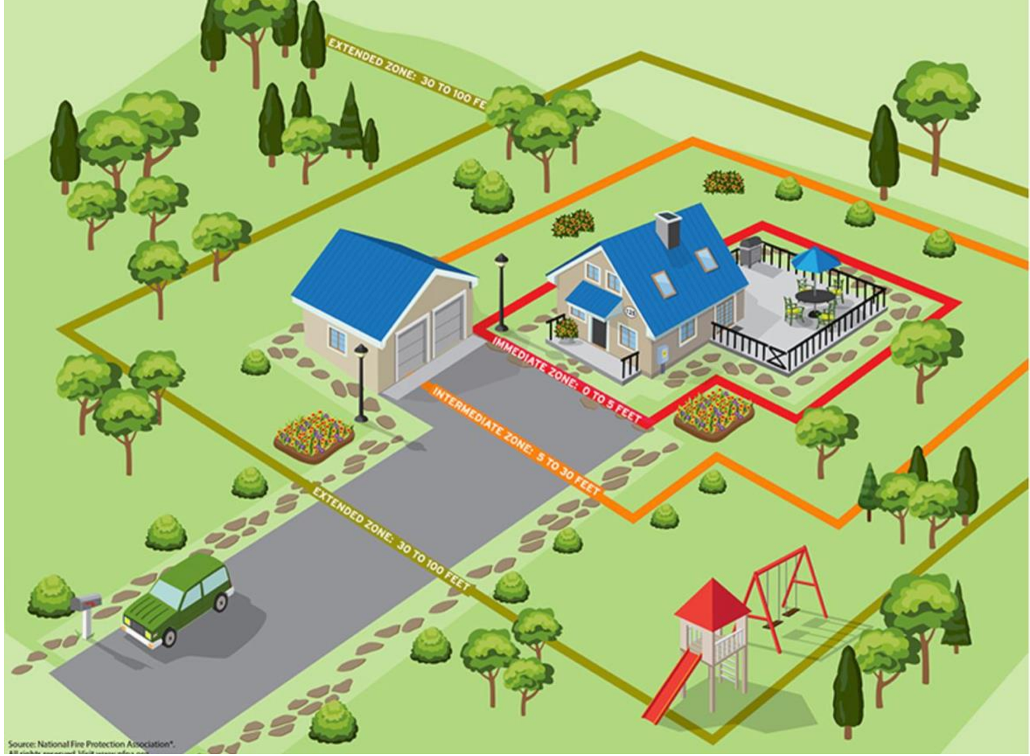
Part II: Zone 0 Vulnerabilities

- QUESTION: Do foundation plantings buffer the structure from the radiant heat of a small burning shed exposed to a 15-mph wind?



Zone 0 Concept

- Zone 0 is an integral part of defensible space, designed to reduce structure ignition by:
  - Preventing small flames from achieving **direct flame contact** (high rates of heating) by moving *ALL* flammables away from walls
  - Reducing **ember ignitions** & accumulation by removing flammable materials near base of walls
  - Removing potential "**pathways**" for flames between neighboring structures or flammable materials to the side of the structure



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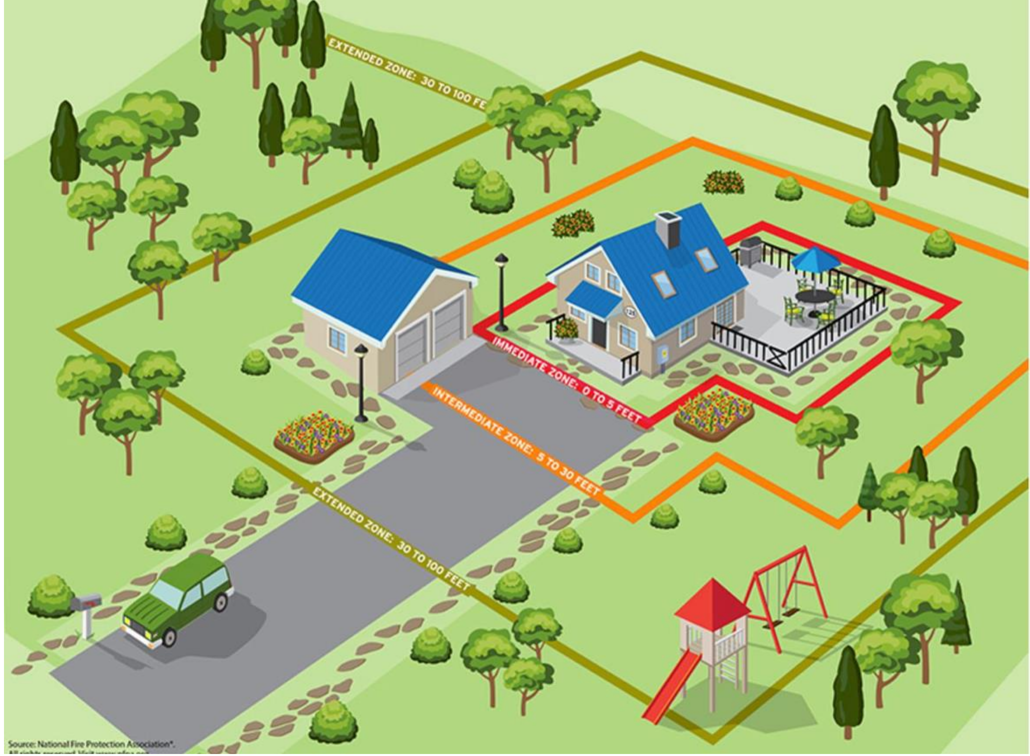


<u>3 types of studies investigating effectiveness</u>

1. Experiments – lab to full scale
2. Post-fire investigations on-the-ground
3. Remote-sensing/statistical post-event investigation

Motivation

- **Defensible Space Focus on Zone 0 (0–5 ft)** around structures is a critical question in wildfire risk mitigation following major building loss in wildfires and passage of AB 3074 (2020).
    - Prior studies confirm: *cleared Zone 0 reduces fuels and ignition risk*.

- **City of Berkeley** asked for assistance in July 2025 from UC Berkeley and UCANR following the passage of their own Zone 0 regulation (EMBER, 2025)

- **Knowledge gap:** the effect of *partially vegetated* Zone 0 and *plant moisture conditions* on heat flux and ignition is poorly quantified.
    - *Aim*: provide **experimental evidence** to inform defensible-space policy and homeowner guidance.

Experiment Design and Key Points

- **Three treatments, four replicates:**
  - No plants
  - Hydrated, healthy or “wet” plants placed in front of the wall
  - Stressed “dry” plants placed in front of the wall (still visibly green and pliable)

- **Fuel** was dried wooden pallets (4’ tall x 8’ wide, 4’ deep), with 15 mph winds, 10 feet apart from a 16-foot-wide instrumented, fireproof target wall with 18” eaves.

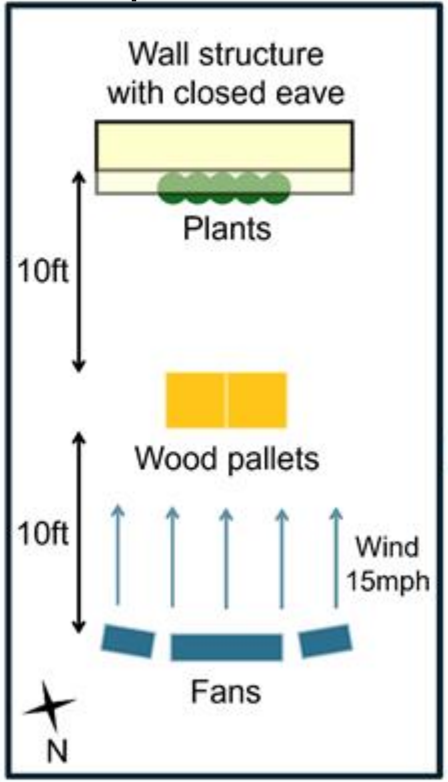
- Flame lengths approached but did not sustain contact with vegetation or the wall.

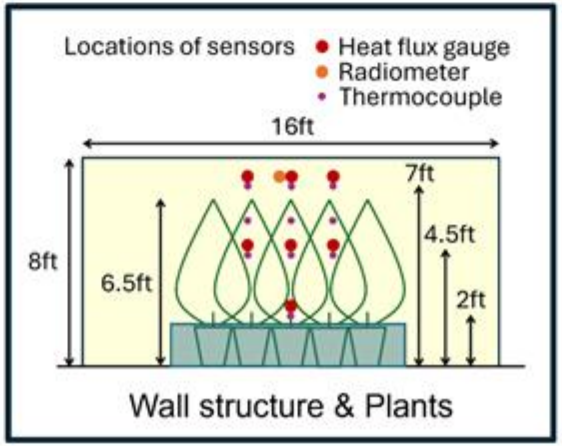
- **Average sustained heat fluxes** to the wall ranged from 20 - 40 kW/m2 for 3-4 minutes.
  - These heat fluxes are within the range of those observed from a fully involved structure about 10’ apart without wind. [Gorham et al. 2025]

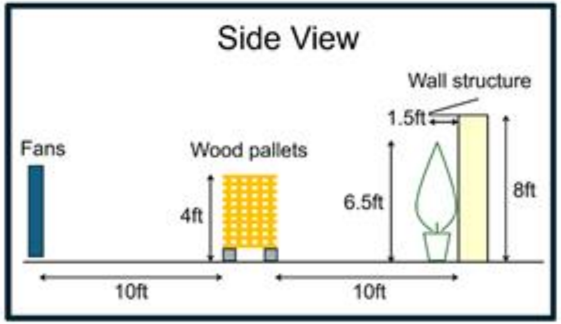
Gorham, Daniel J., Joseph M. Willi, and Gavin P. Horn. "Residential Exterior Wall Reaction to Post-Flashover Compartment Fires." *Fire and Materials* (2025).

Experimental Design

We used a non-flammable structure to observe heat flux at the wall to avoid rebuilding the structure for each replicate and to have a quantitative measure of heat exposure.







Ornamental Vegetation

- **Species:** *Pittosporum tenuifolium* ("Kohuhu")
  - Common **foundation and/or hedge shrubs** in residential landscaping.
  - Broad, flat leaves; open architecture
  - Characterized as relatively inflammable when compared to other New Zealand natives (Sultana et al. 2025)
- **Healthy / well-hydrated plants:**
  - ~168% live fuel moisture content (~3 parts water to 2 parts dry material)
  - Irrigated frequently (by nursery) leading up to testing and each morning of testing (by team, to container capacity).
  - No accumulation of dead leaves or twigs.
- **Stressed "dry" plants:**
  - ~65% live fuel moisture content (~1 part water to 2 parts dry material).
  - No irrigation in the 3 weeks leading up to testing.
  - Leaf curling visible, but leaves still green and pliable.
  - No accumulation of dead leaves or twigs.
- Each plant placed in **sealed non-combustible box** to isolate effects and prevent ember ignition at base.

Sultana, Niger, Cate Macinnis-Ng, Sarah J. Richardson, Md Azharul Alam, Xinglei Cui, Sarah V. Wyse, Daniel C. Laughlin, Katherine Seward, George L.W. Perry, and Timothy J. Curran. "Testing Key Tenets of Pyro-Ecophysiology: Indicators of Drought Response in Relation to Shoot Flammability. *Annals of Botany* (2025).

Test Comparison

Stressed "dry" plant test

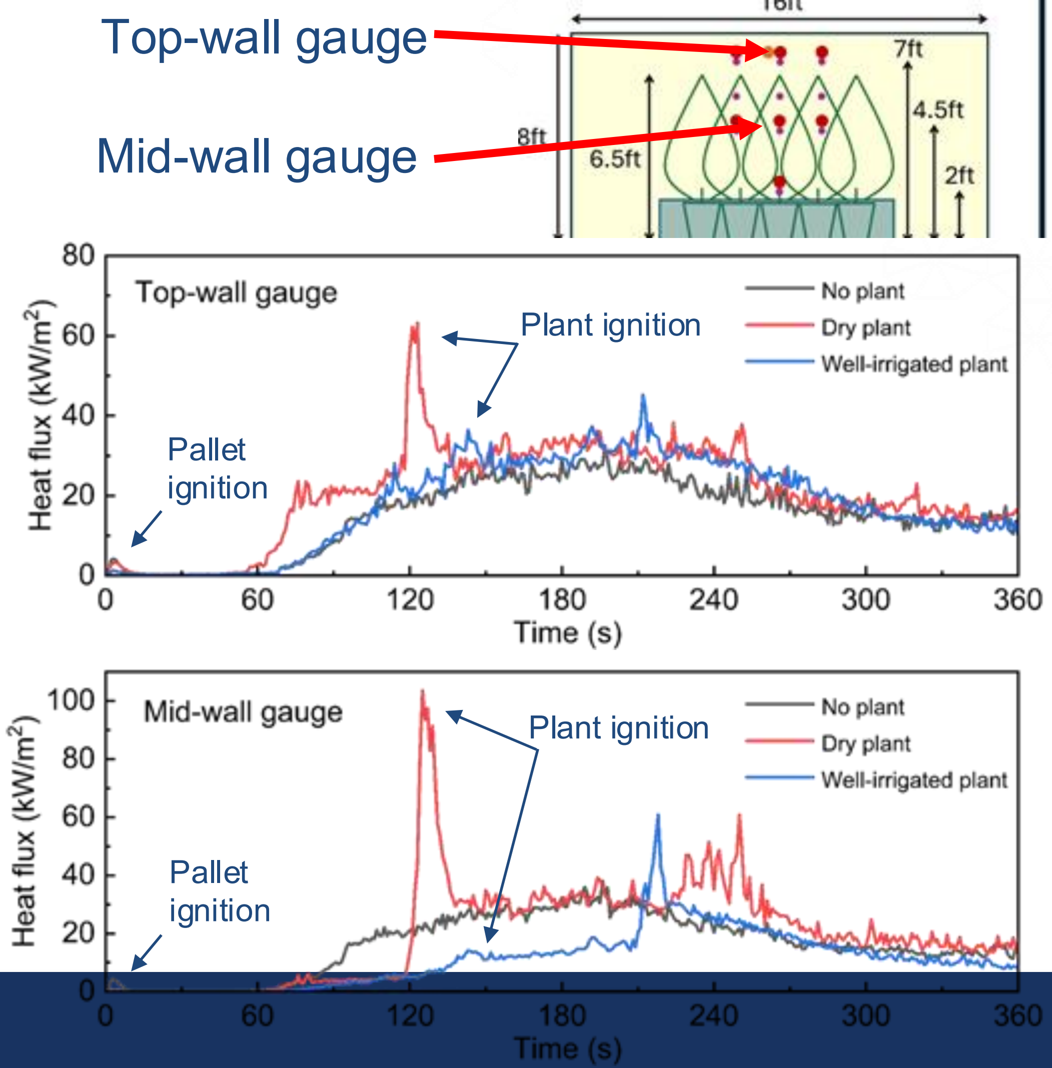
- Plant ignition at 2 mins following after pallet ignition
- Re-ignition a 4 mins

Well-irrigated, "wet" plant test

- Plant ignition at 2 mins following after pallet ignition
- Flame spread over next 2 mins

Heat Flux Measurements

- Top gauge provides the eave heat flux. This is the most common location for ignition in structure to structure spread and is not influenced by the plants before ignition
- At the top/eave little difference is observed between a bare wall and a wall with tall plants
- At the center height of the plants **some attenuation** of radiation is observed early in tests compared to a baseline test, however that is **quickly overcome following ignition of the vegetation**



Take home points

- In our study, we found that any potential buffering by a healthy, well-hydrated woody shrub 5 feet tall and adjacent to structures was 1) temporary and 2) overcome by accumulated heat exposure and ignition of the adjacent plant.

- Plants in either a healthy, well-hydrated, or a stressed condition were observed to ignite at 15 mph wind speeds with fire exposures mimicking an adjacent burning structure in less than 2 minutes

Take home points- Plant conditions, age factor

- The healthy plant tested in this experiment was in the best condition possible
- Plants were young, vigorous, and thin.
- No surface fuels or dead materials
- An older maintained plant would still have vulnerable places for embers or flame contact

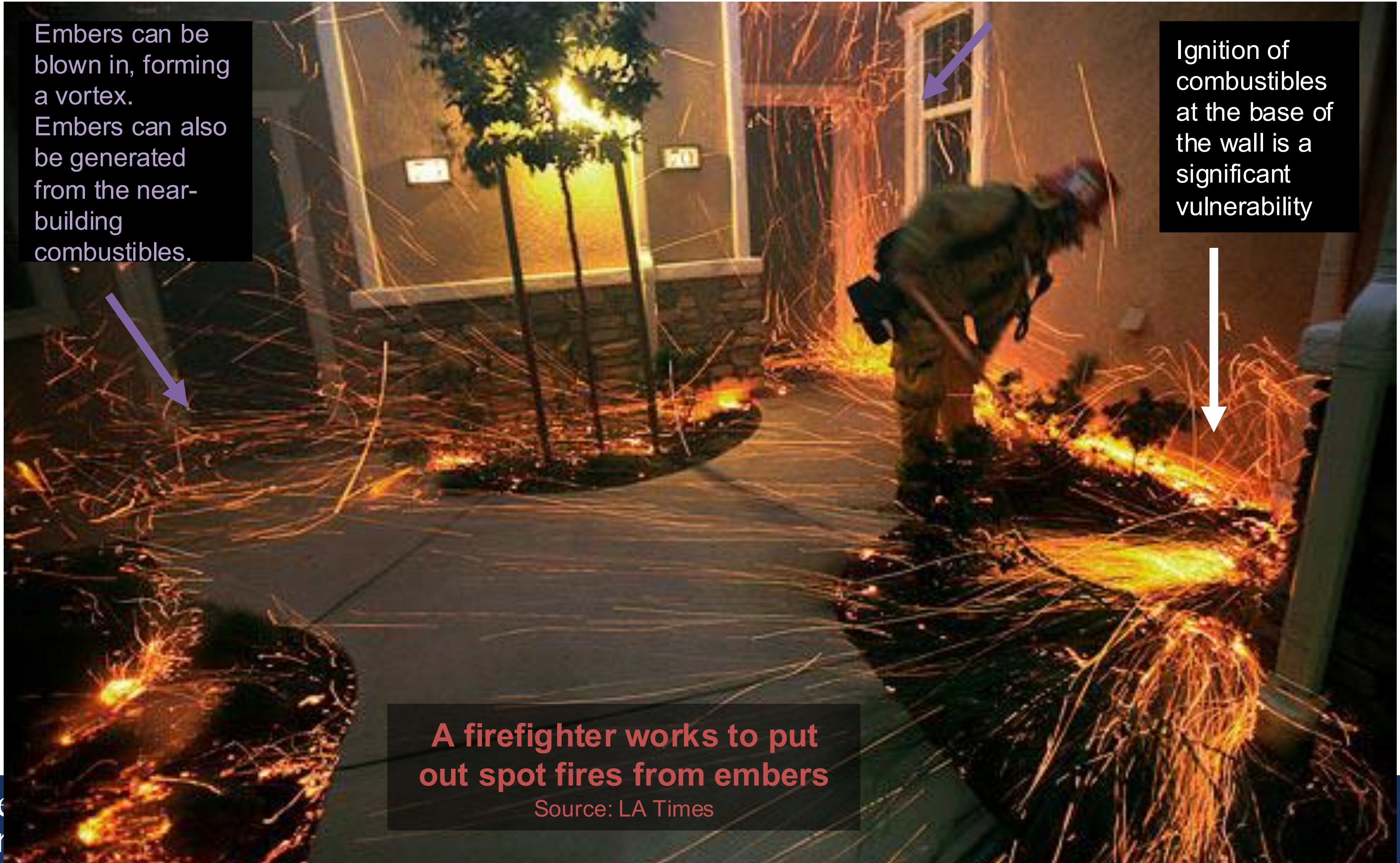
Photos Jessie Godfrey

Take home points- Plant flammability in relation to a building

- We need a standard testing protocol for plants in Zone 0.

- What exposure scenarios should be tested?
    - Under what **weather** conditions (humidity, temperature, wind velocity)?
    - For what **types of buildings** (siding type, location of and type of window, age of building, level of maintenance, etc.)?
    - What **fire exposure** scenarios (radiant heat, direct flame contact, embers)?

- California does not have a testing facility to evaluate plants, building materials, and fire exposures

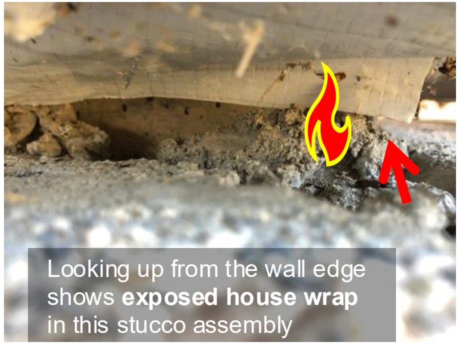


A firefighter works to put out spot fires from embers
Source: LA Times

Base of wall vulnerabilities

Best scenario: a 6-inch elevated perimeter foundation, with metal base flashing, and noncombustible cladding.

Common vulnerabilities



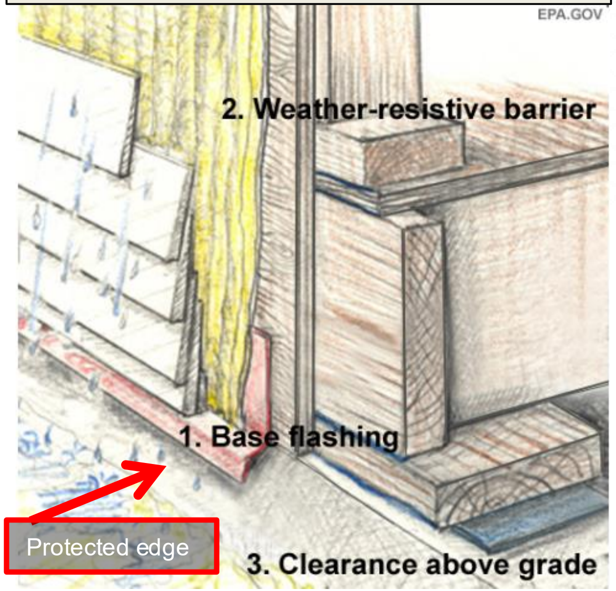
Stucco assembly concerns:

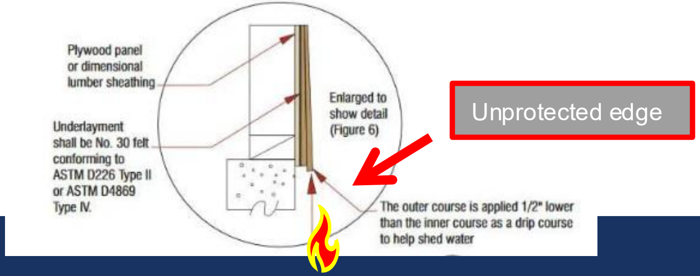
- No base flashing present = unprotected edge
- Combustible house wrap is exposed at the base of the wall,
- Fire may get behind the stucco

Wood cladding concerns:

- The baseplate is wood
- Unprotected wood shingle edge
- Ignition of the wood siding and wood baseplate may occur

Wall assembly details





Under eave-vulnerabilities

Issues:

- Heat and flames can become trapped under the eave.
- Embers can be caught.
- Exposed rafters and open eave construction commonly have gaps and openings where embers or flames can penetrate.

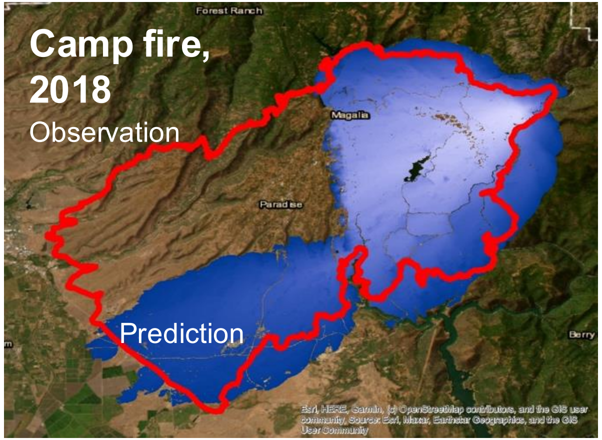
Solutions:

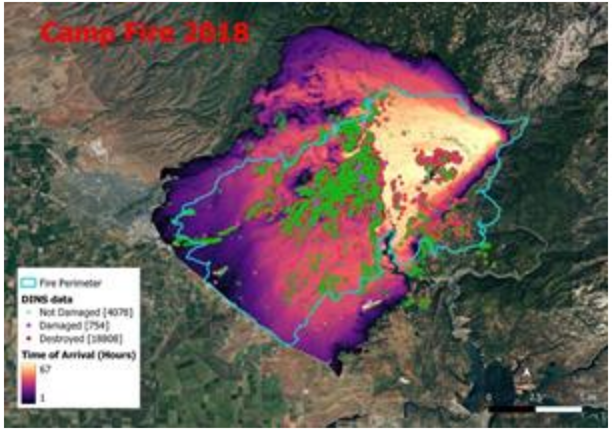
- Use ignition-resistant or noncombustible construction materials to "box-in" the eave.
- Upgrade vents to resist flames and embers
- Reduce near-to-building combustibles to prevent flames in this area.

Photos: Steve Quarles

What’s coming next?

- Fire modeling tools
  - WUI Structures
  - Risk assessment
  - Planning





- More test results!
  - Exposure conditions
  - What components fail?
  - Can we design more tests to certify products?
    - Windows, vents, eaves, etc.
    - Sprinklers, coatings/retardants

Sections

UC Berkeley News

Campus & community, Research, Science & environment, Technology & engineering

Wildfire season is here. UC Berkeley scholars are helping Bay Area communities prepare.

UC Berkeley Professor Michael Gollner and his students are applying advanced wildfire simulation tools to help neighborhoods understand their specific wildfire risks.

By Kara Manke

7tv

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https://news.berkeley.edu/2025/07/09/wildfire-season-is-here-uc-berkeley-scholars-are-helping-bay-area-communities-prepare/

Acknowledgements and Thank Yous!

Zone 0 Tests conducted at the Richmond Fire Training Center, with support from the Berkeley Fire Department and led by the UC Berkeley and UC ANR

Gordon and Betty Moore Foundation

CAL FIRE

UC ANR

Berkeley Fire Research Lab
Mechanical Engineering