Isolating the Primary Drivers of Fire Risk to Structures in WUI regions in California

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NSF
CALIFORNIA DEPARTMENT OF FORESTRY & FIRE PROTECTION CAL FIRE SINCE 1885

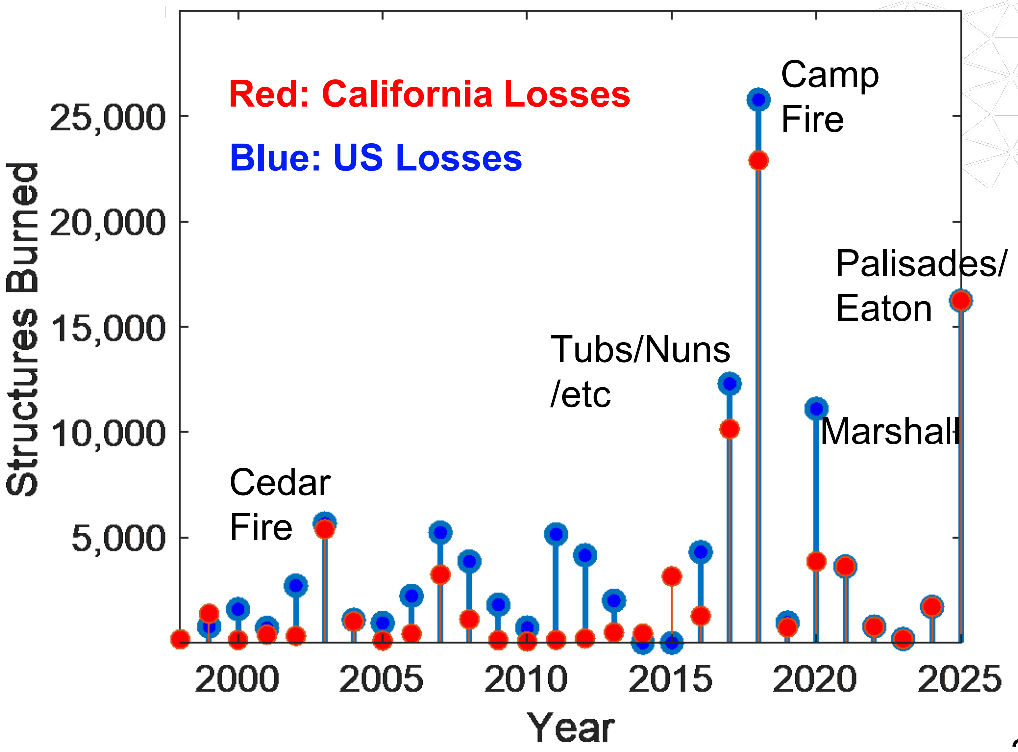
Primary Project Support from Forest Health Grant 8GG21815

Berkeley Fire Research Lab

Photo Credit: Melia Robbinson

Wildland-Urban Interface (WUI) Fires

Tubbs Fire / Melia Robbinson



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


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

Pathways to Fire Spread (Exposure)

Radiation

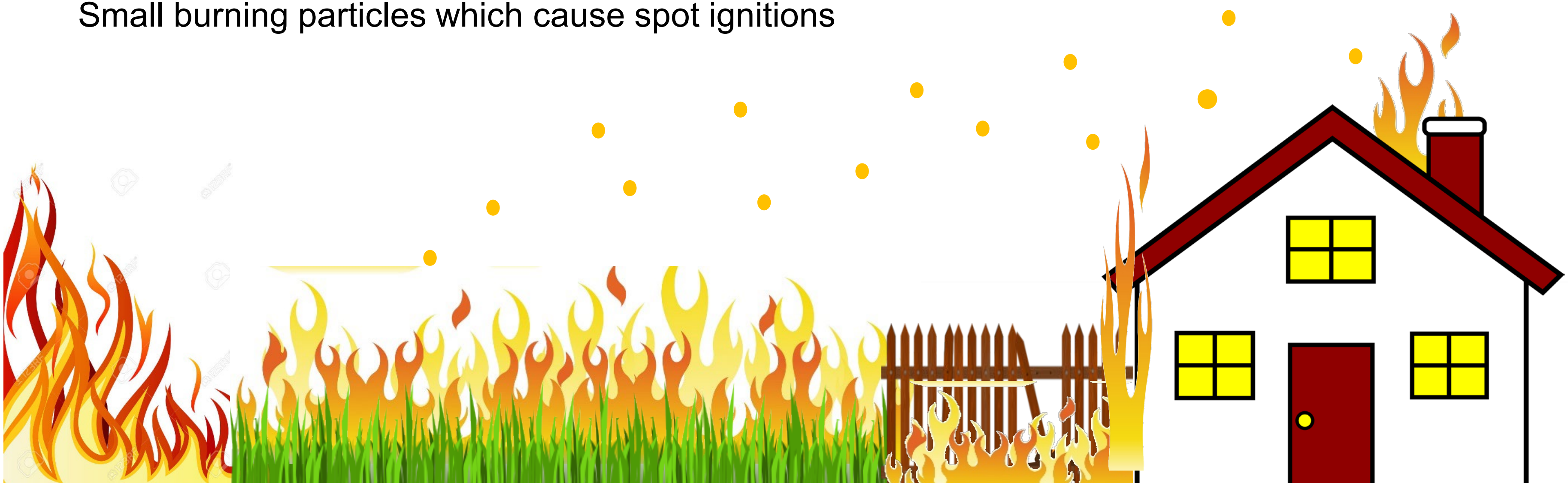
Originally thought to be responsible for most/all ignitions

Direct Flame Contact

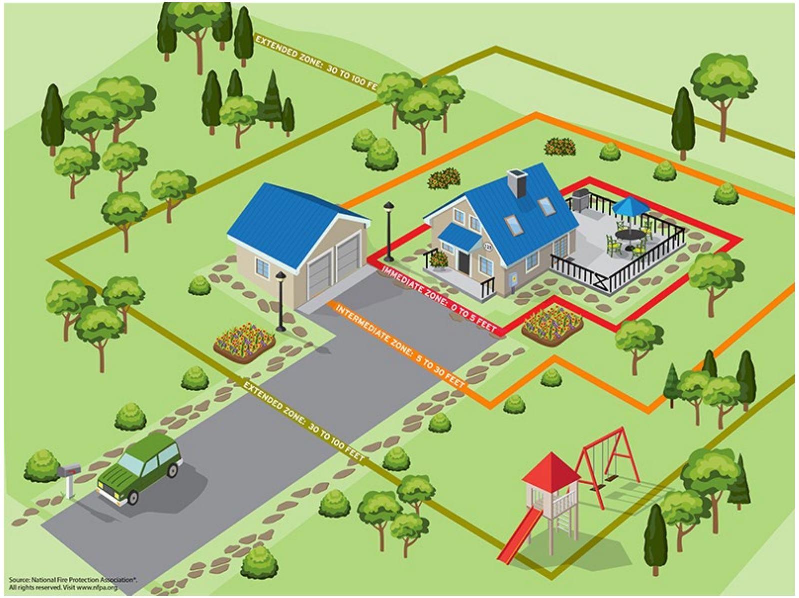
Smaller flames from nearby sources

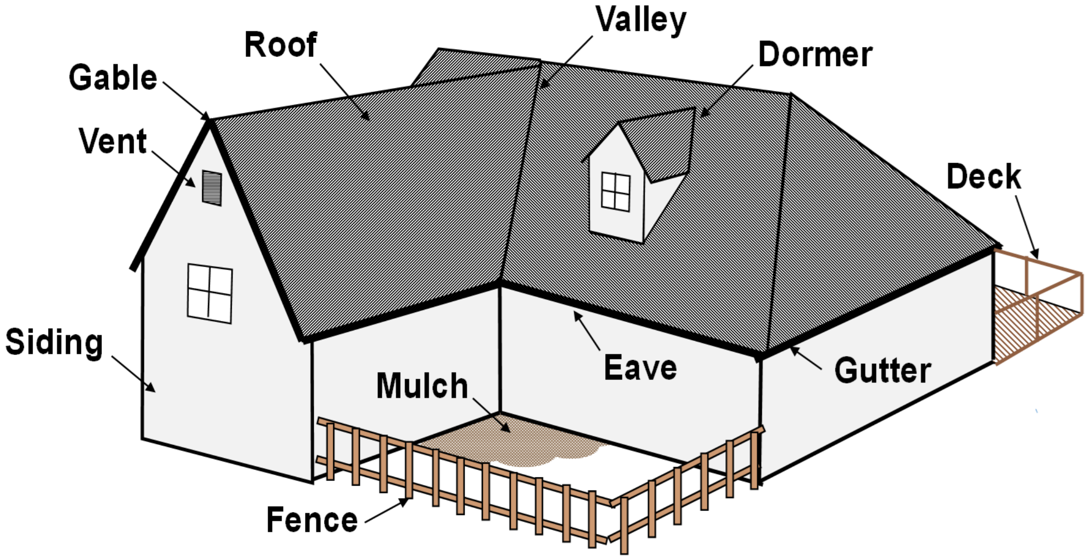
Embers or Firebrands

Small burning particles which cause spot ignitions



Defensible Space and Hardening





Hakes, Raquel SP, et al.." *Fire technology* 53 (2017): 475-515.

Fire Modeling Methodology

Current Limitations

No inclusion of exposure from neighboring structures

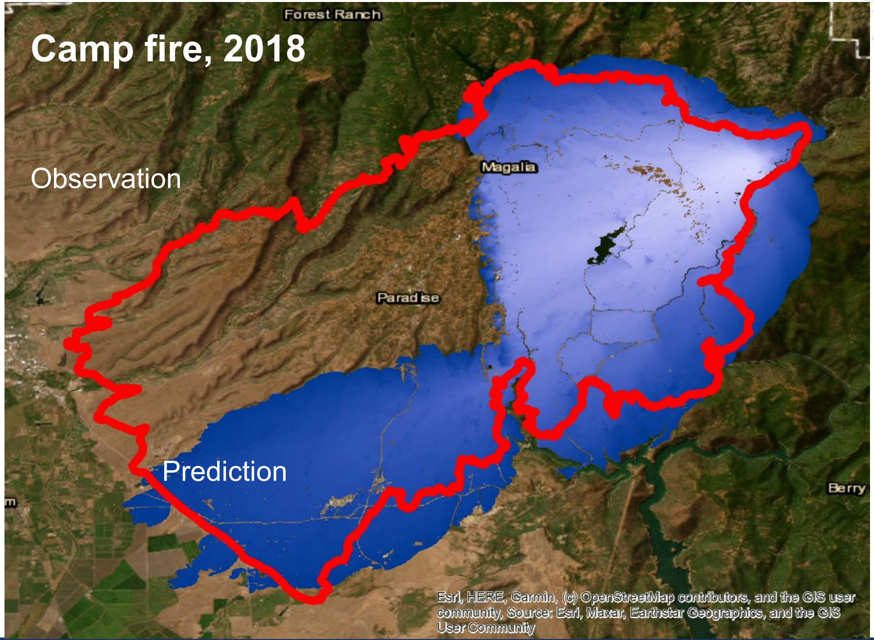
Underlying physics | Validation data | Input data resolution | Structure-to-structure spread

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

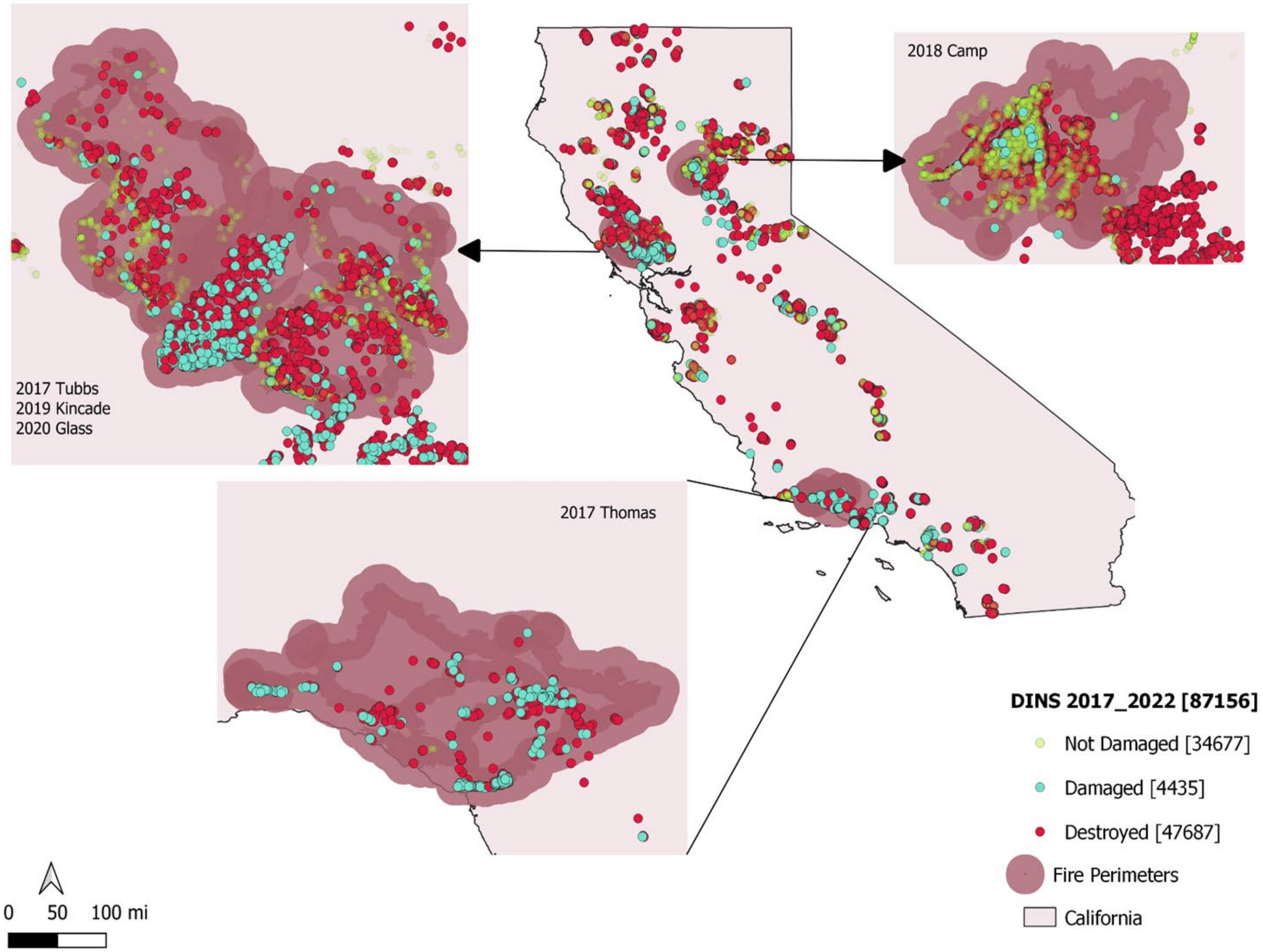
Part 1: Data- Driven WUI Risk to Structures

- 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

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

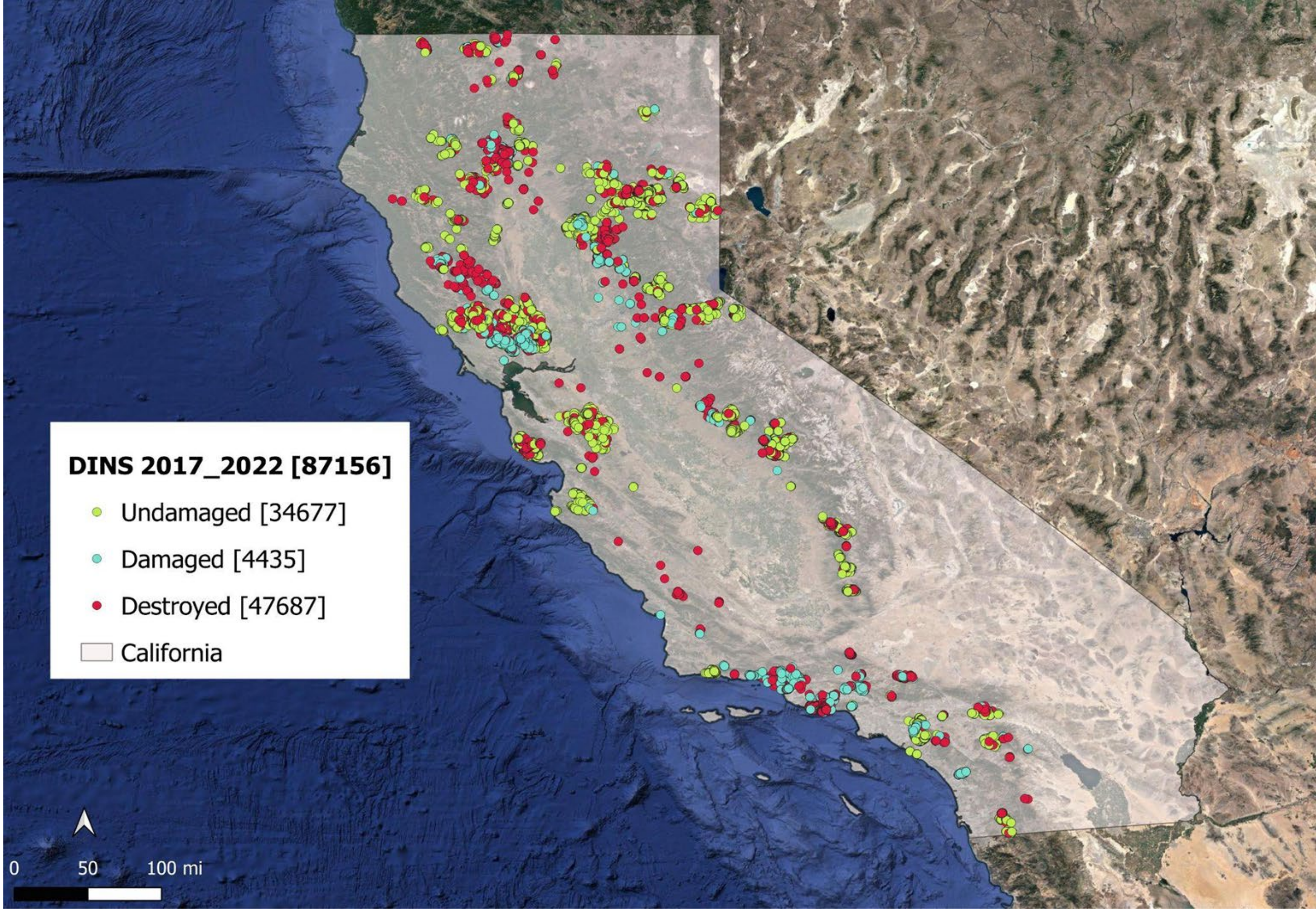

2017 Tubbs
2019 Kincade
2020 Glass
2018 Camp
2017 Thomas
DINS 2017_2022 [87156]
Not Damaged [34677]
Damaged [4435]
Destroyed [47687]
Fire Perimeters
California
0 50 100 mi

Combining and processing datasets

Data type	Category	Details
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**

CAL FIRE DINS - Damage INSpection data

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



Defensible Space Assessment

Zone 0: First five feet

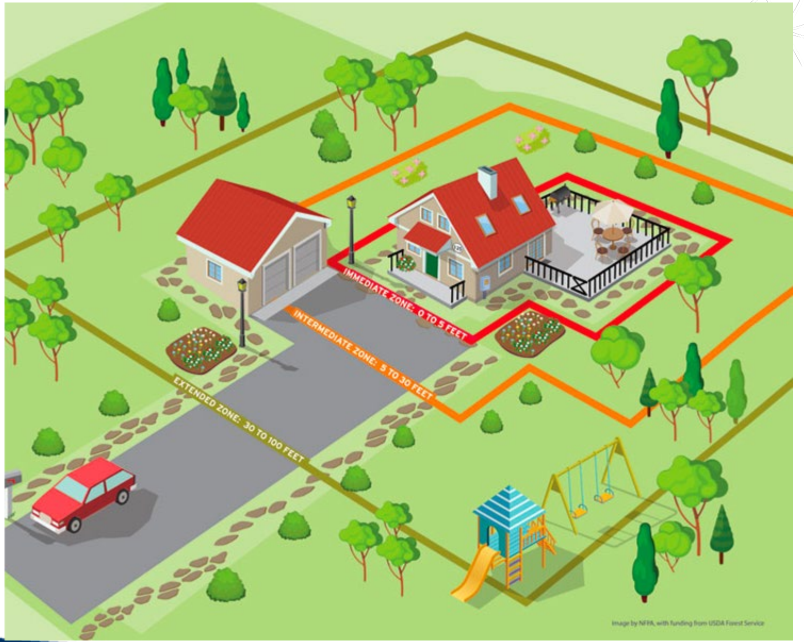
Zone 1:Within 30 feet

Zone 2: Within 100 feet

No defensible space

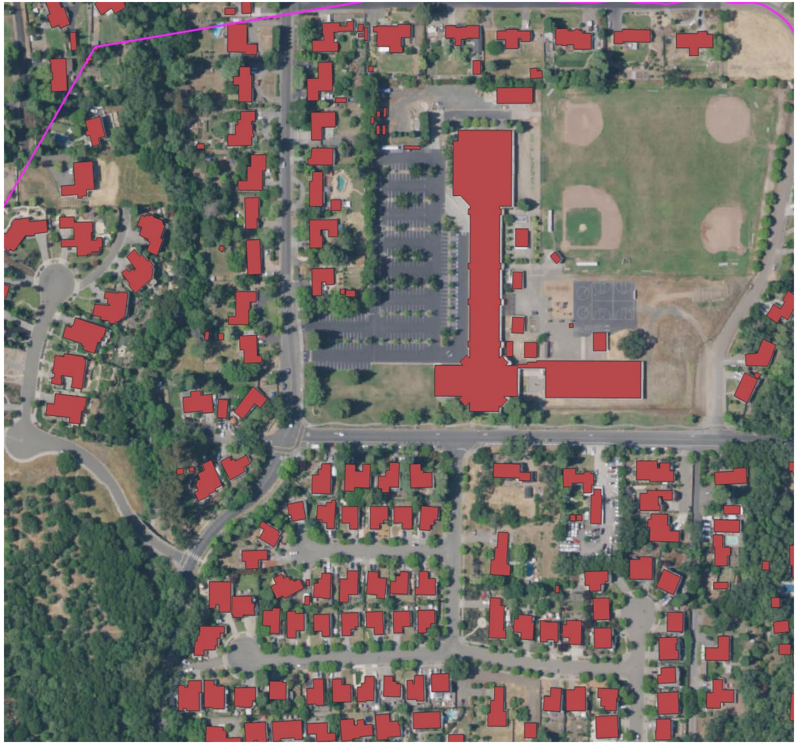
Zone 0 and 1 clear

Defensible space is the buffer between a structure and the surrounding area.



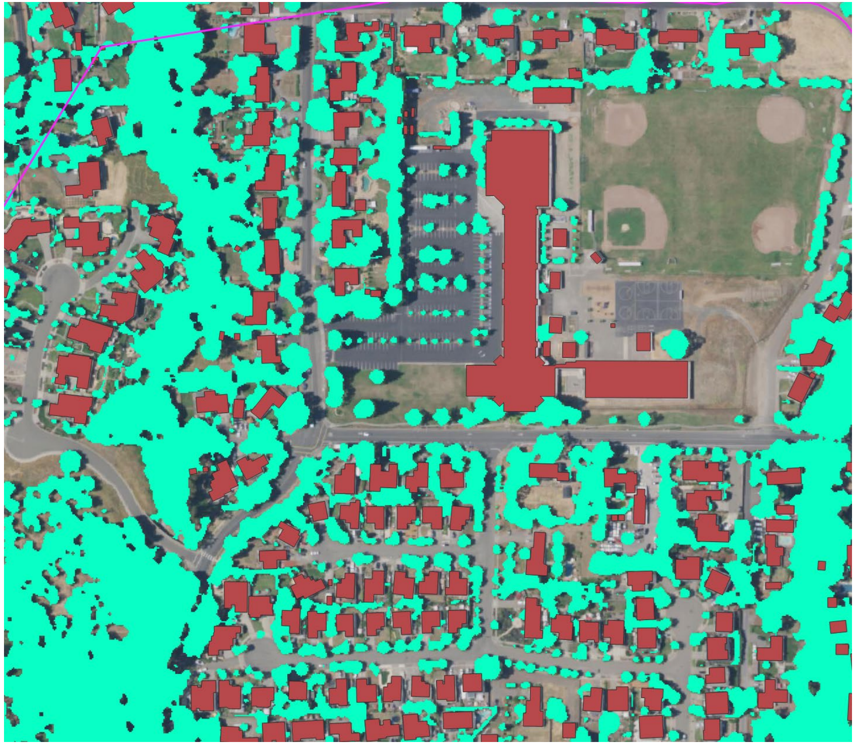
Separation Distance

Structure Separation Distance + Unburned structures



MS Building Footprints - script analysis

Vegetation Separation Distance



LIDAR (Sonoma County)

WUI fire spread model: HAMADA + ELMFIRE

K_d: downwind reach of fire [m]

K_s: sidewind reach of fire [m]

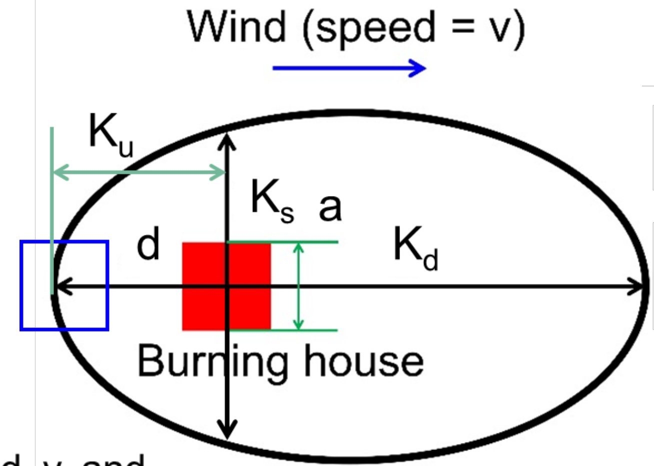
K_u: upwind reach of fire [m]

v: wind speed [m/s]

a: house size [m]

d: separation distance [m]

T_d, T_s, and T_u: are functions of a, d, v, and fire resistant buildings



$$K_d = \left[\frac{(a+d)}{T_d}\right](t)$$

$$K_s = \left(\frac{a}{2} + d\right) + \left\{\left[\frac{(a+d)}{T_s}\right](t - T_s)\right\}$$

$$K_u = \left(\frac{a}{2} + d\right) + \left\{\left[\frac{(a+d)}{T_u}\right](t - T_u)\right\}$$

T_d: downwind propagation time [min]

T_s: sidewind propagation time [min]

T_u: upwind propagation time [min]

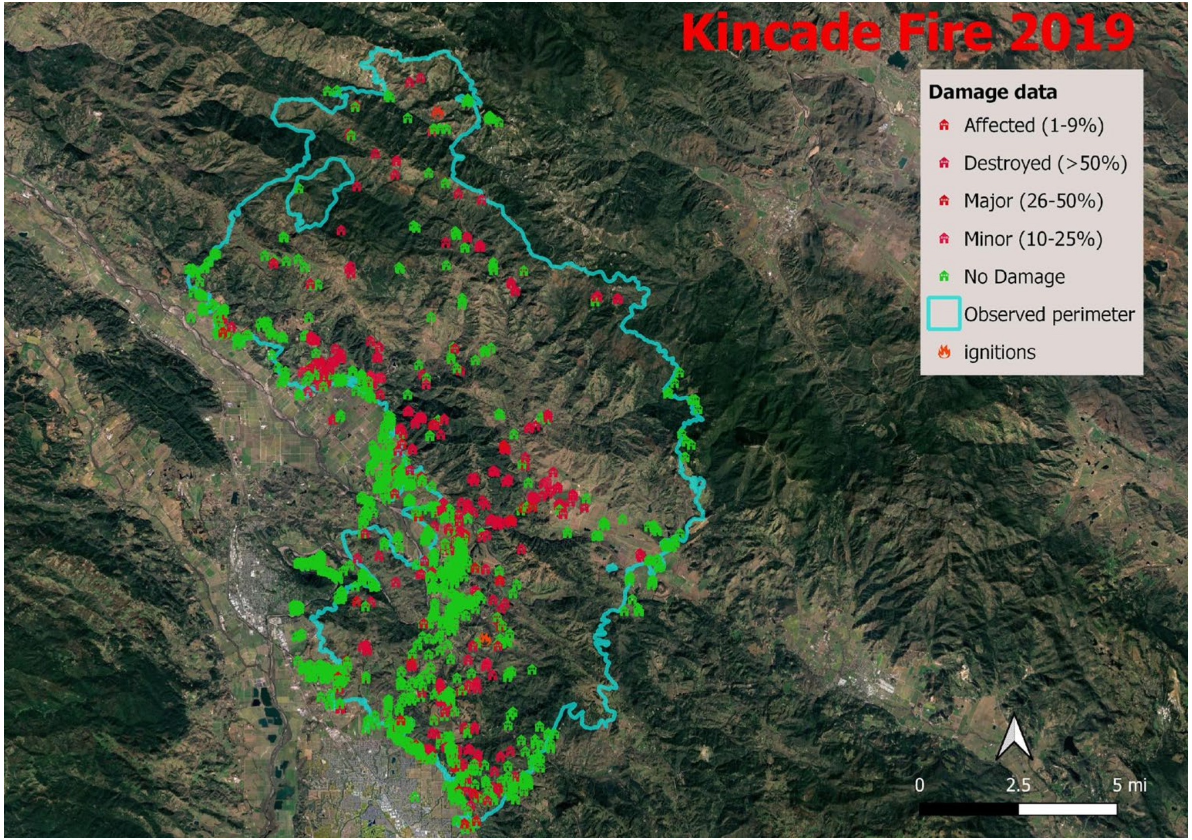
t: characteristic time [min] e.g., 120 min

Hamada, M. (1951). On the Rate of Fire Spread. Study of Disasters, 1.

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

ELMFIRE

Fire Reconstruction: Kincade Fire 2019



Kincade Fire, 2019

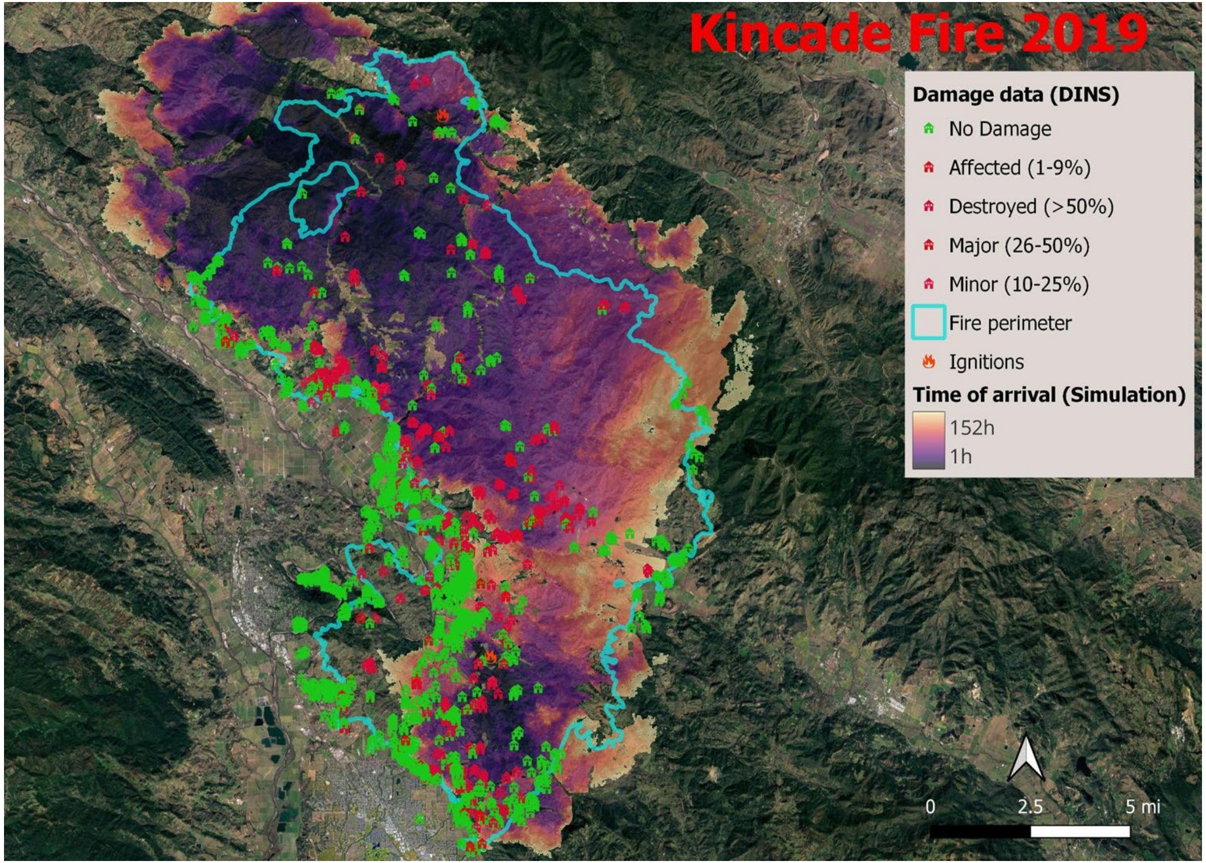
DINS Losses +
Observed fire perimeter:
GeoMac-NIFC

Fire Reconstruction: Kincade Fire 2019

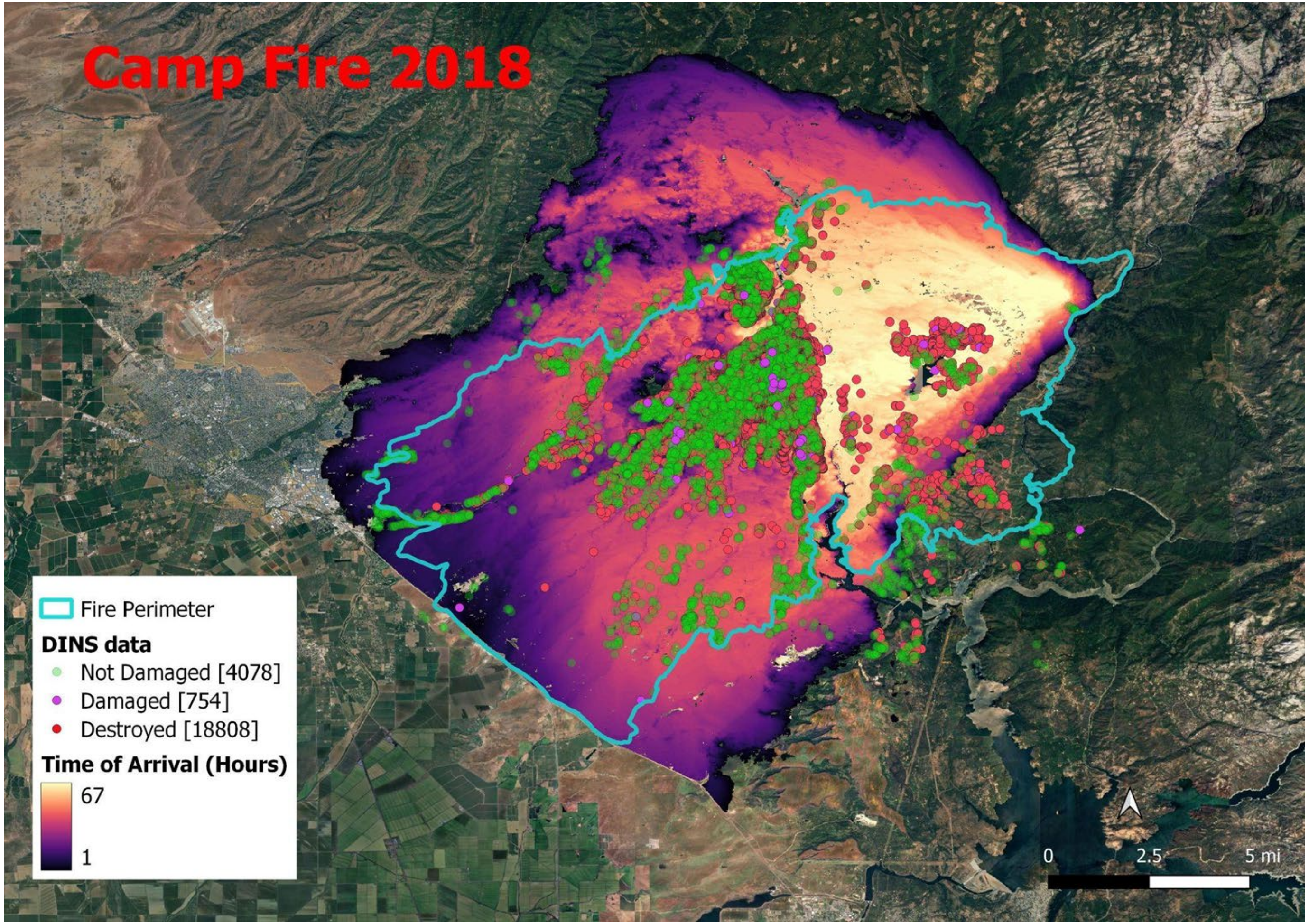
DINS Losses +
Observed fire perimeter:
GeoMac-NIFC

+
SIMULATION:
ELMFIRE + HAMADA

=
Flame Length
Ember



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.

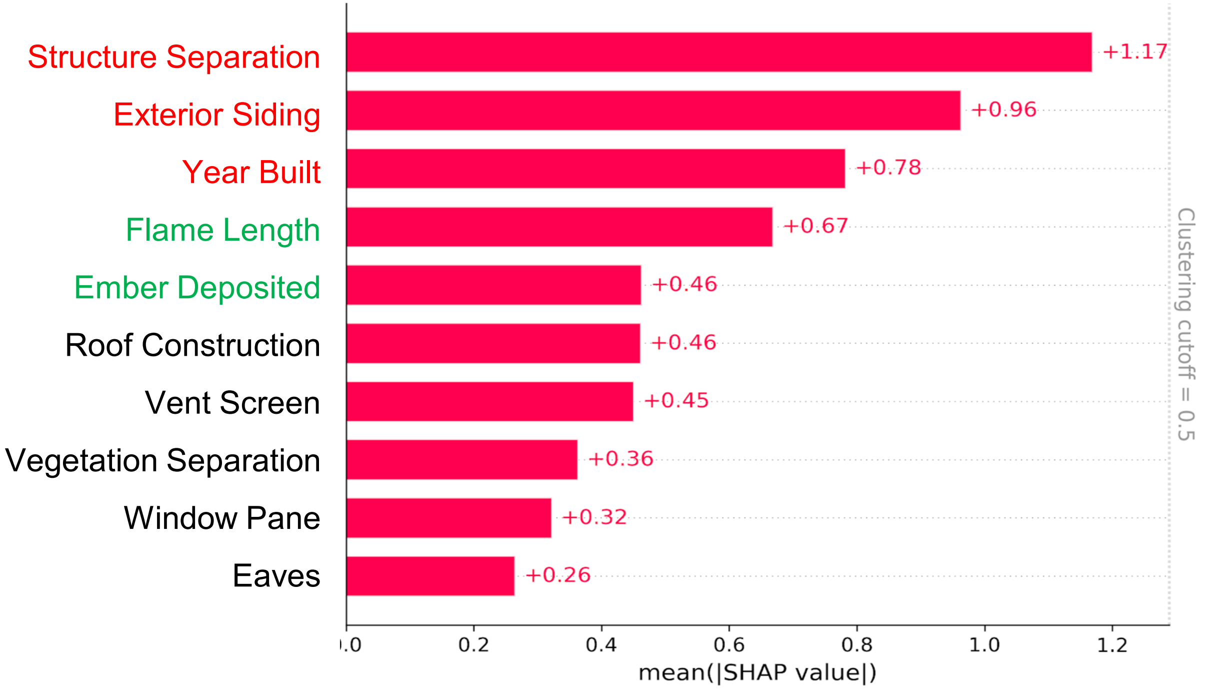
- It is important to first "clean/preprocess" the data and avoid biases, ensuring compatibility and enhancing the overall performance of the models:
  - ***Imputation*** was explored due to the presence of numerous NaN values in the dataset.
  - ***Standardized*** the numerical variables and ***Encoded***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

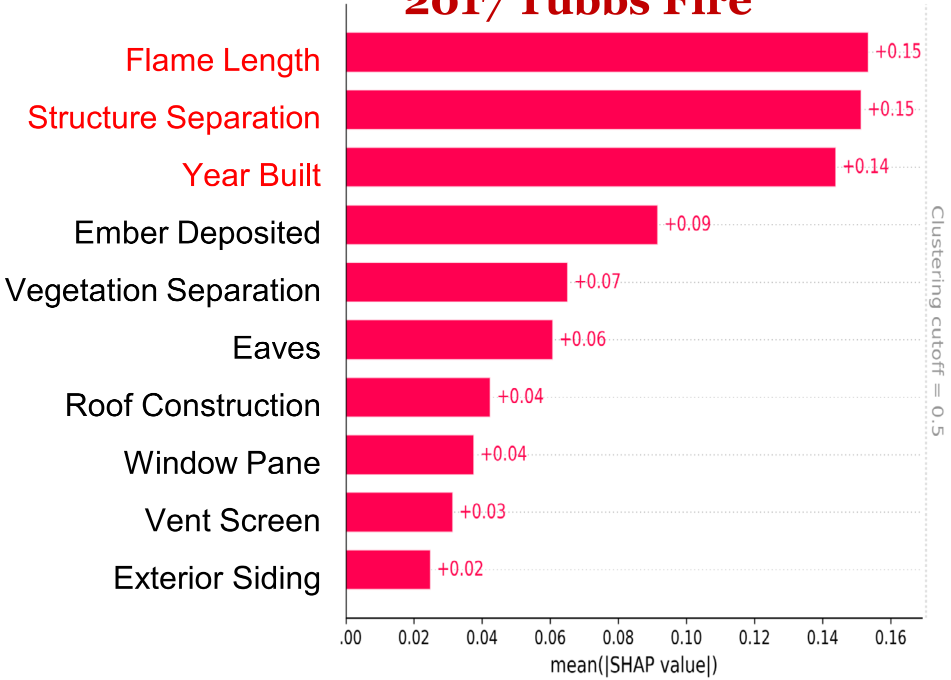
Stacked WUI data: 5 Past fires (2017-2022)



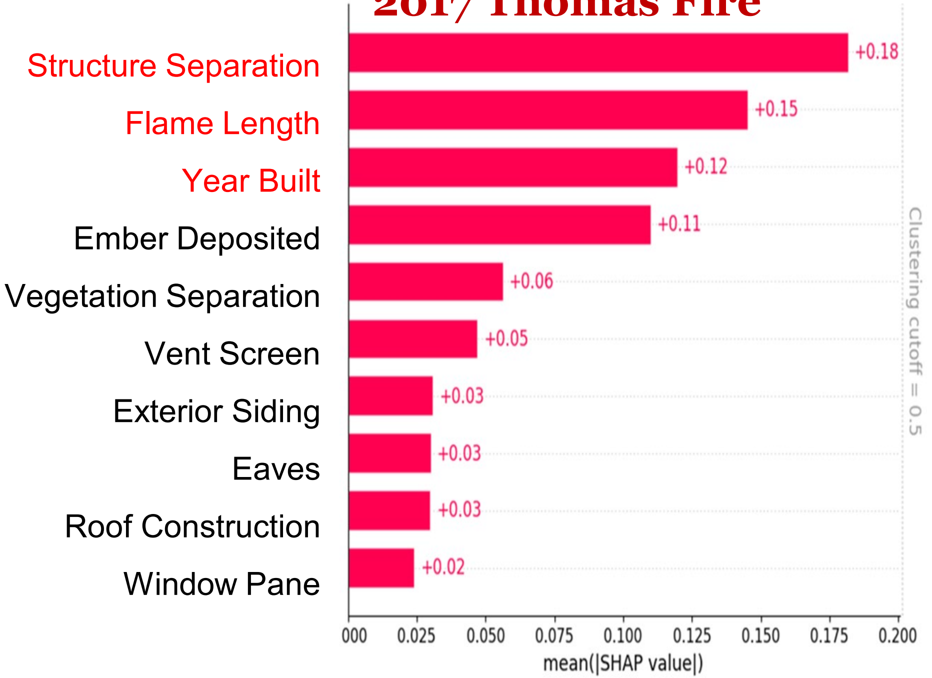
Berkeley Fire Research Lab

Feature Contributions Using XGBoost and SHAP Values

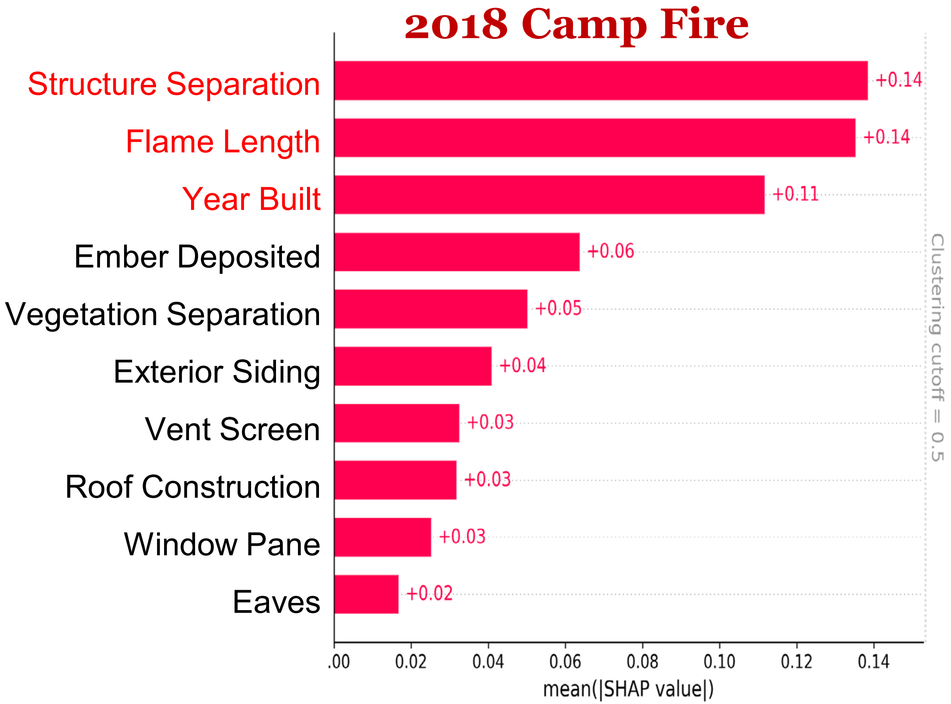
2017 Tubbs Fire

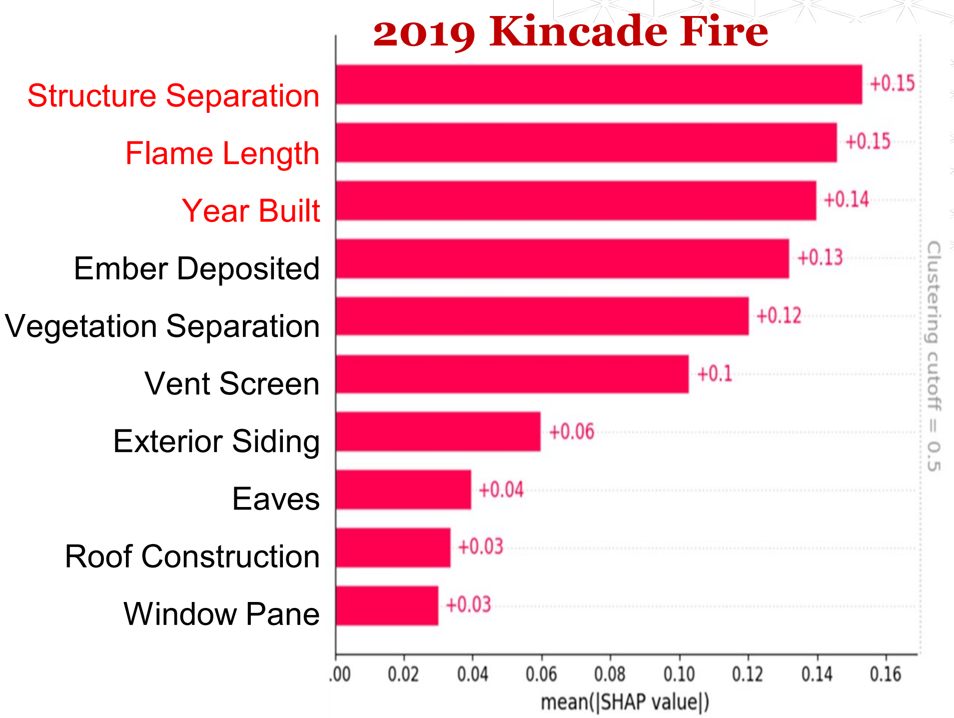


2017 Thomas Fire



Feature Contributions Using XGBoost and SHAP Values





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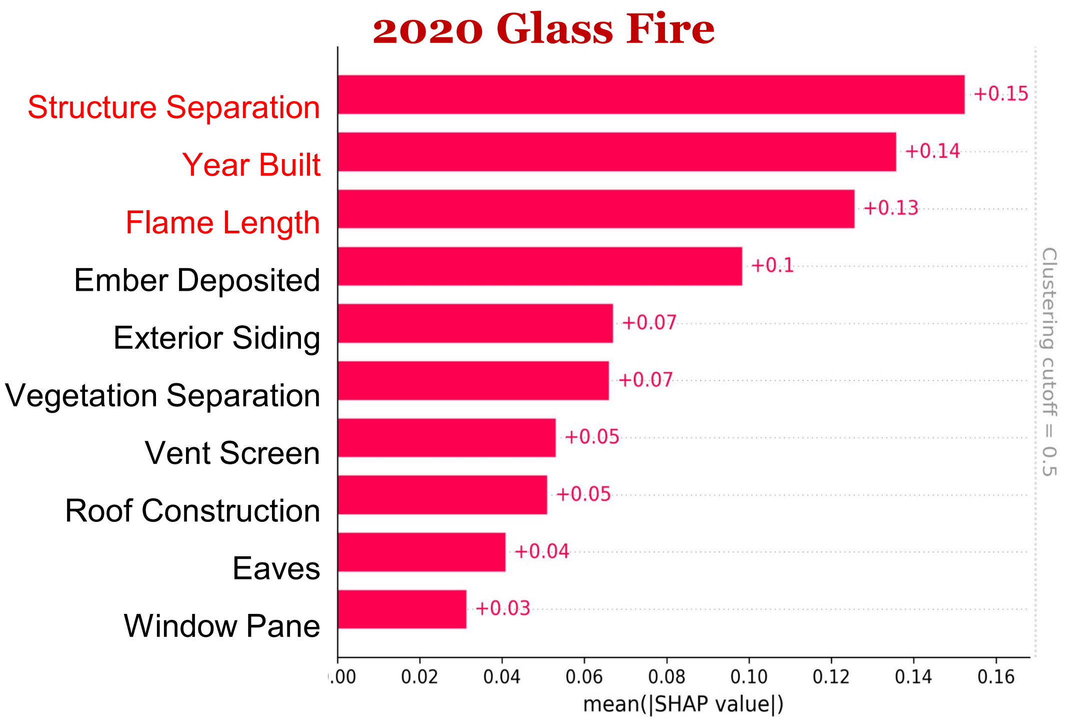


Results - Top 3 factors

- Driving factors to structure destruction
- **Camp Fire**
  - Rapid fire through densely-packed structures Surrounded by heavy canopies and vegetation
  - Structure separation also key in Knapp et al.
    - Closely spaced structures drove spread through communities.
  - Flame length – structures directly impacted by nearby heavy vegetation
  - Year built – older homes fared poorly in the fire
- **Kincade Fire**
  - Structure Separation is key
    - Variations in density – clustered structures can spread fire
  - Low structure density in oak/scrub area surrounded by vineyards
    - Flame length and Year Built

Hector Amezuca / Sac Bee

Noah Berger / AP

Knapp, E.E., *et al.* Housing arrangement and vegetation factors associated with single-family home survival in the 2018 Camp Fire, California. *fire ecol* **17**, 25 (2021).

Results - Top 3 factors

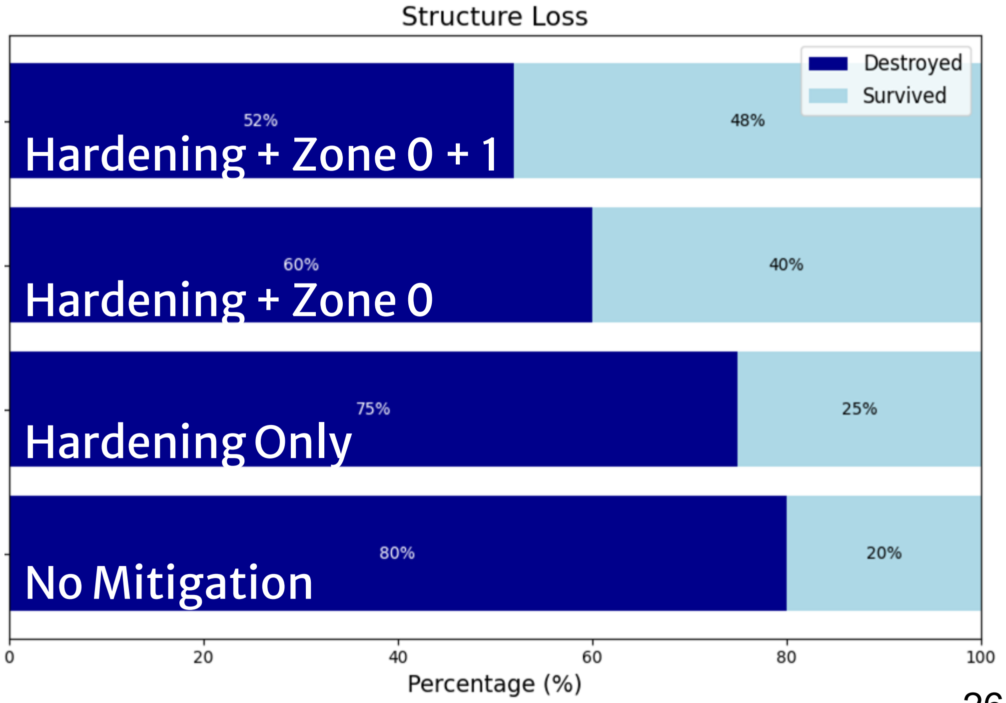
- Driving factors to structure destruction
- **Tubbs Fire**
  - Flame length
  - Structure separation– Fountaingrove, Coffey Park
  - Year built
- **Thomas Fire**
  - Structure Separation – densely populated area
  - Flame length
  - Year Built
- **Glass Fire**
  - Structure Separation – Deer Park
  - Flame length
  - Year Built

Coffey Park, Santa Rosa / Marcus Yam/ Los Angeles Times

Los Padres National Forest, Ventura County / USFS photo

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



PART II: New WU-E Model

HAMADA: a summary

- A function of **house size**, **separation distance**, **wind speed**, and **hardening density**

HAMADA: a summary

- A function of **house size**, **separation distance**, **wind speed**, and **hardening density**

- **Capabilities:**
    - Provide **time of arrival** outputs
    - Provide **ember cast** outputs
    - Provide **fireline intensity** outputs. Intensity **given** by a burning structure.
    - **Variations** in house **size**, **separation** distance, and **hardening** density.

HAMADA: a summary

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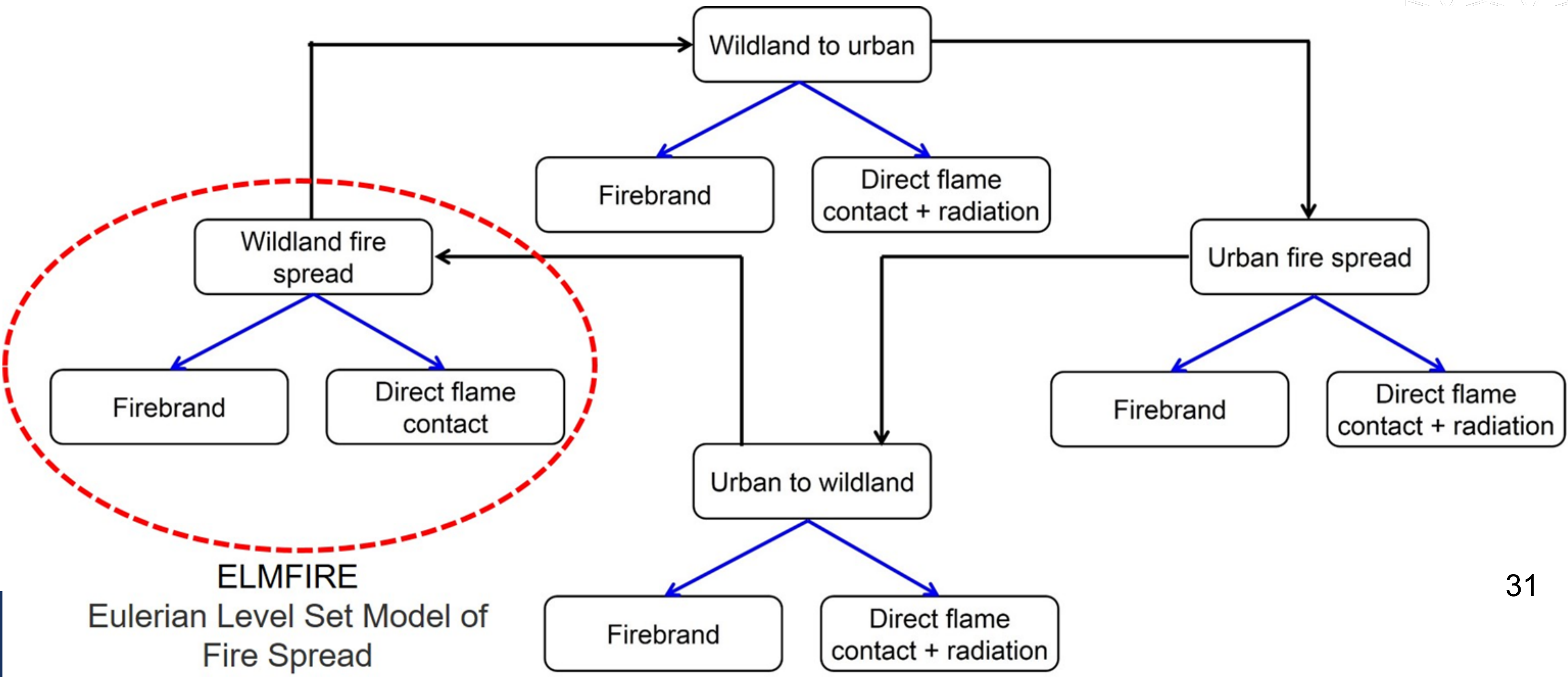
    - Provide **fireline intensity** outputs. Intensity **given** by a burning structure.
    - **Variations** in house **size**, **separation** distance, and **hardening** density.

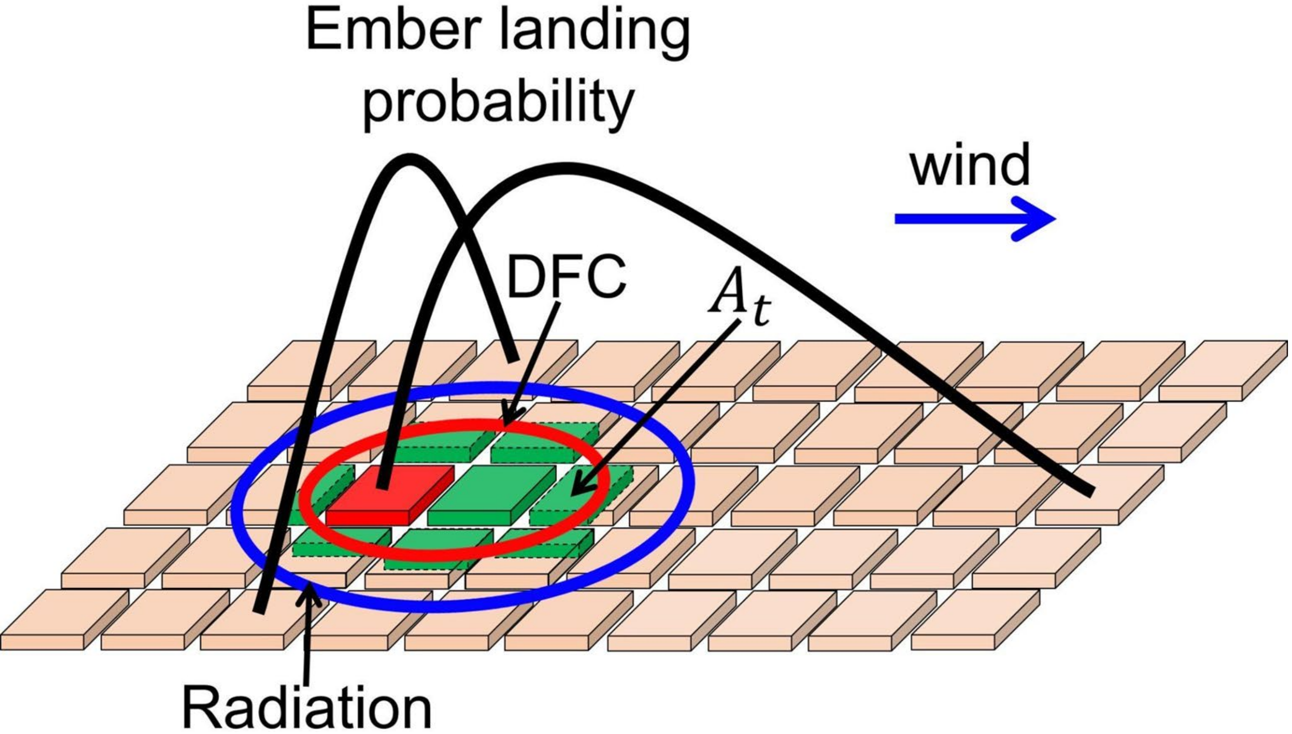
- **Drawbacks:**
    - **Limited** structural **properties variations** (e.g., different combustible fraction)
    - **No fire incident intensity** outputs. Intensity **received** by a structure from other burning structures.

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



WU-E (cont'd)



Q_t: heat received by target [kW]

$\dot{q}_c$: DFC at target cell [kW]

$\dot{q}_r''$: radiation from source [kW/m^2]

HRR: heat release rate [kW]

α_c : DFC coefficient

α_r : radiation coefficient

A_t: contact area with flame [m^2]

Δx: cell size [m]

μ: mean

σ: std. deviation

Purnomo, D. M. J., et. al. (2024). Reconstructing modes of destruction in wildland–urban interface fires using a semi-physical level-set model. *Proceedings of the Combustion Institute, 40*(1–4), 105755. https://doi.org/10.1016/j.proci.2024.105755

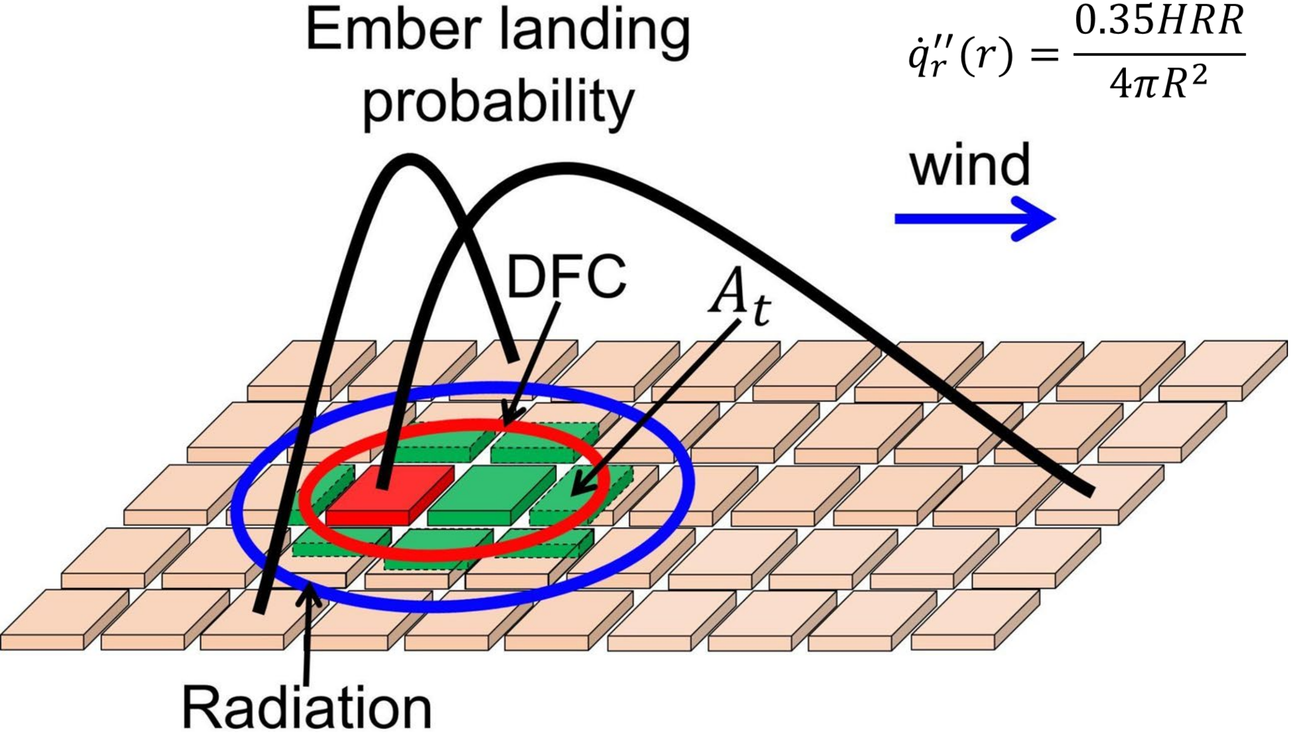
WU-E (cont'd)

DFC **radiation**

$$Q_t = \alpha_c \dot{q}_c + \alpha_r \dot{q}_r'' A_t$$

$$\dot{q}_c\,(x,y) = \frac{HRR \cdot A_t}{\Delta x^2}$$

$$\dot{q}_r''(r) = \frac{0.35 HRR}{4\pi R^2}$$



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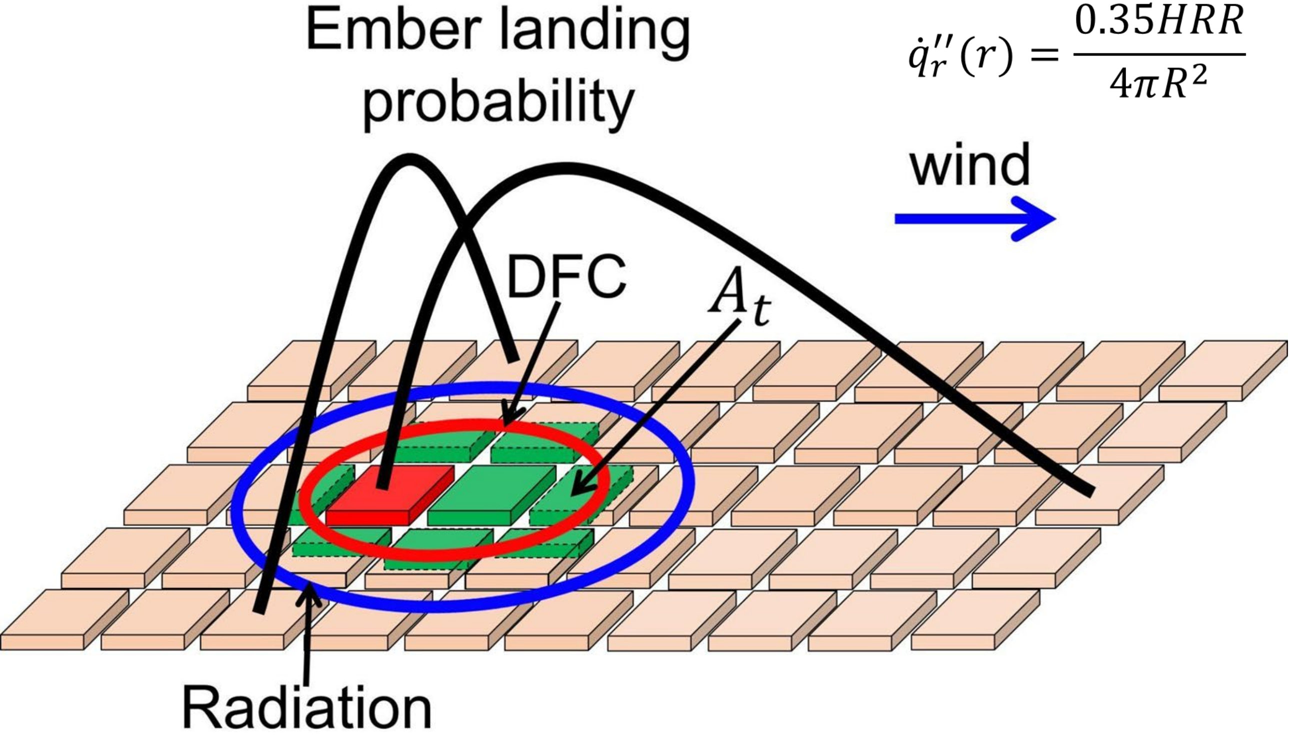
WU-E (cont'd)



DFC **radiation**

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$$\dot{q}_c(x,y) = \frac{HRR \cdot A_t}{\Delta x^2}$$

$$\dot{q}_r''(r) = \frac{0.35HRR}{4\pi R^2}$$

Ember

lognormal

$$P(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right).$$

normal

$$P(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^2}$$

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$\dot{q}_r''$: radiation from source [kW/m^2]

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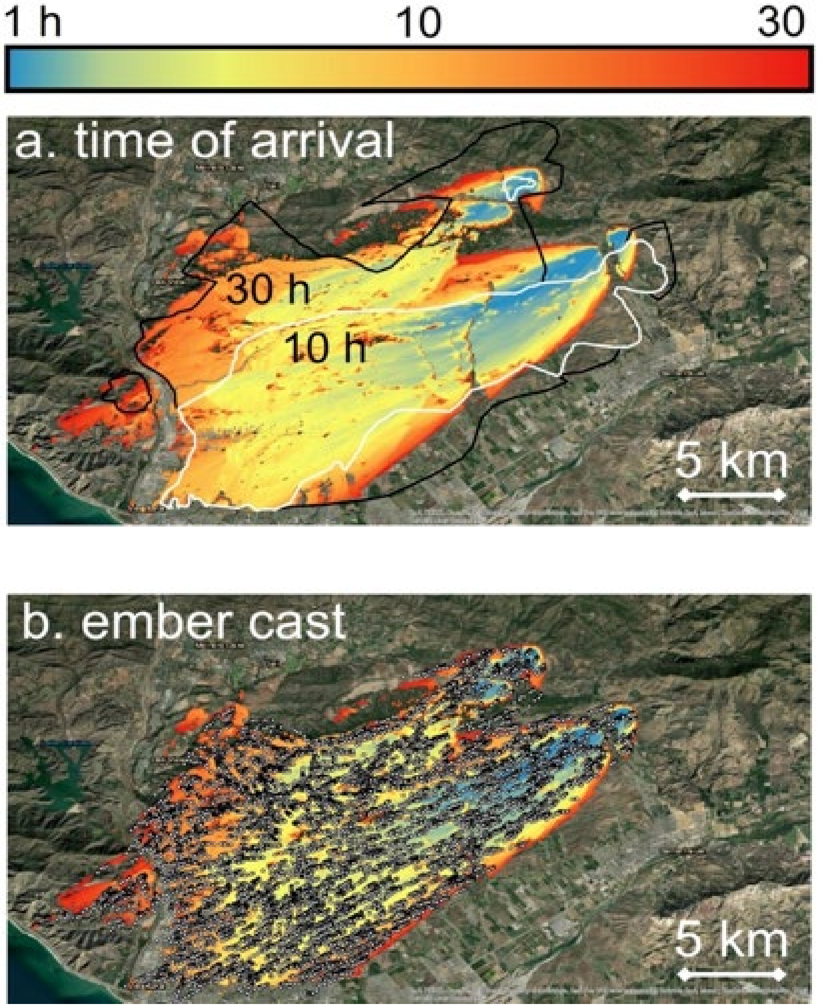
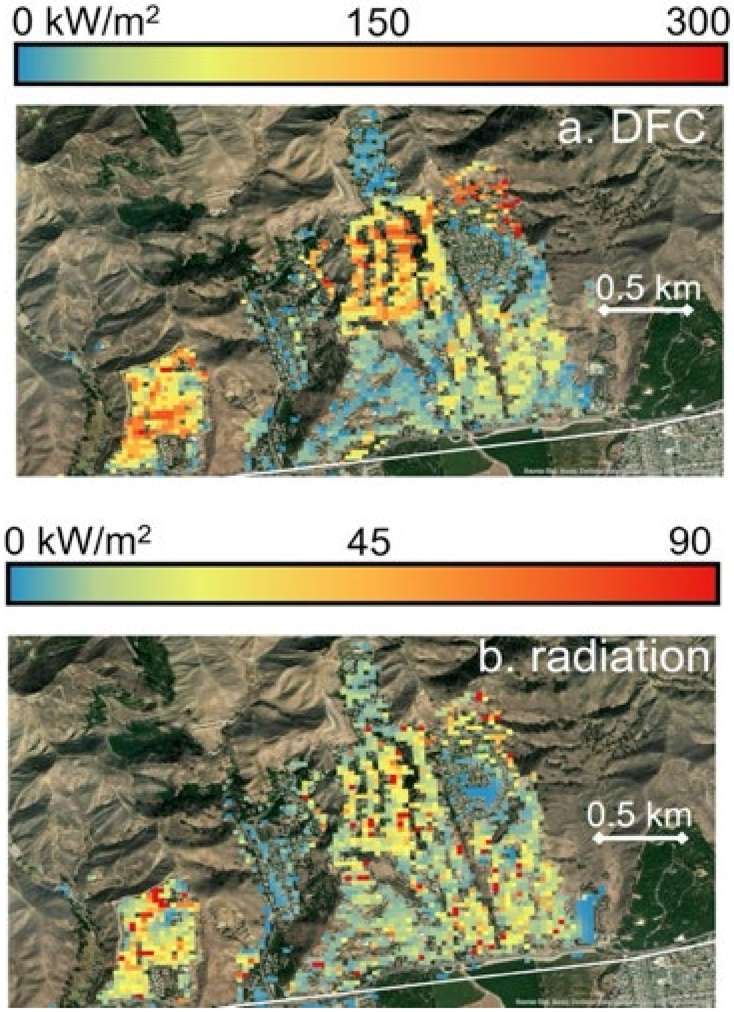

1 h
10
30
a. time of arrival
30 h
10 h
5 km
b. ember cast
5 km


0 kW/m²
150
300
a. DFC
0.5 km
0 kW/m²
45
90
b. radiation
0.5 km

Comparison of WUI models capabilities

HAMADA

- Provide **time of arrival** outputs
- Provide **ember cast** outputs
- Provide **fireline intensity** outputs.
- **Limited** structural **property variations**

WU-E

- Provide **time of arrival** outputs
- Provide **ember cast** outputs
- Provide **fireline intensity** outputs.
- **Flexible** structural **property variations**
- Provide **fire incident intensity** outputs
- **Physical framework for improvement**

Concluding Remarks

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
- Newly model, **WU-E**, improved previously-used model (HAMADA), by providing fire incident intensity outputs, flexible structural properties variations, and an adaptable physical framework for spread.

Preprint paper: https://doi.org/10.21203/rs.3.rs-5776626/v1; ELMFIRE Code: https://elmfire.io/

Thank you!

GORDON AND BETTY MOORE FOUNDATION

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