Fire Risk to Structures in California: Focus on Zone 0

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Photo Credit: Melia Robbinson

Pathways to Fire Spread

Radiation

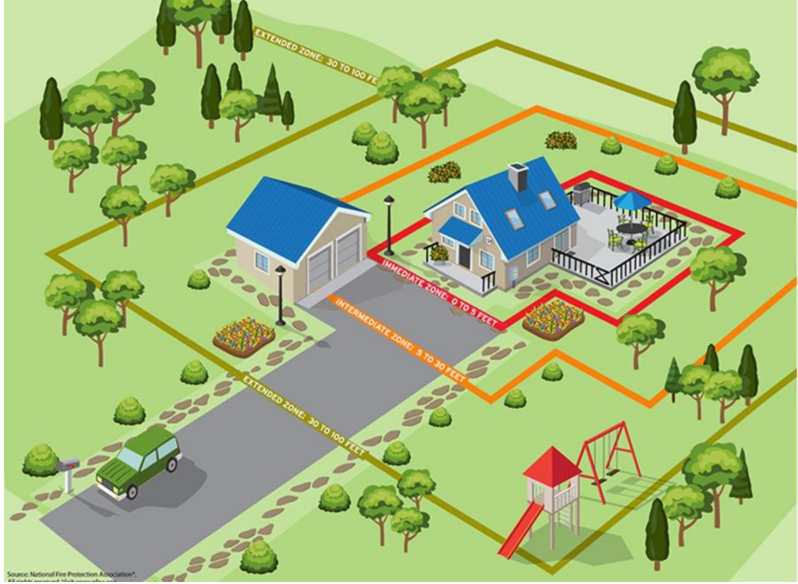
Originally thought to be responsible for most/all ignitions

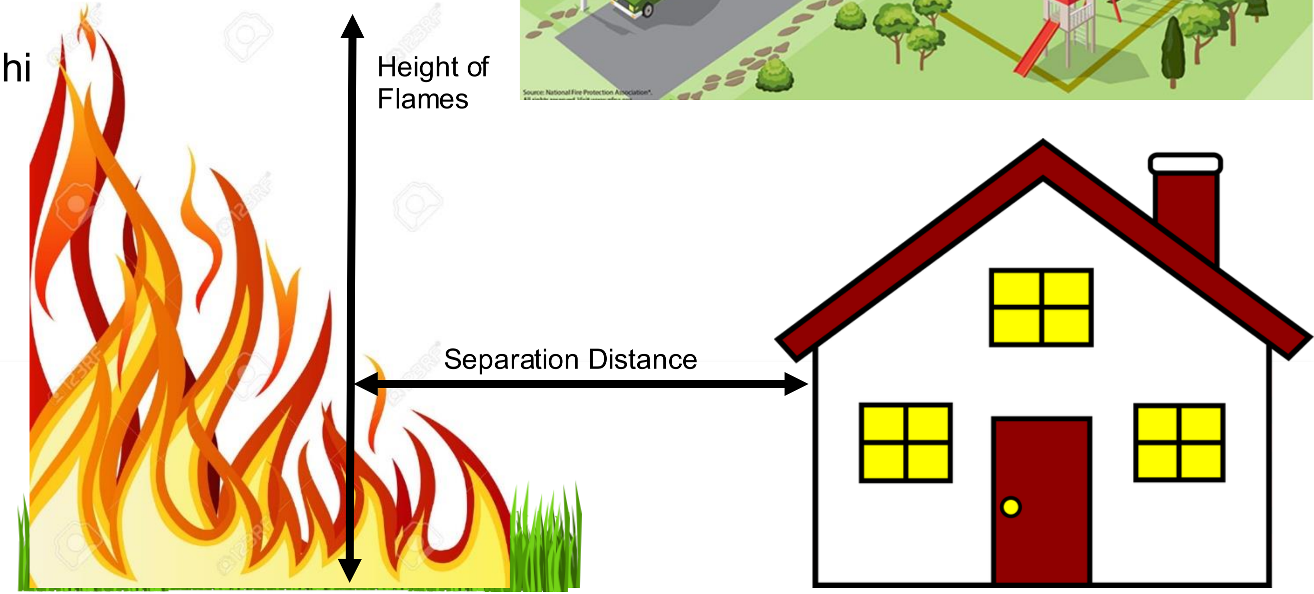
Direct Flame Contact

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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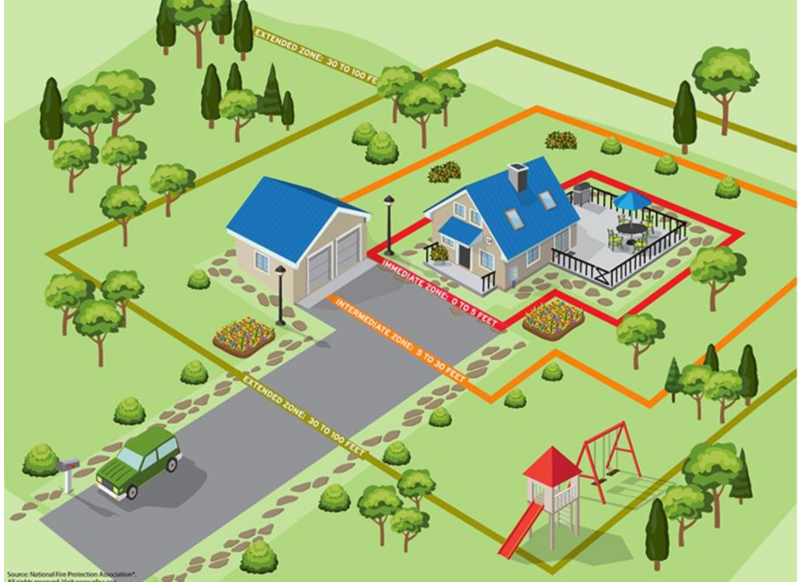
Small burning particles which cause spot ignitions



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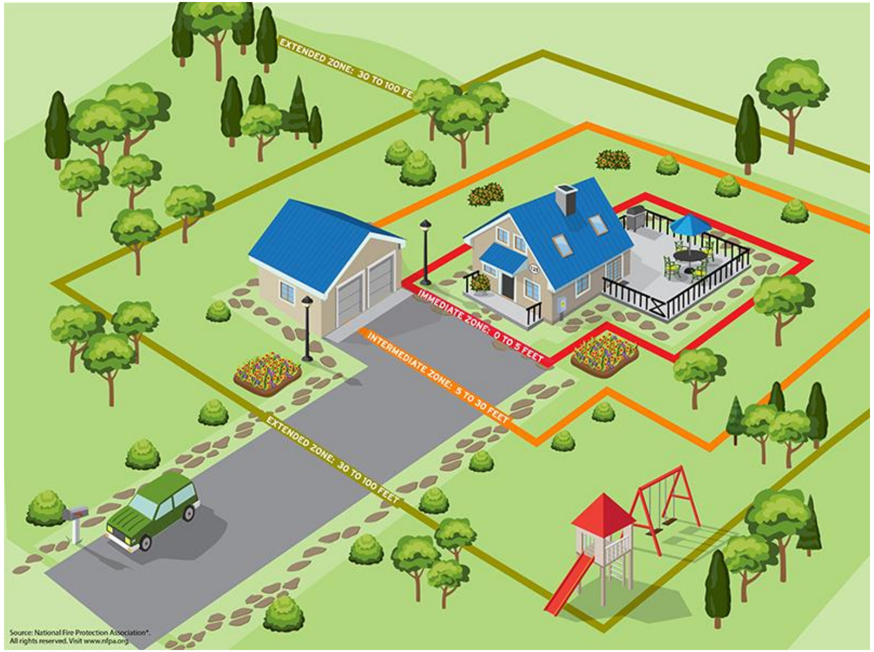
Nathan Trauernicht, UC Davis Fire @ Tamarack Fire

Mitigation Approaches:

- Remove Fuels
- Reduce Fuels
- Relocate Fuels

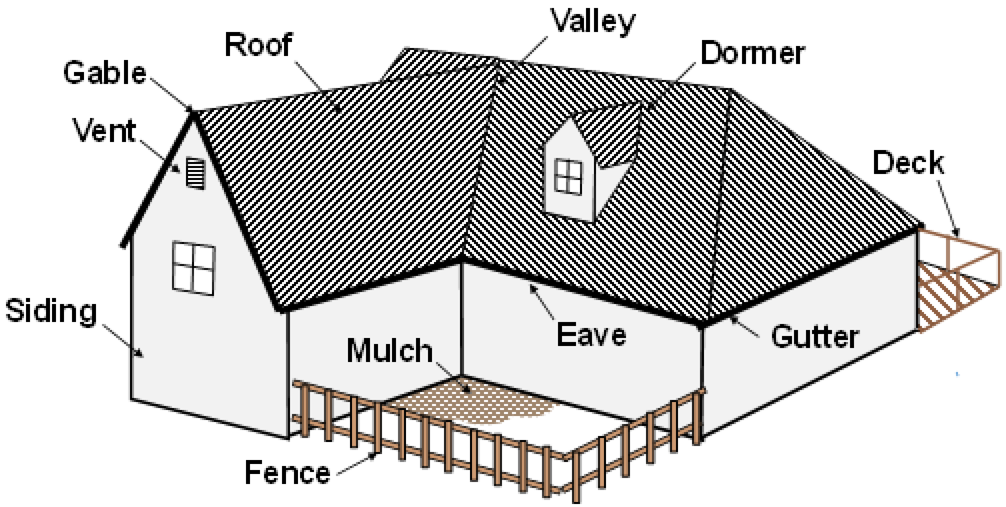
- Fire Resistant Design
- Community Design
- Ignition/Fire Spread Resistant Materials
- Active Systems

Defensible Space



Reduce or clear nearby fuels

Home Hardening

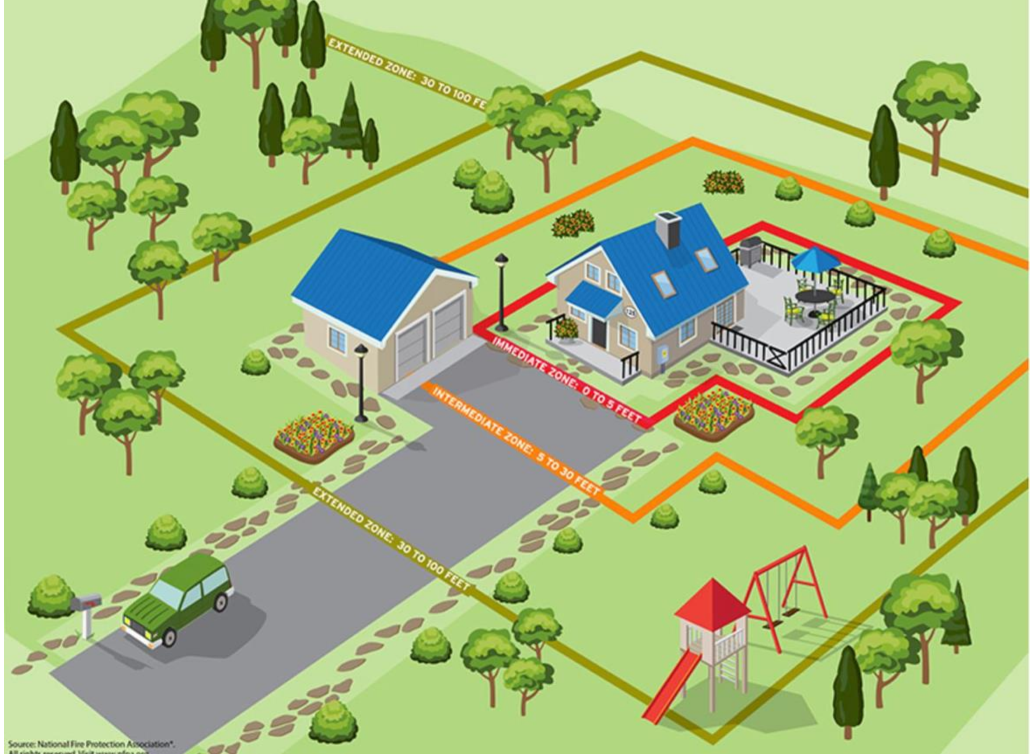


Prevent ignition from small flames/embers

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

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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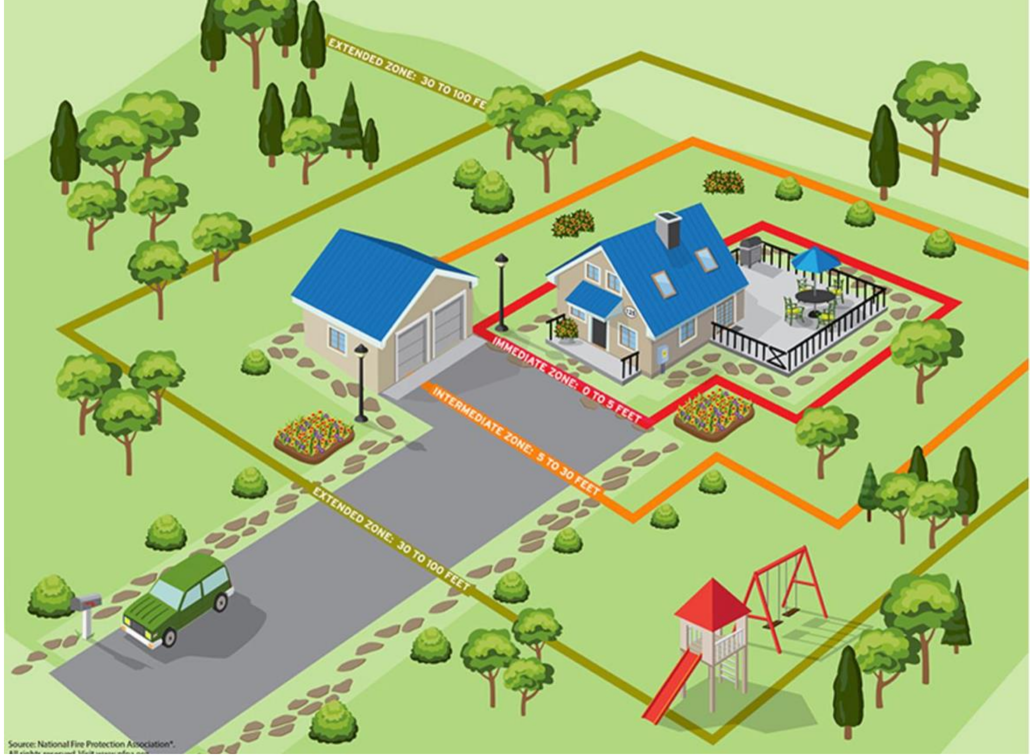

<u>3 types of studies investigating effectiveness</u>

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

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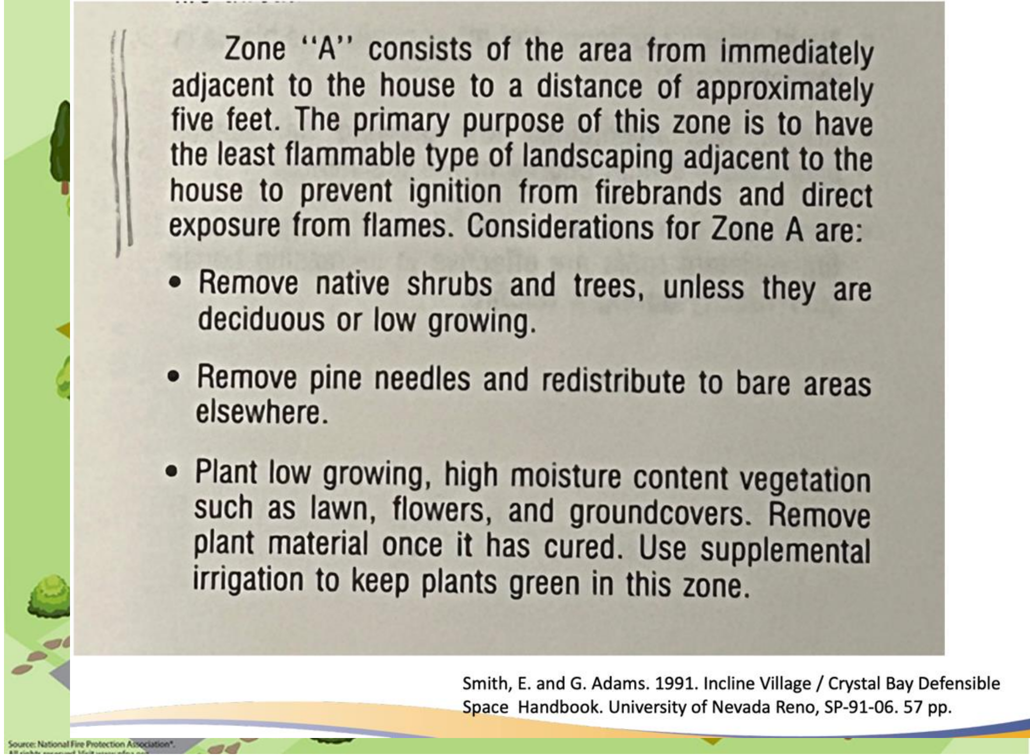

Zone "A" consists of the area from immediately adjacent to the house to a distance of approximately five feet. The primary purpose of this zone is to have the least flammable type of landscaping adjacent to the house to prevent ignition from firebrands and direct exposure from flames. Considerations for Zone A are:

- Remove native shrubs and trees, unless they are deciduous or low growing.
- Remove pine needles and redistribute to bare areas elsewhere.
- Plant low growing, high moisture content vegetation such as lawn, flowers, and groundcovers. Remove plant material once it has cured. Use supplemental irrigation to keep plants green in this zone.

Smith, E. and G. Adams. 1991. Incline Village / Crystal Bay Defensible Space Handbook. University of Nevada Reno, SP-91-06. 57 pp.

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Practical knowledge from firefighters:
First steps for WUI protection in guidebooks include actions to

- *"Remove combustibles immediately next to the structure and scatter firewood"*
- *"Remove vegetation from the immediate area of the structure"*
- (FireScope California, 2023).

3 types of studies investigating effectiveness

1. Experiments – lab to full scale
2. Post-fire investigations on-the-ground
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FireScope California, Wildland Urban Interface Structure Defense, October 21, 2023

Post-Fire Investigation Highlights

- Cohen – "Home Ignition Zone" – not just the home, but vegetation/materials surrounding the home are most responsible for fire spread/structure loss
  - Most homes ignited by embers directly (on structure), indirectly (via surrounding vegetation/materials), or neighboring structures which may originally have ignited by embers. (Grass Valley Fire, Lake Arrowhead, CA)
- Fences, nearby flammable materials found to:
  - Provide a pathway for direct flame spread: "House–fence–house–fence–house"
  - Act as sources of firebrands and use firefighter resources
  - NIST investigations (2011 Amarillo Fire, 2012 Waldo Canyon, etc.)
- Overhanging vegetation
  - Increases risk to structures, especially through litter (Leonard et al. 2009) Australian Black Saturday Fires
- Combustible connected fuels
  - Vegetation, vehicles, etc. contribute to rapid fire spread in the Lahaina Fire (IBHS, 2024)
- Presence of combustible vegetation adjacent to structures
  - Ornamental evergreen shrubs were judged to be among the more common heat sources causing early ignitions of Fort McMurray homes (Westhaver, 2017).

Cohen, Jack D., and Richard D. Stratton. "Home destruction examination: Grass Valley Fire, Lake Arrowhead, California." *Tech. Paper R5-TP-026b. Vallejo, CA: US Department of Agriculture, Forest Service, Pacific Southwest Region (Region 5).* 26 p. (2008).

Leonard, J., et al. (2009). Post-fire surveys following the Black Saturday bushfires. Appendix to the Victorian Bushfires Royal Commission Report. CSIRO Sustainable Ecosystems.

Lahaina: From Conflagration to Resilience, IBHS, 2024

Westhaver, A., Why some homes survived: Learning from the Fort McMurray wildland/urban interface fire, Institute for Catastrophic Loss Reduction, March 2017

Maranghides, A., & McNamara, D. (2016). *2011 Wildland Urban Interface Amarillo Fires Report# 2: Assessment of Fire Behavior and WUI Measurement Science*. NIST

Maranghides, A., McNamara, D., Vihnanek, R., Restaino, J., & Leland, C. (2015). A Case Study of a Community Affected by the Waldo Fire Event Timeline and Defensive Actions. NIST Technical Note (NIST TN) - 1910

*Video dash-cam footage taken by a **Fort McMurray** resident during the evacuation on May 04 provides vivid evidence of the capacity of ornamental shrubbery as a source of home ignition; the sequence of events leading from ember > mulch bed > cedar/juniper > full home ignition took place in the elapsed time of approximately 40 seconds.*

Westhaver, A., Why some homes survived: Learning from the Fort McMurray wildland/urban interface fire, Institute for Catastrophic Loss Reduction, March 2017

https://www.youtube.com/watch?v=PCc1FvZ3g0Q

Additional videos demonstrating vegetation > structure fire spread

Palm Tree

Experimental Studies

- Mulch beds, litter, ground cover – highly susceptible to ignition
  - Often low flame lengths, so recommend removal closest to structures
  - Litter from vegetation or blown in can accumulate at the base of walls.
- Fences
  - Wood, composite fences can spread fire to structures when located too close.
- Wood piles, landscape timbers, etc.
  - High ignition hazard from embers. Creates fires that can ignite structures.
- Sheds, gazebos, playsets
  - Structures not built to resist embers/flames. If ignited can easily spread to structures
- Decks
  - Studies have shown ignition of many wooden decks, which can spread fires to structures
- Embers accumulate at base of structures, litter may also be present, increasing risk of ignition of materials in Zone 0 (Quarles et al, 2023)
- Extensive technical reports
  - IBHS – quantified the 5 foot zone being enough to prevent ignition from most materials

Lin, S., Li, C., Conkling, M., Huang, X., Quarles, S. L., & Gollner, M. J. (2024). Smoldering ignition and transition to flaming in wooden mulch beds exposed to firebrands under wind. Fire Safety Jou
148, 104226.
Lin, S., Cui, W., Wang, S., Qin, Y., Chen, Y., Zhang, Y., Huang, X., Quarles, S.L., & Gollner, M. J. (2025). Susceptibility to ignition of landscaping mulches exposed to firebrand piles or radiation. Fi
Safety Journal, 104388.
Johnsson, Erik L., et al. *Wind-driven Fire Spread to a Structure from Firewood Piles*. US Department of Commerce, National Institute of Standards and Technology, 2023.
Hedayati, F., Quarles, S. L., & Standohar-Alfano, C. (2022). Evaluating deck fire performance—limitations of the test methods currently used in California's building codes. *Fire*, *5*(4), 107.
Quarles, Stephen L., et al. "Factors influencing ember accumulation near a building." *International journal of wildland fire* 32.3 (2023): 380-387.
Insurance Institute for Business & Home Safety (IBHS). *Near-Building Noncombustible Zone Technical Report*. IBHS, 2019. https://ibhs.org/wp-content/uploads/member_docs/Near-Building_Noncombustible_Zone_Report_IBHS.pdf
Suzuki, S., Johnsson, E., Maranghides, A., & Manzello, S. L. (2016). Ignition of wood fencing assemblies exposed to continuous wind-driven firebrand showers. Fire Technology, 52, 1051-1067.

Vegetation Flammability

- Flammability broadly defines a material's ability to ignite & burn
  - Ignitability – ease of catching fire (ignition time)
  - Sustainability – how long it burns (flame duration)
  - Combustibility – intensity of burning (heat release rate)
- Major drivers of flammability
  - Particle size – thin fuels ignite faster, dry faster, etc.
  - Arrangement – loosely packed, exposed fuels ignite & burn easier
  - Fuel moisture – drier fuels ignite faster, no moisture to evaporate
  - Chemical content – eucalyptus and conifers have oils, etc.
- Influence of Moisture
  - Moist fuels are harder to ignite and burn
  - The particle size of the vegetation
  - Fuel moisture in vegetation is *complicated* – it does not linearly release
- Ganteaume, Moritz and others have used laboratory methods to measure flammability of ornamental vegetation

Ganteaume, Anne, et al. "Flammability of some ornamental species in wildland–urban interfaces in southeastern France: laboratory assessment at particle level." *Environmental Management* 52.2 (2013): 467-480.

Ganteaume, Anne; Jappiot, Marielle; Lampin, Corinne; Guijarro, Mercedes; Hernando, Carmen. 2013. Flammability of some ornamental species in wildland-urban interfaces in southeastern France: laboratory assessment at particle level. Environmental Management 52(2):467-480.
Muñoz, Juan Antonio, et al. "A New Full-Scale Method for Ranking Flammability of Ornamental Vegetation." *Fire and Materials* (2025)

Ignition of Live (moist) Vegetation

- Convective vs. radiative heating affects ignition, too.
- Direct flame contact is driven more by *Convection*. While fine fuels (needles, litter, etc.) are difficult to ignite by radiation when moist, they are still *ignitable* from direct contact of a flame. High heating rates quickly dry out fuels and they aid in fire spread.
  - Notable example: Crown fires spread through very live tree canopies due to fine fuels, open arrangement, and high heating rates.
- Important to emphasize laboratory-scale flammability tests do not always reflect large-scale behavior (wildfire & structures)
- Small % of dead fine fuels (litter) can drive flame spread and ignite under high heating

Flaming ignition was seen for all dead fuels at 500°C, but the live fuels mostly showed glowing ignition. At 600°C, all fuels showed flaming ignition within 1-26 sec. Interestingly, all live fuels were still actively releasing water at ignition, implying there are steep temperature gradients within these physically thin fuels (i.e. not thermally thin).

McAllister, S., & Finney, M. (2014). Convection ignition of live forest fuels. *Fire Safety Science*, *11*, 1312-1325. 0 At 600°C, all fuels showed flaming ignition within 1-26 s

Selected Remote Sensing/Post-Fire Studies

- Many studies find strong correlation between "Defensible Space" and reduced probability of destruction
  - Knapp et al. (2021) Found a strong correlation between distance to nearest structure and vegetation within 100 m and home survival in the Camp fire
    - Structures were more likely to survive a fire with an effective defensible space "immediately adjacent" to them.
  - Syphard et al. (2014) analyzed San Diego County losses and defensible space
    - Structures were more likely to survive a fire with defensible space immediately adjacent to them
    - The most effective actions were reducing woody cover up to 40% immediately adjacent to structures and ensuring that vegetation does not overhang or touch the structure.
  - Penman et al. (2018) found a strong correlation with local vegetation increasing risk of destruction to structures in 27 Australian Bushfires
  - *In a letter from myself and Dr. Syphard to the board: "Our collective research has suggested that defensible space done closest to the house is most effective and does significantly improve the odds of house surviving a fire; but that anything beyond 100 feet does not add significant or substantial additional protection."*
- *Several studies have not found as strong of a correlation with defensible space, emphasizing arrangement (spacing), hardening, topography, and surrounding vegetation*
  - *For example, Alexandre et al., 2016 did not find a strong correlation, suggesting connectivity may be more important*
  - Most previous work did not specifically focus on or resolve zone 0 and could not distinguish surface vs. elevated fuels
  - Mockrin et al. (2023) – used higher resolution imagery on the 2018 Woolsey Fire. Emphasized greater role of building materials and environmental context than defensible space, however the vast majority of structures in the area had vegetation adjacent to the structure, so that could be a cause for this not appearing as an important variable
  - *Many factors in other studies (spacing, surrounding vegetation, etc.) are acknowledged as important, and sometimes more important, but the influence of Zone 0 and defensible space has not been clearly isolated in comparison to other factors.*

Knapp, Eric E., et al. "Housing arrangement and vegetation factors associated with single-family home survival in the 2018 Camp Fire, California." *Fire Ecology* 17.1 (2021): 25.

Syphard, A. D., Brennan, T. J., & Keeley, J. E. (2014). The role of defensible space for residential structure protection during wildfires. *International Journal of Wildland Fire*, *23*(8), 1165-1175.

Syphard, A. D., J. E. Keeley, A. B. Massada, T. J. Brennan, and V. C. Radeloff. 2012. Housing arrangement and location determine the likelihood of housing loss due to wildfire. PLoS ONE 7:e33954.

Alexandre, P.M., S.I. Stewart, M.H. Mockrin, N.S. Keuler, A.D. Syphard, A. BarMassada, M.K. Clayton, and V.C. Radeloff. 2016. The relative impacts of vegetation, topography and spatial arrangement on building loss to wildfires in case studies of California and Colorado. Landscape Ecology 31 (2): 415–430. https://doi.org/10.1007/s10980-015-0257-6.

Mockrin, M. H., D. H. Locke, A. D. Syphard, and J. O'Neil-Dunne. 2023. Using high-resolution land cover data to assess structure loss in the 2018 Woolsey Fire in Southern California. Journal of Environmental Management 347: 118960.

Metz, A. J., Fischer, E. C. & Liel, A. B. The Influence of Housing, Parcel, and Neighborhood Characteristics on Housing Survival in the Marshall Fire. *Fire Technol.* (2024) doi:10.1007/s10694-024-01616-7.

Penman, S. H., Price, O. F., Penman, T. D., & Bradstock, R. A. (2018). The role of defensible space on the likelihood of house impact from wildfires in forested landscapes of south eastern Australia. *International journal of wildland fire*, *28*(1), 4-14.

Part 2: 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*

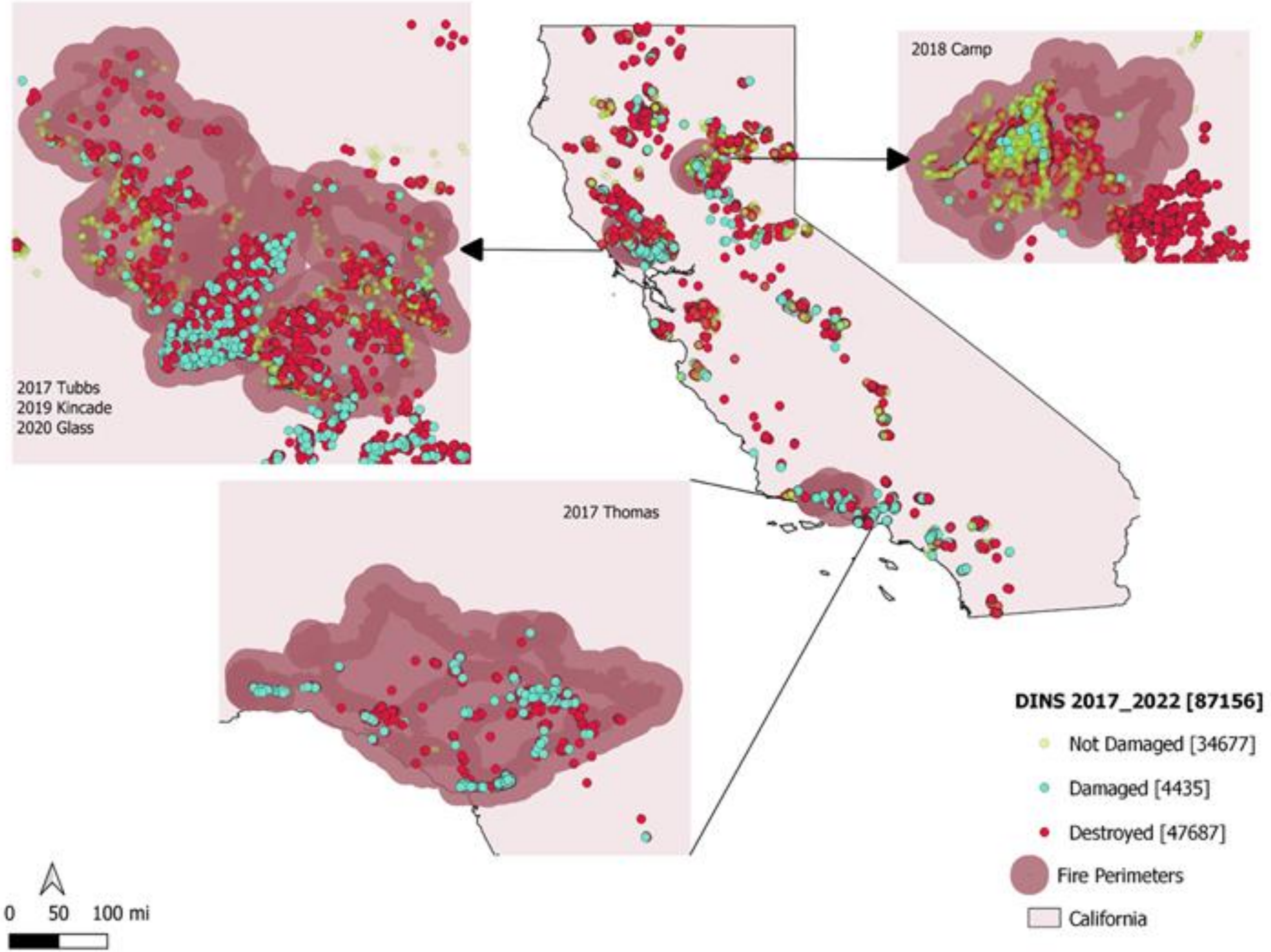
Data- Driven WUI Risk to Structures

- 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

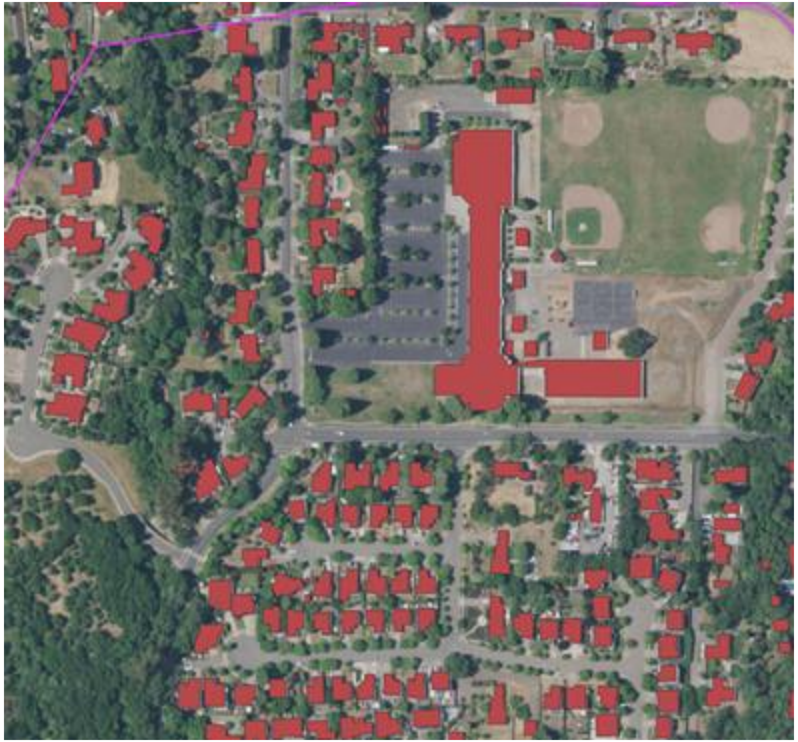
Zone 0 and 1 clear

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

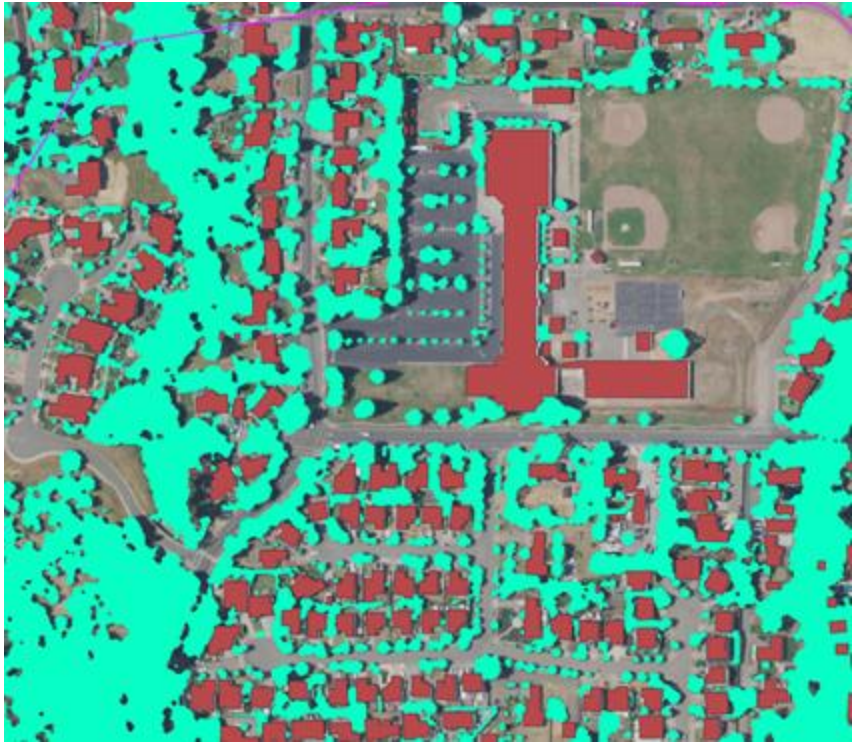
Separation Distance

Structure Separation Distance + Unburned structures

Vegetation Separation Distance



MS Building Footprints - script analysis



LIDAR (Sonoma County)

Exposure from Fire Modeling

Current Limitations

No inclusion of exposure from neighboring structures

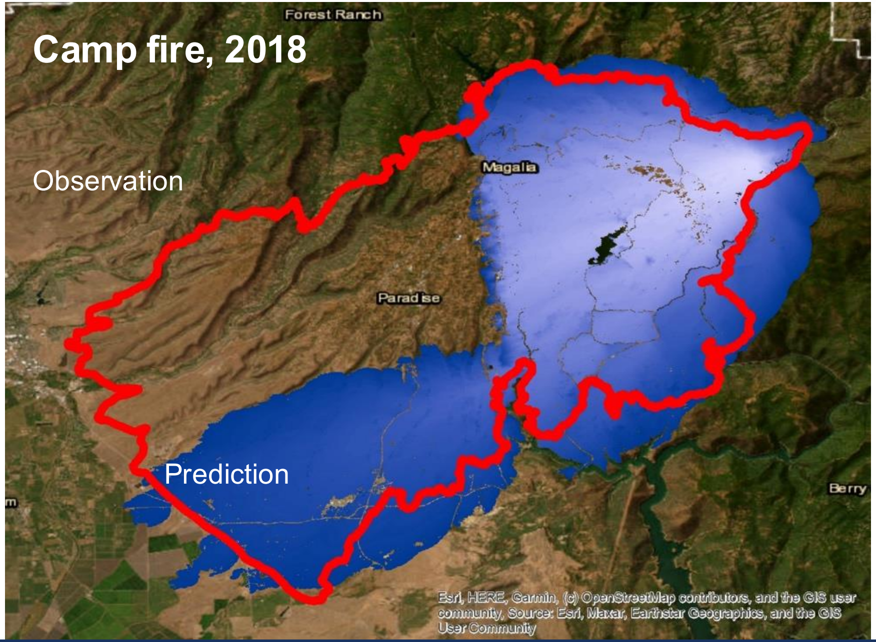
Inputs
- Vegetation
- Weather
- Topography

Models
- Surface fire
- Crown fire
- Ember

Wildfire model: **ELMFIRE**

Outputs
- Spread rate
- Ember cast
- Flame length

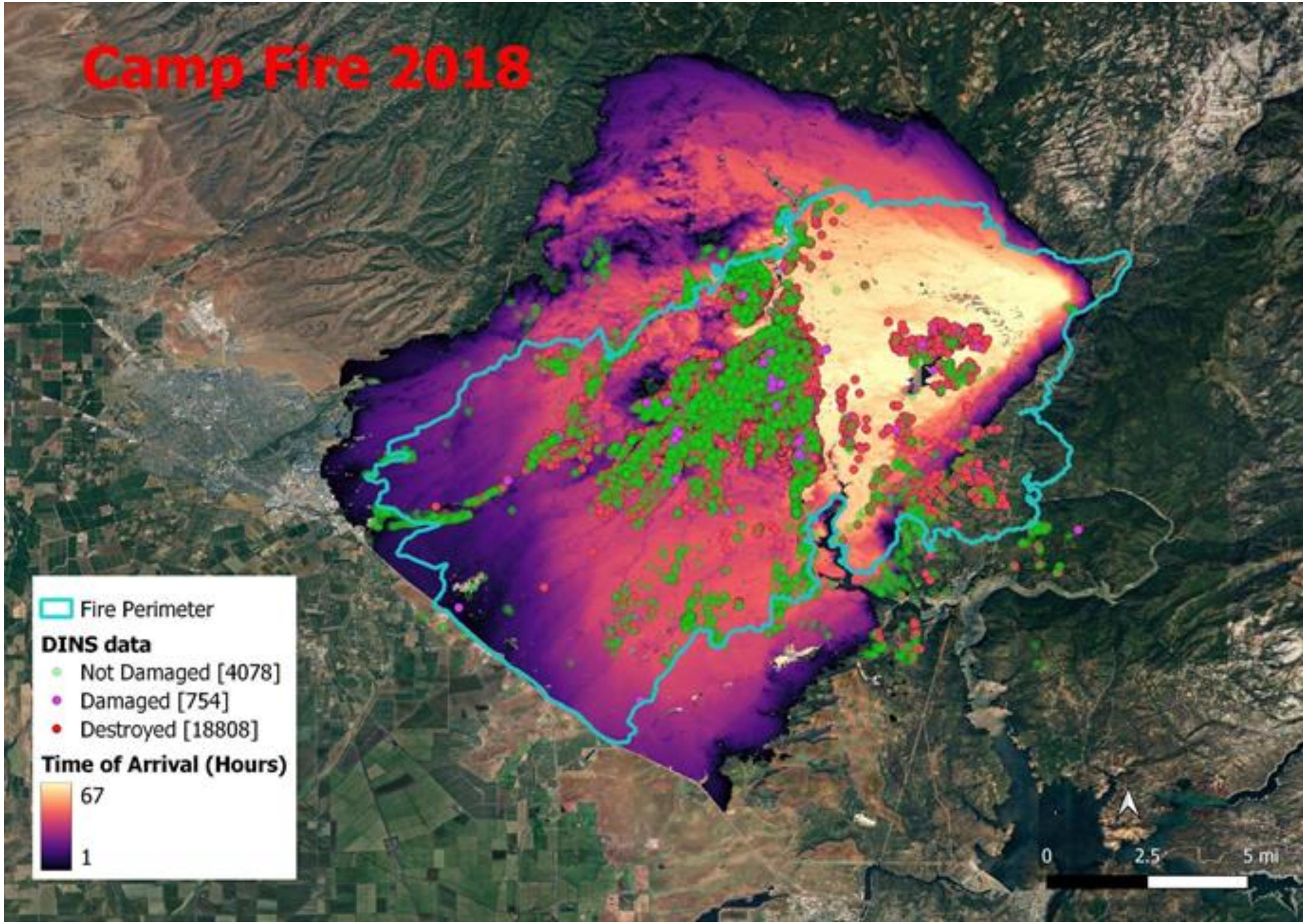
Underlying physics | Validation data | Input data resolution | Structure-to-structure spread



Berkeley Fire Research Lab

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.

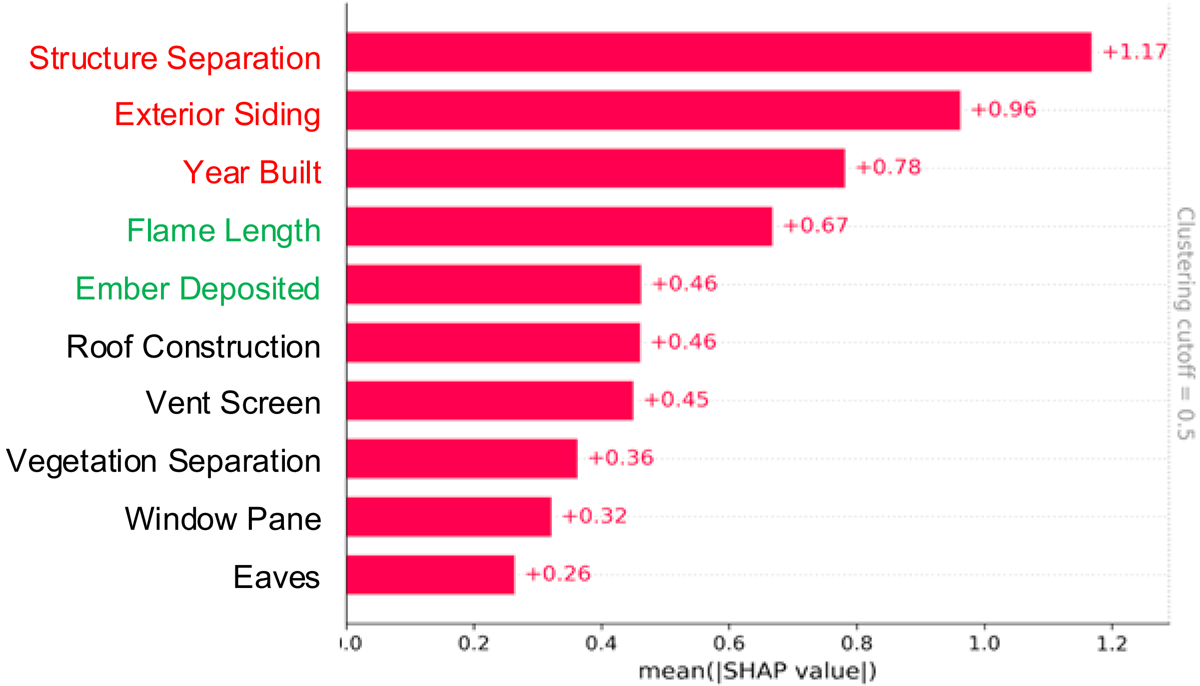
- It is important to first "clean/preprocess" the data and avoid biases, ensuring compatibility and enhancing the overall performance of the models:
  - ***Imputation*** was explored due to the presence of numerous NaN values in the dataset.
  - ***Standardized*** the numerical variables and ***Encoded***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



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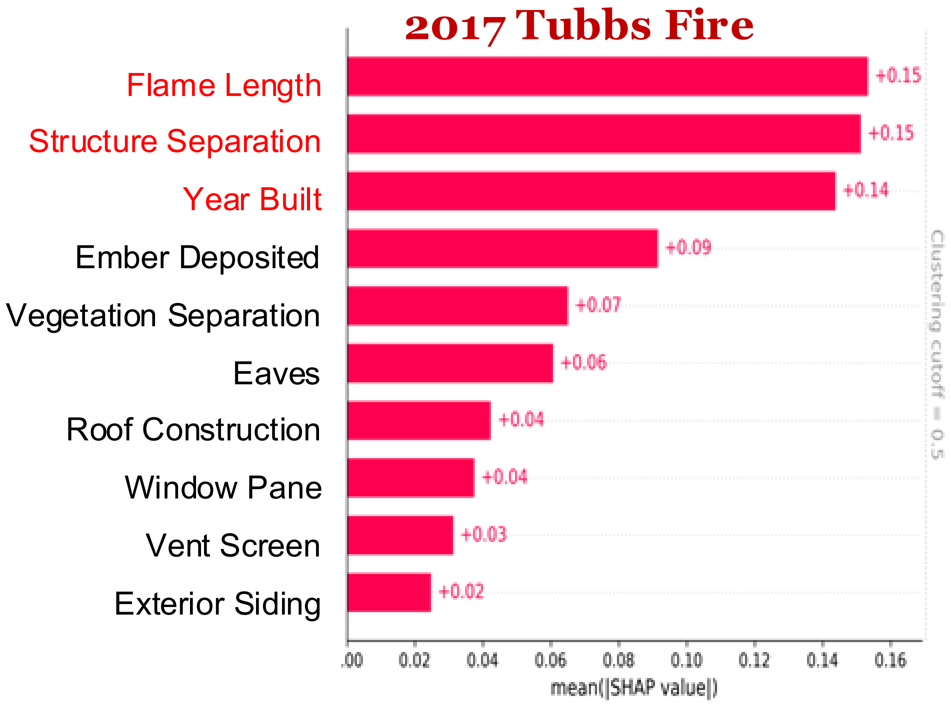

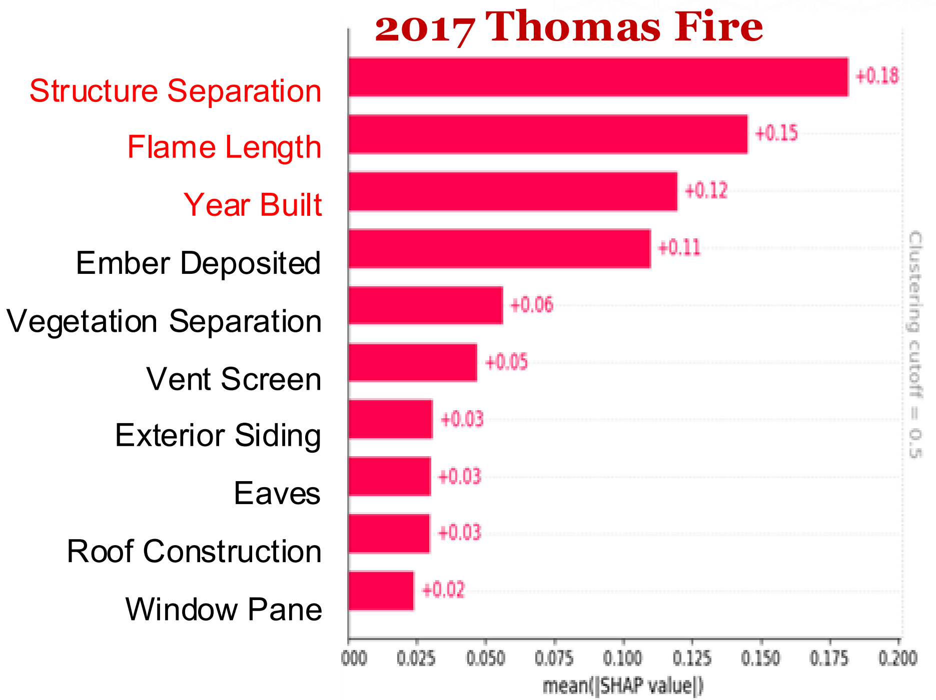

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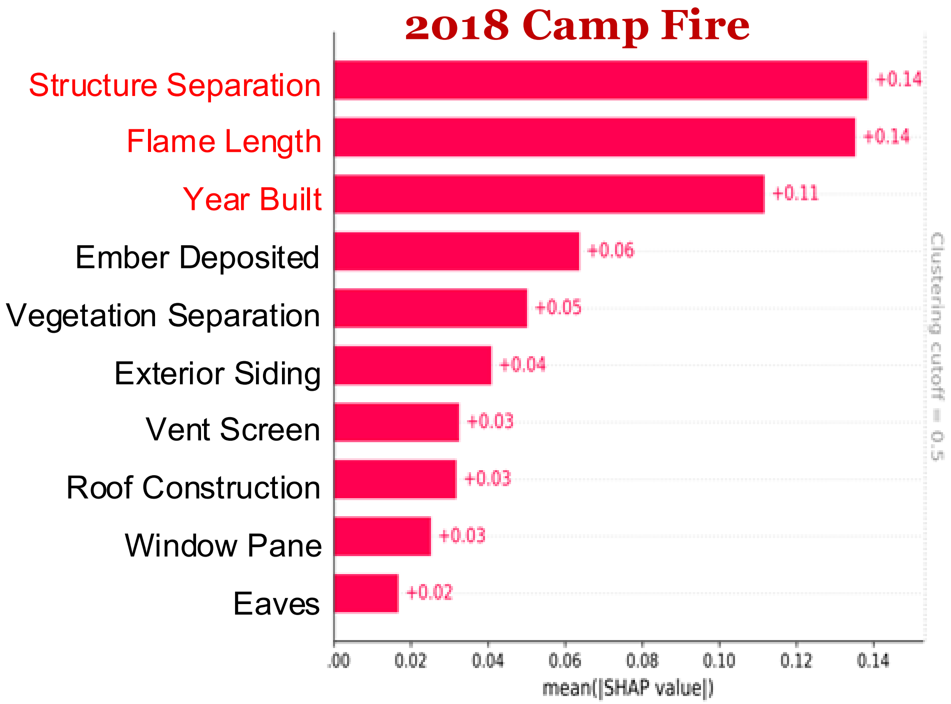
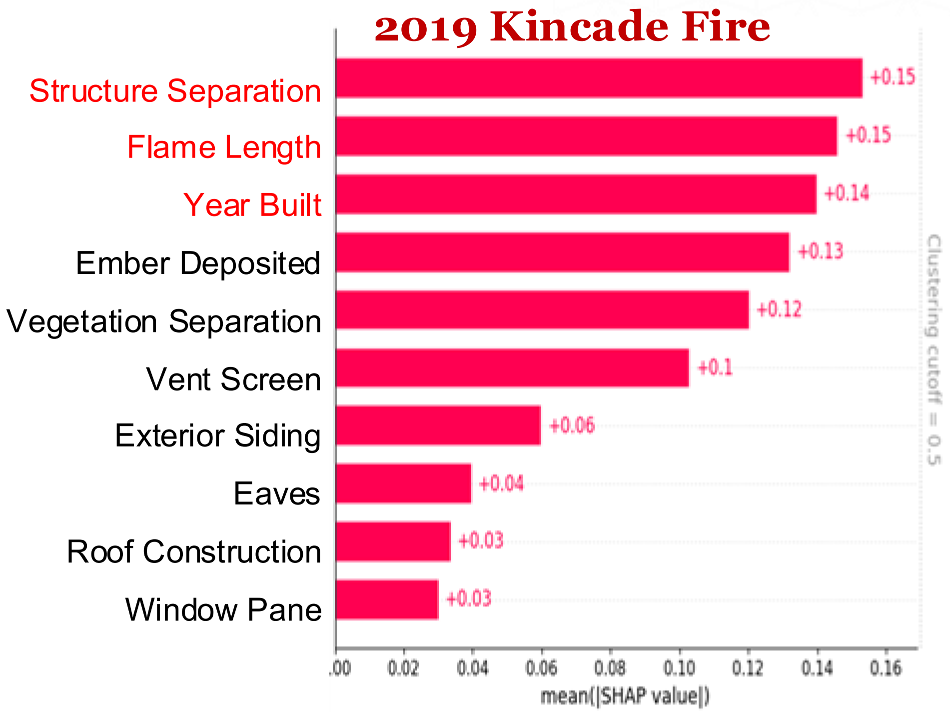
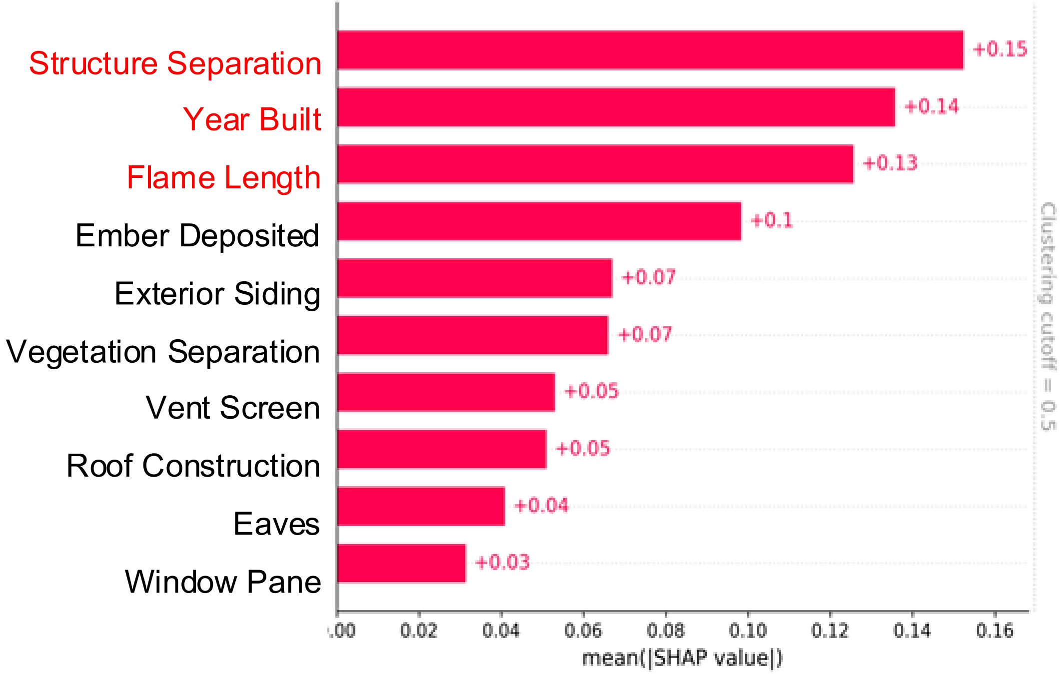




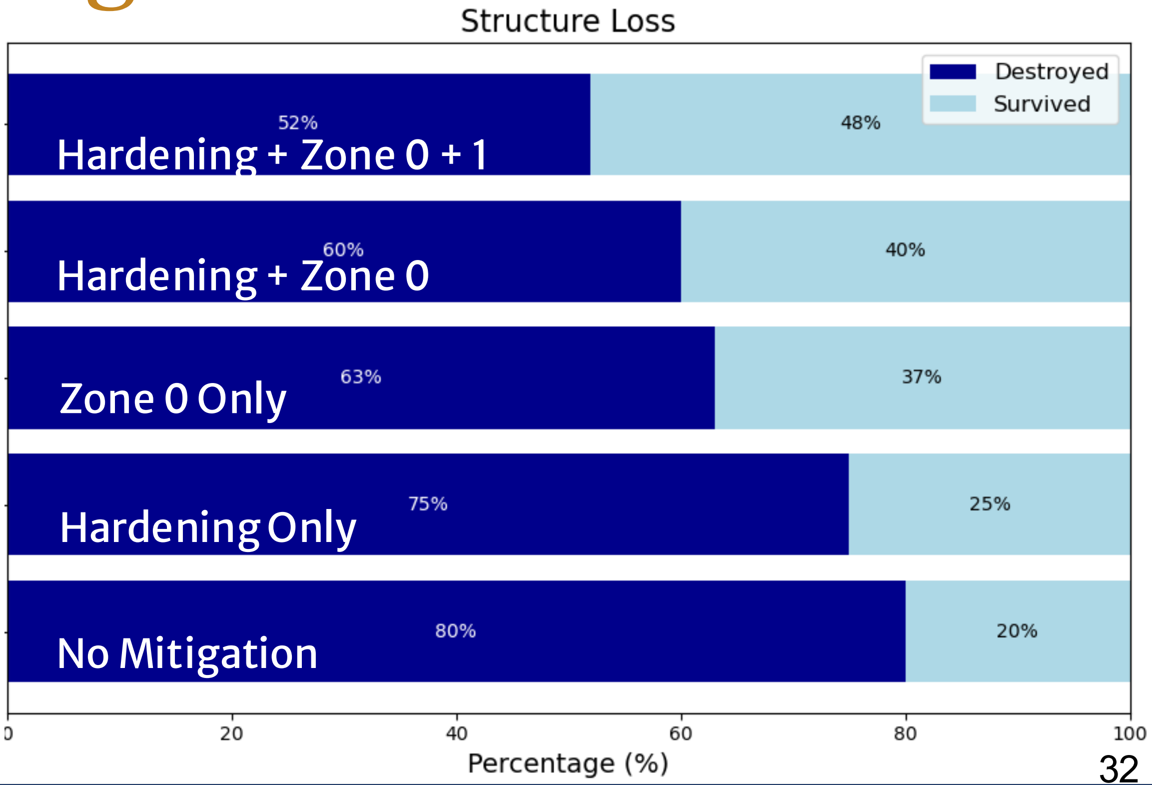
Feature Contributions Using XGBoost and SHAP Values

2020 Glass Fire



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

- Both hardening and defensible space play important roles in reducing the likelihood of structure ignition, become more effective when widespread in a community
  - Clear mechanistic reasons for preventing pathways to fire spread through mitigation
- Dense communities with little separation between structures help to support urban fire spread, however losses can still be reduced with *widespread application* of mitigation measures
- Broad evidence exists in the literature to support the effectiveness of a non-flammable Zone 0 in reducing structure ignition risk
  - Experimental, post-fire, and larger remotely-sensed studies
  - There are still gaps in the literature. It is particularly difficult to judge the effectiveness of partial application of mitigation measures, including Zone 0.
- Many questions on ornamental vegetation have arisen
  - While there is broad evidence of it contributing to fire hazard in some situations, there are few comprehensive studies.
  - No clear evidence found in the literature for a positive influence of vegetation adjacent to structures. No mechanistic evidence of ember or radiation blocking effects, currently hypotheses.

Thank you!

Work supported by Forest Health Grant 8GG21815