

ABSTRACT

Title of Dissertation: **STUDIES OF WILDLAND FIRES:
INCLINED FLAME INSTABILITIES AND
FIRE EXPOSURE TO STRUCTURES**

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The present work investigates two aspects of the wildland fire problem: instabilities occurring in inclined laminar flames and the coupling between fire exposure and structure loss. The first study analyzes the structure and stability of a laminar diffusion flame that forms either on the topside or the underside of a semi-infinite inclined fuel surface. Experiments have found substantial structural differences between flames developing on the upper and lower sides of an incline. The effect of instabilities on flame morphology is investigated as they influence the development of structures, such as peaks and troughs in the flame, observed downstream. These structures influence heat transfer processes that govern pre-heating of downstream fuels and, as a result, drive flame spread. The solution of the stability eigenvalue problem determines the downstream location at which the flow becomes unstable. The analytical solution finds that instabilities emerge farther downstream in the flame for underside flames than for topside flames, in agreement with existing experimental observations.

The latter study applies reconstruction modeling to reproduce exposure conditions

to structures from a wildland fire using 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 relation between exposure conditions, structure 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 flame and ember exposure increase the likelihood of damage or destruction; however, there is a stronger relationship between ember exposure and destruction than between flame length and destruction. Relatively low levels of ember exposure still result in relatively high likelihoods of destruction, highlighting the importance of ember spread. Current models cannot model structure-to-structure fire spread; additional limitations are highlighted for future work.

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STRUCTURES

by

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List of Abbreviations

T	temperature
v	velocity vector
x	streamwise coordinate
y	transverse coordinate
z	spanwise coordinate
<i>Abbreviations</i>	
BC	boundary condition
CALFIRE	California Department of Forest and Fire Protection
CRS	Coordinate reference system
ELMFIRE	Eulerian Level set Method of Fire Spread
GIS	Geographic information system
MC	moisture content
MODIS	Moderate Resolution Imaging Spectroradiometer
NIROPS	National Infrared Operations
PMMA	polymethylmethacrylate
RxCADRE	Prescribed Fire Combustion and Atmospheric Dynamics
Research Experiments	
SAV	surface area to volume ratio
WRF	Weather Research and Forecasting
WUI	wildland-urban interface
<i>Nondimensional Numbers</i>	
Gr	Grashof number
Le	modified Lewis number
Le_F	Lewis number
Pr	Prandtl number
Re	Reynolds number
<i>Greek Symbols</i>	
η	self-similar coordinate
μ	dynamic viscosity
ϕ	angle of inclination from the vertical
ρ	density

Θ dimensionless temperature

Subscripts

B boiling

c critical value

s stoichiometric value

w wall value

η derivative with respect to η

∞ ambient value

Chapter 1: Introduction

1.1 Problem Description

In the last decade, large wildland fires threatening communities, called wildland-urban interface (WUI) fires, have become increasingly frequent and severe. These fires have caused increasing damage and destruction to property and life across the world. For example, fifteen of California's twenty most destructive wildland fires (measured in terms of homes destroyed) have occurred from September 2015 onward [10], with the most destructive, the 2018 Camp Fire, destroying over 18,000 structures. Six of California's twenty largest wildland fires occurred in a two-month period of 2020 alone, cumulatively burning more than 2.6 million acres [10]. Globally, in the last five years alone, major destructive fires have occurred in Canada (2016), Australia (2020), Chile (2019), Greece (2018), Portugal (2017), and more places. These trends are reflected both across the United States and across the world. The increase in destructive WUI fires is anticipated to continue, due to the combined effects of climate change and increasing development in the wildland-urban interface, the area where structures and wildland fuels interface or intermix.

The wildland fire problem is multifaceted with several gaps in present research. This dissertation explores two ends of the spectrum of wildland fire problems: a

fundamental problem on inclined flame spread and an applied problem on structure loss as structures are affected by wildland fire spread. These projects are connected by wildland and WUI fire spread modeling. Many wildland fire models, particularly those used operationally, use simplified descriptions of fire spread which do not capture the complex three-dimensional heat transfer and fluid dynamics that drive forward fire spread propagation. Even physically-based computational fluid dynamics (CFD) models are unable to reliably replicate instrumented controlled fires. There are many limitations to the current wildland fire models, from lack of validation data to the enormous range of scales present in a wildland fire to understanding the underlying physics driving fire spread. The first part of this project, a study on instabilities in inclined flames, is motivated by the need to better understand flames on inclined surfaces, a configuration which frequently occurs to accelerate wildland fire spread.

Despite their limitations, operational wildland fire models are used extensively. Such models are used to make fire management and suppression decisions or used to derive ignition and fire risk throughout the world. The second portion of this project investigates the use of an operationally used wildland fire model to reconstruct the 2017 Tubbs Fire in California, the second most destructive fire in California history. This fire exposed over 8,000 structures in a period of under six hours, thus providing a large database of structure information, as well as a relatively shorter computational requirement for modeling when compared to other similarly destructive fires. Fire reconstruction provides critical insights into fire behavior and conditions which are not measured during a fire event. The fire reconstruction study is motivated by a need for simulation of exposure conditions necessary to model home destruction and make steps

toward accurate WUI fire simulation.

The 2017 Tubbs fire demonstrated how wildland fires can quickly transition to urban conflagrations resulting in significant loss of life and property; however, there are currently no widely available models to describe fire spread into and through both structures and wildland fuel in the WUI. Fire spread in the WUI occurs differently from fire spread in the wildland due to structure to structure fire spread and the role played by ember ignition. Understanding structure ignition in terms of both exposure from wildland fire and structure vulnerabilities is therefore vital to both modeling and practical decision making. The final part of this project is motivated by the ultimate goal of understanding how key features of structures and communities in the WUI are affected by wildland fire exposure to influence structure damage and destruction. A framework is constructed to describe the relationship between wildland fire exposure and structure loss in the WUI. This study uses results of the reconstruction modeling to describe fire exposure conditions. It is a key first step toward gaining the knowledge necessary for developing a WUI fire model, by understanding what features influence ignition, spread, and structure destruction.

1.2 Inclined Flames

Fires developing over inclined surfaces are commonly encountered in both the built and wildland environments. Rates of flame spread over inclined surfaces are known to be enhanced by buoyancy effects. Inclined flame spread has been a relevant topic of study in the context of fires within enclosed spaces [11] and larger-scale wildland fires.



Figure 1.1: Streaks in flame show both vortex and wave instabilities in experiments using an inclined porous gas burner of width 0.595 m [1].

While the majority of these studies have assumed the flame structure to be essentially two-dimensional, recent studies have shown that flames often form unique three-dimensional structures driven by instabilities in the flow, such as spanwise waves and streamwise streaks, shown in Figure 1.1, which may contribute to augmented heat transfer, resulting in faster flame spread [12, 13]. Additionally, studies have found that the flame lifts off the surface at some distance after having been attached to the surface previously. When the flame detaches from the surface, it changes the heat transfer mechanism governing heating to the fuel. These behaviors are also affected by whether the flame develops on the topside of an inclined surface, such as the examples given above, or on the underside of an inclined surface, such as a fire spreading on the inside of an attic. Both the structure and stability of the flame, as well as the attachment length, are altered in the underside configuration.

Despite the impact of these three-dimensional flame structures on heat transfer and

rates of spread, the instabilities developing in a flame that forms over an inclined fuel surface have not been well-studied analytically. There is a need to better understand instabilities in the flame and the impact they may have on the subsequent growth and structure of the flame. Additionally, there are still many open questions about the processes governing liftoff. Indeed, current models are unable to predict where liftoff will occur and thus are unable to describe a fundamental piece of the fire spread problem. It is expected that understanding both flame attachment and liftoff will have a significant impact on modeling flame spread [14].

In this portion of the study, topics relevant to inclined flame spread are investigated at the small scale to understand the underlying physical processes that govern flame development over an inclined surface. In order to do this, a stationary laminar diffusion flame is studied analytically. In particular, the focus is on the stability of the flame and a comparison between a developed theoretical model and laboratory experiments available in the literature. Relevant to the built-environment application, a comparison between the stability of the flame forming on the underside as opposed to the topside of a fuel surface is conducted.

1.3 WUI Exposure and Risk

As discussed previously, WUI fires are increasing in frequency and destructiveness (i.e. the number of structures destroyed annually). Current mitigation strategies to protect homes from wildfire vary extensively and, for the most part, have little quantitative data supporting their effectiveness. Certain aspects of this problem have been studied, such as

the impact of ember showers, the deposition of large numbers of small pieces of burning materials, on specific home components (e.g. roofs, decks); however, a framework to estimate and describe risk to structures from WUI fires is lacking.

Risk can be defined, generally, as the product of hazard and vulnerability [15]. 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 [15]. Despite the importance of fire exposure from the wildland, risk assessment at the community scale has neglected to include the conditions to which a structure was or may have been exposed [16, 17], primarily because such information has been out of reach.

Given the impact of WUI fires, it is critical to understand the risk to WUI communities from wildland fire, to develop tools to mitigate these risks, and, ultimately, to model fire spread through the WUI. Although some places, such as California, have begun to collect post-fire data on structure losses, this data cannot yet be correlated with unmeasured fire conditions to determine why some homes survive and others do not or are only partially damaged. This study seeks to develop a risk assessment framework for structures and communities in the WUI by leveraging reconstruction fire modeling, which can be used to connect the exposure conditions from the fire and the characteristics of a structure or community to the amount of damage a structure experiences.

In this study, structural and community risk from wildfires is investigated using a two-part methodology. To be able to predict risk from WUI fires, it is necessary to connect fire conditions with characteristics of structures vulnerable to fire exposure. Due to the

lack of measurements regarding fire conditions during an actual wildfire, the first part of this study consists of modeling a case study fire to estimate the fire exposure. Second, a risk assessment methodology framework is developed, leveraging risk assessment methods used in other disaster fields (e.g. floods, hurricanes). Incorporating fire exposure results, such as flame length and ember deposition, from simulations and mapping key structure and community features from a past wildland fire, the objective of this study is to quantify the relative importance of different components and vulnerabilities on damage due to fire exposure. This framework will provide insight into what features of structures and communities are important in determining the impact of WUI fires on communities.

Chapter 2: Literature Review

The literature relating to the two areas of study has, in general, little overlap. Sections 2.1-2.2 pertain to the study of inclined flame structure and stability, and includes a review of research on inclined flame spread, instabilities in flames and the flow over a heated plate, and flame attachment. The latter portion of the literature review, Sections 2.3-2.6 pertains to reconstruction fire modeling and the WUI risk investigation. It includes a summary of fire spread in the wildland and into the WUI, the current state of wildland fire models and validations, and risk assessment in both the WUI and relevant disaster fields.

2.1 Flame Spread

The configuration of flame spread over an inclined surface is both common and potentially dangerous, as rates of spread are often higher over inclined or vertical rather than horizontal surfaces. In a review of relevant studies on inclined flame spread, Gollner *et al.* [14] highlight the difficulty of modeling flame spread, as well as the effects of both flow and geometry on spread. Studies on upward flame spread have developed simplified theoretical models for steady laminar vertical flames [18].

A review of relevant small-scale experimental studies on flame spread of an

inclined surface is provided here. Drysdale and Macmillian [11] conducted flame spread experiments on computer cards and polymethylmethacrylate (PMMA), varying the angle of inclination of the fuel. They found that, for small angles of inclination (near the horizontal), the rate of spread reached a quasi-steady state; however, for steeper angles, the flame spread rate accelerated. Overall, the average flame spread rate was found to increase as the angle was increased from a horizontal to a vertical configuration. The authors noted a change in flame structure which occurred at 70-75° from the vertical and caused enhanced heat transfer, causing a “jump” in both flame spread rate and heat flux. This angle is consistent with the transition from an unattached to an attached flame

Quintiere [19] conducted experiments on the effects of inclination angle on the rate of flame spread for two thermally-thin materials. The experiments considered both flame spread along the top of an inclined fuel and along the underside of the fuel, as well as both gravity-assisted and gravity-opposed flow. The experiments were compared with 1-D theoretical predictions of flame spread, which used ignition temperature assumptions and correlations from heat flux and flame length data found experimentally by Ahmad and Faeth [20, 21, 22]. Theoretical predictions compared well for experiments using paper, but poorly for experiments using metalized polyethylene terephthalate, which exhibited 2-D variations in spread. The Grashof number Gr was used to determine the location where the flow transitioned to turbulence [19].

Experiments by Gollner *et al.* [23] on thermally-thick PMMA found that the maximum rate of flame spread occurred for spread along the underside of the surface at angles near the vertical. It was found that the maximum spread rate did not correspond with the maximum burning rate; rather the maximum burning rate occurred for a

horizontal configuration.

2.1.1 Structure of Stationary Inclined Flames

Flame spread is often studied using stationary flames that provide a snapshot of what the flame looks like for a moment in time during the spread. Studying stationary flames can provide valuable information about the structure of the flow and the heating mechanisms that drive spread. Many studies on stationary flames investigate the shape of the flame, often defined by the flame standoff distance, and the burning rate of the fuel.

A study by de Ris and Orloff [4] investigated the effects of angular orientation and B number on burning rates for turbulent flames. The Spalding B number is the ratio of the chemical energy released to the energy required to vaporize a unit mass of fuel [24]. Steady burning rates decreased as angle was increased from the horizontal to the vertical, with a minimum burning rate occurring near a ceiling fire configuration. This finding, which does not agree with previous results for laminar flames [25], is expected to result from the decrease in turbulent kinetic energy generation in the ceiling fire configuration. Additionally, radiative heat transfer was found to dominate over convective heat transfer for values of $B > 1.0$ [4].

Subsequent work [20, 21] on laminar and turbulent flames forming over a vertical wall investigated the validity of different theoretical predictions of burning rate, velocity, and temperature. Experimental results were compared with predictions obtained using laminar boundary-layer equations, turbulent boundary-layer equations using a mixing length model, and an integral model. The integral model neglected radiation, which

was found to be a reasonable assumption for laminar flames, where radiation comprised only 10-20% of heat flux to the surface. Negligible radiation was found to be a poor approximation for turbulent flames, where the fraction of radiant heat flux was as high as 89%.

Zhang *et al.* [26] conducted experiments on methanol and ethanol soaked porous wicks at orientations ranging from the horizontal to the vertical and considered burning both on the topside and underside of the fuel surface. The width of the wick was held constant, but the length was varied from 1 to 10 cm. Flames burning with longer wicks were found to transition to turbulence. The theoretical integral modeling approach used by Ahmad and Faeth [20, 21] was extended to include the effects of a cross-flow buoyancy term resulting from the pressure gradient in the momentum equation. This modification allowed Zhang *et al.* to improve average burning rate predictions, but did not improve flame standoff predictions, which were more than double the measured standoff distances [26]. Other theoretical predictions using laminar boundary-layer theory have also found that flame standoff predictions were 1.5 times higher than experimental data [27].

Experiments have found that the flame shape and structure change when flames develop on the underside of an inclined surface rather than the topside of the fuel surface [2, 23]. These differences can be seen for a variety of angles in Figure 2.1. Visually, the flame developing on the underside of the incline lies closer to the surface, similar to the vertical wall case. Flames on the upper surface detach for angles towards the horizontal, while flames on the lower surface continue to lie in the boundary-layer for the entire extent of the flame, even for flames near the horizontal.

Numerical studies on laminar methanol flames describe flame shape, velocity and

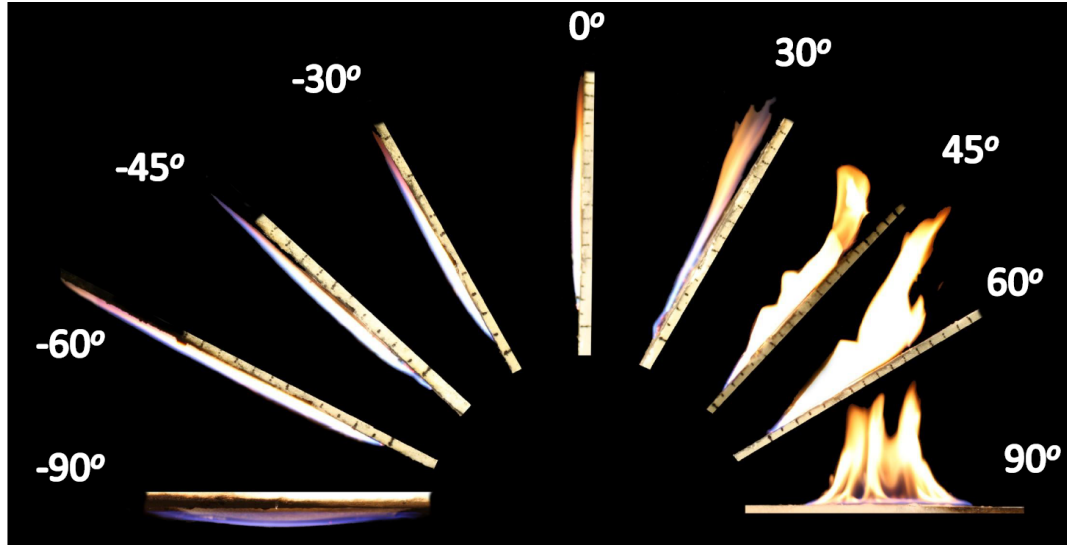


Figure 2.1: Flames form on the underside and topside of matchsticks at a range of angles from the horizontal to the vertical, image from Huang *et al.* [2].

temperature fields, and mass burning rate [6, 28]. An analytical study of cylindrical fuel surfaces oriented at angles from the horizontal to the vertical used a similarity solution to the governing equations to predict burning rate. Predictions were in agreement with experimental results for methanol; however, the theory over-predicted burning rates of higher molecular weight fuels, such as benzene and toluene. The authors attribute this poor prediction for higher molecular weight fuels either to the high sooting behavior of these fuels or to the assumption of a unity Lewis number of the fuel [29].

Additional studies have focused specifically on either horizontal or vertical burning configurations [25, 30]. Some of these results are still relevant to the inclined configuration. Experiments on small methanol and acetone flames [25] found that burning velocity for laminar flames depended only on Gr .

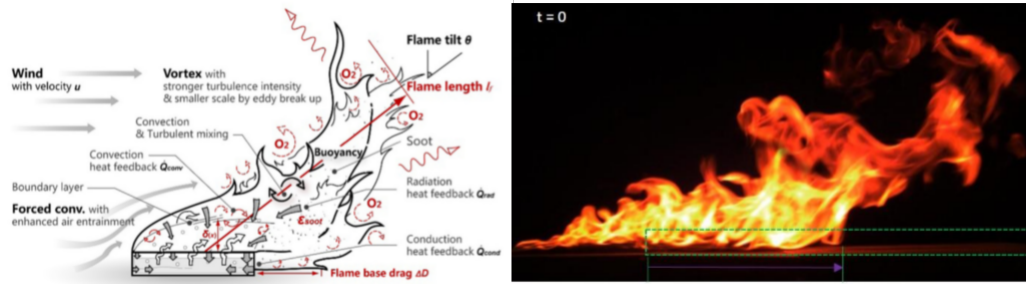


Figure 2.2: Flame attachment and liftoff shown schematically (left) reprinted from [3] with permission from Elsevier, and experimentally (right) from [1]. Both figures are under wind; nonetheless, flame shapes are analogous to what is observed for inclined flames that lift off the surface.

2.1.2 Flame Attachment and Liftoff

As shown in Figure 2.1, a flame may either lie attached to the surface or may detach or lift off from the surface. Several studies have noted that as the attachment length changes and the flame lifts off from the surface, heat transfer mechanisms change, resulting in changes in flame spread rates [11, 19, 31]. Figure 2.2 shows a schematic indicating the heat transfer processes involved when the flame lifts off from the surface [3] and a flame with the attachment length and liftoff location denoted [1]. Both of these figures are under a forced flow; however, for lower wind speeds, flames under a forced flow exhibit similar characteristics to inclined flames at small angles.

Kashiwagi and Newman [31] found that for angles below 60° , measured from the vertical, the flame appears more like a boundary-layer flame. For higher angles (closer to the horizontal), the flame separates from the surface. When the flame attaches to the surface, the spread rate increases [19]. Experiments by Drysdale and Macmillan [11] further investigated the impact of flame attachment on spread rates. By attaching sidewalls to their experimental setup, they created a “trench effect” [32], which resulted in increased

flame attachment lengths and caused large increases in flame spread rate [11].

2.2 Flow Stability

The presence of instabilities in an inclined flame can affect the structure of the flame and the development of coherent flame structures that will alter downstream heat transfer. Most instability studies in boundary layers focus on transition to turbulence, as instabilities initiate, grow, and transition the flow. Previous studies on the stability of flames have focused primarily on experimental observations. A similar problem to the stability of a flame is the stability of flow over an inclined heated plate. The solution of the stability of the flow over an inclined heated plate can provide valuable insight on how to approach solving the stability of an inclined flame. A summary of both flame stability and stability of the flow over an inclined hot plate is provided.

2.2.1 Instabilities in the Flow Over an Inclined Heated Plate

Although no previous studies have addressed the stability of an inclined flame, a similar problem, the structure and stability of the flow over an inclined heated plate, has been studied extensively over the last fifty years. Early experiments [33, 34] and theoretical analyses [35, 36] found two modes of instability, namely, a vortex instability, characterized by stationary Görtler-type streamwise vortices, and a wave instability, characterized by Tollmein-Schlichting spanwise traveling waves. These instabilities develop to form streaks and waves of finite amplitude that interact in a nonlinear fashion, eventually leading to a transition to turbulence.

Sparrow and Husar [33] found that the number of streaks across a heated plate increased as the angle of orientation was increased towards the vertical. Experiments by Shaukatullah and Gebhart [37] used thermocouples to investigate the spanwise variation of the temperature of the streaks with respect to the spanwise variation of velocity. Their measurements indicated that there was a correlation between the vortex instability, denoted by the presence of streaks, and the temperature and velocity profiles. Their results additionally found that the wavelength of the vortex instability had little dependence on inclination angle.

Cheng and Kim [38] studied the effect of the angle of inclination on the development of a secondary flow pattern, as seen from a cross-sectional view of the plate. These structures changed with angle, downstream distance, and wall temperature. The need to further determine the relationship between the instabilities and the transition from laminar to turbulent flow was highlighted [38]. Work by Kimura *et al.* [7] studied the problem of transition to turbulence further. They also found that the vortex instability influenced the transition to turbulence and that the vortices detached from the surface after the laminar boundary-layer region, enhancing the heat transfer to the surface.

A number of analytical studies have investigated the stability of the flow over an inclined heated plate to the two modes of instability described. Haaland and Sparrow [35, 36] first investigated the stability of the flow, assuming the Boussinesq approximation, and compared results assuming nonparallel flow effects with the common strictly parallel flow assumption. Considering nonparallel effects was found to have an important influence on the calculated stability of the flow. Subsequent studies, also assuming the Boussinesq approximation, investigated the stability of the flow using linear stability analyses. Most

studies utilized a temporal linear stability analysis, comparing parallel and nonparallel effects [39, 40]; one study employed a spatial linear stability analysis, assuming parallel flow [41]. This study found that theoretical predictions of the stability of the flow were enhanced by considering the growth of the perturbations [41].

While most early analytical studies assumed the Boussinesq approximation, recent analyses have considered non-Boussinesq effects in describing the structure [42] and stability [43] of the buoyancy-driven flow over an inclined heated plate. The inclusion of larger temperature differences is found to have an impact on the onset of instability. The former study on flow structure [42] found that the flows over the topside and underside of an inclined heated plate are identical. The latter [43] found that, for the topside configuration, the flow becomes increasingly unstable as the value of the plate-to-ambient temperature ratio is increased.

Both experiments and analytical studies have found that, for small values of the inclination angle ϕ below a certain crossover value ϕ_c , the wave mode was found to be dominant; for larger angles, the vortex mode was found to be dominant. Early experiments found a range of ϕ_c between 14° and 17° [34, 37] from the vertical. Linear stability analyses, both those assuming the Boussinesq approximation [39, 40] and those including non-Boussinesq temperature differences [43], predicted higher crossover angles of $\phi_c = 22^\circ$ [39, 40] and $\phi_c = 23.8^\circ$ [43] for small temperature differences. Rajamanickam *et al.* [43] found that ϕ_c increased from 23.8° to nearly 50° as the dimensionless wall temperature $\Theta_w = T_w/T_\infty$ was increased from 1.0 to 1.8. For $\Theta_w > 1.8$ no crossover angle between the wave and vortex instabilities was found, indicating that the wave mode would be dominant for all angles. The authors indicated a

need to account for transverse pressure differences in a revised stability analysis.

Some studies have looked at the transition between forced and free convection over inclined heated plates. Raju *et al.* [44] modified a mixed convection parameter, introduced for vertical flows [45, 46], which depended on Gr and the Reynolds number, Re , to provide a description of the temperature and velocity profiles for mixed convection over both horizontal and vertical surfaces. They found that a similarity solution worked well near the wall, but was a poor approximation farther from the wall.

2.2.2 Instabilities in Inclined Flames

There is a lack of quantitative data on instability development in inclined flames. Two studies explore certain aspects of instabilities for vertical and wind-driven flames. An experimental study by Blackshear and Murty on vertical flames [25] observed the location of instability onset as a distance from the leading edge, denoted visually by flame wrinkles. They varied the molecular weight of the fuel and did not find a strong correlation between the molecular weight of the fuel and the onset location of instabilities.

A study of flames under wind found similar streak-like structures to those observed over an inclined heated plate [13]. Flame streaks occurred at locations of velocity perturbations. The streak-like structures were amplified with the development of the flame downstream. The authors expect that these instabilities affect the heat transfer and promote the transition to turbulence. Measured heat fluxes were found to be highest in the regions between flame streaks, which was attributed to the flame lying closer to the surface in those regions [13]. A subsequent study found that the streaks merged and

formed coherent structures which had a larger length-scale than the upstream streaks [47].

2.3 Fire Spread

The subsequent literature review is relevant to wildland fire spread modeling and WUI risk analysis. A review of fire spread specifically related to the wildland is provided, as the growth and behavior of a fire must be modeled in order to perform fire reconstruction analysis. Wildland fire modeling is primarily based on formulas describing the rate of flame spread, which are related to fuel, topography, and ambient conditions. Here we review how fire spreads through both the wildland and the WUI. Understanding mechanisms of fire spread provides insight into understanding the exposure conditions that structures may experience.

2.3.1 Three Flame Spread Processes in Wildland and WUI Fires

Fire can spread into the WUI and ignite structures via three pathways: radiation, direct flame contact, and firebrands [48]. A structure can ignite via radiation either from the main flame front of the wildland fire or from the radiation of a nearby, flaming structure. Despite the high radiative heat fluxes from a large flaming front, such high heat fluxes are not often sustained for a long enough period of time to make radiation the primary form of structure ignition. Additionally, due to the fact that radiative heat flux is proportional to distance squared, structures not immediately abutting the wildland are unlikely to reach critical ignition heat fluxes. A study by Cohen [49] investigated the ignition of wooden sheds due to radiant heating by a full crowning fire (a fire in which the

canopy of the forest is fully involved) at different separation distances. Only sheds within 10 m of the fire ignited; sheds at farther distances did not ignite. Adjacent structures, on the other hand, can be both closer to a home than the main fire front and burn for a longer period of time. As a result, structure-to-structure spread is another ignition pathway.

Ignition via direct flame contact occurs when there is an unbroken fuel path that leads from the wildland fire to a structure, such as a wooden fence, mulch, or ornamental vegetation. Ignition occurs due to flames directly in contact with structural elements of a home [48]. This ignition pathway is often addressed by clearing the area around a structure of vegetation with the cleared area often termed defensible space.

Burning embers, also known as firebrands, are small pieces of burning material which are lofted in the fire plume and may travel large distances in front of the fire [48, 50]. Embers can be generated both from vegetation and structural elements and range in size from a few grams to, on rare occasions, small logs. Embers can land either in a glowing or flaming state, but commonly land in the glowing state as flames are suppressed when they are lofted in the fire plume. Embers commonly form piles on structural elements [51] and may smolder for several hours [52] before transitioning to flaming and causing structure ignition. Embers are found in post-fire investigations, discussed in Section 2.4.1, to be responsible for the majority of structure ignitions [53]. Although embers cause the majority of structure ignitions, there are many gaps in the understanding of ember generation, transport and ignition [50]. In general, generation of and ignition by embers has been understudied. Transport has been more studied and transport models (reviewed in [48]), in particular maximum transport distance models, are used to describe the influence of embers in many wildland fire spread models.

2.3.2 Wildland Flame Spread through Vegetation

The previous section focused specifically on wildfire spread into and through the WUI. Flame spread through the wildland, specifically vegetation, follows the same overarching methods with some key differences. Wildfires spread through vegetation via the same mechanisms of radiation, flame contact, and ember transport; however, it is more helpful to think of spread through vegetation as occurring via two methods, the main fire front and ember ignitions.

Whereas in WUI fire spread direct flame contact plays a relatively smaller role, flame contact is a critical driver of the spread of the fire front through the wildland. Radiation and convection both play key roles in advancing the flame front by igniting vegetation. Flame spread can occur in different regions of vegetation: along the ground, along the surface, or through the tree crowns. Fire spread along the ground refers to spread through duff, downed needles, etc. Often, ground spread may occur via smoldering rather than flaming. Flaming spread occurs primarily along surface fuels such as grasses, shrubs, and other fuels where vegetative matter is below the canopy. Crowning occurs when the flaming surface fire transitions into the canopy of a contiguous area of trees and spreads through the canopy rather than (or faster than) along the surface.

In addition to flame spread, spread in vegetation can also occur via spotting. As described in the previous section, embers can be generated both from vegetation and structural elements and are lofted in the fire plume. Spotting occurs when an ember or several embers land in vegetation and ignite a new fire. In wind-driven fires, spotting plays a major role in driving forward fire spread [54].

2.4 WUI Structural Vulnerabilities

The pathways of fire spread into the WUI represent the different mechanisms leading to structure ignition or the exposure mechanisms with respect to risk. The effect on a structure of this fire exposure is altered depending on the vulnerabilities of a structure [55]. Post-fire investigations and experiments provide (often qualitative) information on structural vulnerabilities. Despite the fire and building codes that recommend methods to mitigate specific structural vulnerabilities, there is little quantitative data available on the usefulness of mitigation methods or which vulnerabilities are the main contributors to structure loss.

2.4.1 Post-Fire Investigations

For most wildland fires, basic information such as the number of structures damaged or destroyed, the size of the final fire perimeter, and the ignition location is recorded. For some wildland fires, often fires for which there is substantial damage, more complete investigations are conducted. Such investigations are used to draw conclusions about structural vulnerabilities and mechanisms of structure ignition. For example, most past fire investigations have found that embers are responsible for the majority of structural ignitions during WUI fires. Embers are regularly estimated to be responsible for more than 50% of structure ignitions in a WUI fire [56, 57].

In the United States, the National Institute of Standards and Technology (NIST) has conducted several detailed post-fire investigations, including of the Witch and Guejito fires in California in 2007 [53, 58], the Waldo Canyon fire in Colorado in 2012 [59], and

the Camp Fire in California in 2018 [60, 61, 62]. The Insurance Institute for Business and Home Safety (IBHS), also in the United States, investigated the 2017 and 2018 California wildfire seasons [63].

Ramsay *et al.* [56] surveyed 1153 homes affected by the Ash Wednesday fires that occurred in Australia on 16 February 1983. The authors defined six damage levels for the homes affected by the fires; however, they also noticed that most damage was either minimal or total. Subsequent studies and post-fire investigations by the California Department of Forestry and Fire Protection (CALFIRE) and others have found similar results in their investigations [64], that most structures damaged by wildfires experience either minimal damage or complete structural destruction. A study by IBHS [63] surveying fires which occurred in California in 2017-2018 found similar results.

A detailed investigation of the Witch and Guejito fires in San Diego in 2007 found that decks were significant sources of home ignition, with decks ignited by embers or local flame contact, and the ignited deck serving to ignite the main structure [53, 58]. Investigations also found that 45% of homes with attached fences were destroyed. Additionally, vegetation near the home was found to substantially increase the chance of ignition in comparison to homes without vegetation. Spread in these fires was found to be primarily structure-to-structure. Preliminary results found that firefighter interventions made a large difference in increasing the likelihood of structure survival, but were specifically more effective if other risk mitigation had been implemented.

The 2012 Colorado Waldo Canyon fire investigation [59] highlighted similar home vulnerabilities and fire spread mechanisms, with both decks and wood fences being major sources of ignition. This investigation more extensively looked into the effect of fire

service intervention, again highlighting its critical role in saving homes. The effects of firefighter intervention were also highlighted by the IBHS study [63].

A series of NIST investigations of the 2018 Camp Fire [60, 61, 62], the most destructive fire in California history which damaged or destroyed 19,531 structures and resulted in 85 fatalities, assessed damage to 132 residential structures. The investigation focused on fire progression reconstruction [62] using over two thousand observations about fire spread and behavior. This study highlighted the pathways for structure ignition and spread into the WUI and noted that extreme destruction occurred even in communities which were well-prepared for the fire. Additionally, this study highlighted that fire conditions varied *substantially* both spatially and temporally. These conditions varied significantly even from parcel to parcel (on the structure level) [62]. Temporal aspects of spot fires were shown by analyzing the cumulative number of spot fires over the time of the fire in the town of Paradise. Steady increases in the number of spot fires were noted during the first 1-1.5 hr of measurement, followed by a decline in new spot fires. Additionally, although spot fires were densest on the edge of the community, spot fire ignition occurred throughout the entire community, highlighting the importance of ember ignition for WUI fire spread. The study notes the ignition type for a selection of individual buildings and the distance from the source of ignition (e.g. a shed or fence) to the structure itself.

A post-fire investigation of the California wildfires of 2017 and 2018 by IBHS [63] noted evidence of structure-to-structure spread and investigated the effect of different structural vulnerabilities and characteristics on home survival. Defensible space was an important characteristic of homes that survived, but was alone insufficient to guarantee

survival. The investigation found that mitigation strategies appeared to be effective up to a certain “thermal exposure intensity”, but above a certain exposure, wildfire resistant building materials and design had limited effectiveness. The authors posited that mitigation strategies, while sometimes insufficient in themselves, make it so that firefighters have more time to respond, a critical aspect of saving homes. The IBHS study [63] found that, on its own, building attribute data “offered little predictive value”. They indicated the likelihood of a home surviving is affected by many complex factors. These results highlight the need to consider exposure characteristics, previously not investigated in the literature, to try to disentangle what factors may have a large impact on home survivability.

2.4.2 Experimental Studies of Structural Vulnerabilities

Some of the structural vulnerabilities highlighted in post-fire investigations have been the subject of experiment or research studies. IBHS and the UL Firefighter Safety Research Institute conducted studies on home to home spread under mild winds to investigate the effect of spacing between homes (summarized in [63]). They found that substantial structure-to-structure spread occurred when homes were fewer than 10 feet apart. A summary of structural vulnerabilities is provided in a review by Hakes *et al.* [55].

2.5 Wildfire Spread Modeling

Overall, there are a number of wildland fire models available, ranging from models that can be used operationally to research models. These models include physical, semi-physical or semi-empirical, and empirical models. The goal of a wildland fire model is to predict the characteristics of the fire, such as the rate of spread (ROS), fireline intensity, and flame length. The models we consider simulate both spatial and temporal behavior of the fire. All of these models have limitations, due in part to the number of open research areas associated with wildland fire spread, as well as the vast range of scales which occur in wildland fires (ranging from mm scale for pyrolysis to km scale for weather). Additionally, the inputs required to model a wildland fire are difficult to measure. Currently, wildland fire models do not attempt to describe spread within the WUI. A few attempts have been made to model spread within the WUI [65, 66]; however, all of these make substantial assumptions and have so far had limited practical utility.

Physical models focus on replicating physical mechanisms which drive fire spread; however, due to substantial computational requirements, these models currently have limited operational use. Semi-physical models pair physical observations of small-scale phenomenon with dimensional analysis to describe the process over the large range of scales experienced in a wildland fire. Semi-physical or semi-empirical models are the most commonly used, at least in the United States. Empirical models provide a statistical description based on observation, and do not include the driving physical mechanisms. These are limited to uses under their tasks conditions.

Fujioka 2002 [67] investigated the errors present in wildland fire modeling,

applying the error methods to the 1996 Bee Fire in San Bernardino National Forest. The study highlighted errors from measurement, such as a fire perimeter improperly located, causing the user to provide incorrect initial conditions or compare with incorrect validation data. The study also highlighted model specification error, such as using the wrong input variables with the wrong functional form. These types of errors are compounded when models are also used for weather simulations which are in turn used as input to the fire models. In a study calibrating the semi-empirical model, FARSITE, for use in Northern Iranian forests, Jahdi *et al.* [68] noted similar sources of error. They additionally discussed sources of error from the accuracy of spatial fuels, distance from a weather station to the location of a fire, and user error.

2.5.1 Rothermel Forward Fire Spread Model

The most commonly used semi-empirical model for flame spread through the wildland is the Rothermel model [69]. It is implemented as the underlying spread model in the vast majority of semi-empirical wildland fire models. Due to its prevalence and its usage in the fire model, ELMFIRE which is used in the studies discussed later in the dissertation, a brief summary of it is provided.

The Rothermel model is based on a conservation of energy calculation of a control volume immediately preceding a spreading flame front. It is based on a model of flame spread through a homogeneous porous fuel bed developed by Frandsen [70]. The Rothermel model assumes a homogeneous fuel bed and steady state spread. The original Rothermel model with its assumptions of steady state and homogeneity cannot be applied

in its present form to wildland fire models.

The Rothermel model calculates the rate of spread (ROS) in the direction of maximum spread with the following equation:

$$ROS = \frac{I_R \xi (1 + \Phi_w + \Phi_s)}{\rho_b \varepsilon Q_{ig}} \quad (2.1)$$

where I_R is the reaction intensity (kW/m²), providing a relative measure of the heat-release rate from the fire; ξ is the propagating flux ratio (-), used to estimate the forward heat flux to unburned fuels, assuming a linear relationship with the reaction intensity; ρ_b is the bulk density of the fuelbed (kg/m³); ε is the surface heating number (-), empirically related to the surface area to volume ratio; Q_{ig} is the heat of preignition required to vaporize unignited fuels and moisture (kJ/kg); and Φ_w and Φ_s are dimensionless factors to account for effects of wind and slope, respectively [69, 71]. The wind and slope factors are effectively multipliers meant to account for spread that takes place under winds greater than 0 m/s and non-flat terrain as the ROS relationship was originally developed spread without wind. Both wind and slope are known to increase the rate of spread of the fire. The current implementation of wind and slope does not account for the physical mechanisms driving these increases. The mechanisms driving sloped and wind-driven spread are active areas of research in the wildland fire field. A number of modifications, discussed below, allow the Rothermel model to be implemented in the widely used 2D operational models.

2.5.2 Expanding Rothermel Spread to 2D

The Rothermel equation describes the spread in the direction of maximum ROS, making it essentially a 1D calculation. Ultimately, surface fire spread needs to be described in 2D (i.e. assuming x, y coordinates along the plane of the earth's surface, with a z coordinate orthogonal to the surface) to be applicable to modeling full fires. In particular, it is necessary to modify Rothermel's spread model to account for spread rates in directions other than the maximum forward rate of spread. The assumptions of homogeneity and steady state are addressed by solving the spread model on a cell-by-cell basis, assuming that the fuels within a single cell are homogeneous.

A number of modifications of Rothermel's equation allow it to be translated from 1D to 2D. These are outlined by Richards [72]. Modifications for slope and wind are provided by Anderson [73] and modified in FARSITE [74]. Empirical models, such as the one described by Alexander [75], are employed to represent the fire as an ellipse, thus allowing for different rates of forward spread, spread along the flanks, and backing spread. When implemented in a fire model, it is necessary to obtain inputs related to vegetation/fuels. The process of retrieving inputs will be discussed in more detail with the case study in Chapter 5.

There are two additional components of fire spread, no longer in the 2D plane: ember spread or spotting and crown fire spread (which, neglecting transition, can be thought of as spreading in a separate, higher, 2D plane). Embers spread the fire by spotting, which occurs when an ember is lofted in the fire plume, transported away from the main fire front, and ignites a new fire upon landing. Crown fire is the spread of

a flaming fire front in the crowns of trees, rather than along the surface. Crown fires typically have a greater rate of spread than surface fires. The transition to crowning is not well understood.

The relationship between ROS and fireline intensity is described using Byram's equation [76]:

$$I = H_f L R O S \quad (2.2)$$

where I is the fire line intensity, H_f is the heat content of the fuel, and L is the fuel load consumed by the flaming front.

2.5.3 Validation Studies

Although the previous sections have focused primarily on operational models built on Rothermel spread, the discussion of validation is applied widely to all types of wildland fire models. Both empirical and semi-empirical models are lumped here with physically-based models because there are a number of limitations of validating wildland fire models, regardless of the type.

Various studies have investigated aspects of past fires using simulations or have attempted to validate models using past fires, both prescribed burns and wildland fires. These two types of fires provide validation data with inherent differences, mainly because prescribed burns are often instrumented to provide *more* data at better spatial and temporal resolutions than is available from a wildland fire. Having both prescribed burns and wildland fires as validation data can provide data for fires at a range of intensities, from low to high intensity.

The most relevant validation using prescribed burns is the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiments (RxCADRE) experiments [77], a series of prescribed burns on different scales conducted from 2008-2016. Linn *et al.* [78] modeled prescribed burns from the RxCADRE experiments using FIRETEC, a physics-based couple fire-atmosphere model. To attempt to reproduce one of the small scale RxCADRE burns, the authors developed heterogeneous fuel inputs and dynamic wind conditions. They found that results were highly sensitive to uncertainties in the inputs, and that there were “ambiguities” in producing inputs from field data. Additionally, they noted that the fire environment and inputs changed on a scale of meters to tens of meters, though the burn they modeled was one of the most consistent. Overall, they summarized that FIRETEC was not fully able to reproduce the low intensity fire due to the “challenges of sufficiently characterizing the dynamic and heterogeneous burn environment when directly comparing simulated quantities with observations” [78].

Perry *et al.* [79] simulated a relatively small (580 ha) wildland fire which burned in Cass Basin, South Island, New Zealand in May 1995 using the model PYROCART, which is based on Rothermel’s spread model. The purpose of this study was to test the applicability of the Rothermel model, developed in the United States, for fuels in New Zealand. The study found that fuel type and slope were main drivers of fire spread. The authors investigated the quantitative predictive performance of the model for different fuel classes as a function of slope and wind. The model overestimated rates of spread under high winds. The authors highlighted a number of limitations of their model, including the lack of a sufficient amount of validation data.

Coen *et al.* [80] reconstructed the 2017 Tubbs Fire, using the model Coupled

Atmosphere-Wildland Fire Environment (CAWFE), a coupled fire-weather model, to investigate the effects of small-scale wind variations. This study compared a reconstruction of the fire with a forecast simulation of the fire. The reconstruction fire used available wind data throughout the fire, while the forecast simulation only used the wind data available at the time of ignition. The forecast simulation was able to match the time of arrival of the fire at Santa Rosa, California; however, the reconstruction underestimated the arrival of the fire at Santa Rosa by an hour. One limitation of the CAWFE model is the lack of explicit inclusion of embers [80]. This work showed that extreme wind occurred “on hills in the WUI of the larger ridges”. The study highlighted that weather stations were unable to capture extreme events, due to a distance between stations an order of magnitude larger than the spatial magnitude of the weather variations.

Zigner et al. [54] investigated the ability of the fire model FARSITE (Fire Area Simulator) to simulate wildfires in extreme wind events by comparing two fires which occurred in Santa Barbara, California: the Painted Cave fire in 1990 and the Sherpa fire in 2016. The study found that FARSITE was able to accurately reconstruct fire size and spread rate for fires with minimal spotting or ember activity; however, when spotting was a major contributor of spread, FARSITE was unable to accurately simulate the fire. This limitation is particularly important, as many large WUI fires occur under extreme wind conditions, where spotting is a major contributor to fire spread.

Lautenberger [81] validated the fire model ELMFIRE by simulating the first 22 hours of spread of the 2007 California Moonlight Fire. ELMFIRE was able to reproduce fire areas reasonably well. The study highlighted that the model was unable to take into account suppression activities and so overpredicted spread along the flanks.

A study of structure-to-structure spread in informal settlements in South Africa [82] used a semi-probabilistic risk model to simulate the 2017 Imizamo Yethu fire in the Hout Bay Valley, South Africa. The model assumed only radiant ignition without embers. The model was found to over-predict fire spread in a number of the zones considered, which the authors attributed to firefighter intervention in the actual event. Although this study is not on WUI fire spread, it is expected that structure-to-structure spread in the WUI will share characteristics. In the WUI, however, it is critical to include the effects of embers.

2.6 Risk Assessment Methods and Studies

As defined previously, risk is the product of both exposure conditions and the vulnerabilities in the structures which are exposed to the fire. As a result, it is necessary to understand the possible exposure conditions from the fire, as well as which aspects of a structure that are vulnerabilities. The most common risk assessments conducted for wildland fires focus occur on the landscape scale and typically focus on potential ignition of or fire spread in a given landscape with regards to resource management [15, 83, 84]. A hazard and risk analysis framework by Scott, Thompson, and Calkin [15] characterizes the likelihood of wildfire in a landscape and its potential impacts on highly valued resources and assets. Their framework does not apply to the community-scale or structure-level risk. Partially, this framework has not been extended due to the lack of data about wildfire conditions at the structure-to-structure level and the current inability of fire models to model spread in the WUI. Of interest to the present work is structure and community risk associated with WUI fires. A review of studies on aspects of community

risk is presented, followed by a discussion of risk assessment methodologies used in other fields which can potentially be applied to wildland fires.

2.6.1 Risk Studies of WUI and Risk Assessment Methods

There are few studies that investigate risk to structures from a wildland fire. This gap is partially due to the difficulty of getting any information about exposure conditions to which a structure was exposed during a fire. On the other hand, it is possible to get some information about the structures themselves, their characteristics and vulnerabilities, and the damage they sustained in a fire. Previous studies on community risk focus primarily on structure characteristics and the surrounding community characteristics.

Jones *et al.* [85] present a framework for quantifying risk from severe and extreme wildland fires, where risk is defined as the “combination of the probability of an event and its negative consequences”. They discuss four potential hazards from wildland fires: embers, radiant heating and direct flame contact, severe wind, and smoke. They recommend the development of fragility curves to correlate damage with the expected hazard. Fragility curve development is followed by damage curve development, which relates financial costs to the exposure. The final step in their framework is the creation of exceedance probability curves, to be compared with historical data, which relate the likelihood of a given wildfire event with the maximum possible loss. They do not apply this proposed framework to any fire events which have occurred.

Studies by Alexandre [16] and Syphard [17] investigate the roles of vegetation, topography, structural characteristics, and spatial arrangement of buildings in relation

to structure loss in wildland fires. The former [16] found that landscape was more important than vegetation as an indicator of structure ignition and that the spatial arrangement of housing was another key indicator of ignition. The latter [17] found that individual structural characteristics played a more important role than defensible space in determining which structures survived or were destroyed by fire. It highlighted the most important characteristics as enclosed eaves, vent screens, and multi-pane windows, as these features rebuffed ember penetration into the house. A major limitation of these studies with regards to risk is that they do not consider exposure conditions from the fire. Although vegetation and topography may be loosely correlated with fire conditions, they cannot predict or describe exposure conditions in of themselves, due to the highly variable and nonlinear relationship between fire spread, fire conditions, and inputs.

The only study of community risk that considers exposure conditions uses the empirical fire model PHOENIX to model seventeen fires that occurred in Victoria, Australia [86]. This study considered over 15,000 houses on an undamaged/destroyed basis, 3572 of which were destroyed. House destruction was found to be a function of landscape characteristics, including vegetation distance, topography, distance to the nearest structure, and fire characteristics. Landscape characteristics and fire behavior were each found to contribute equally to home destruction, which was predicted using a tree-based machine learning model. Convection was found to have the strongest correlation with destruction.

Overall, the main limitations of the current risk assessment studies in the literature is that they do not consider exposure conditions from the wildfire. Due to the complexity of wildfire spread and heating, vegetation and topography data are insufficient to predict

fire conditions.

2.6.2 Relevant Risk Studies and Methodologies of Other Natural Disasters

Risk analysis in the wildland fire field has generally focused on the landscape scale, as there has been insufficient data and available models to move to a smaller community or structure-to-structure prediction level. Other fields studying natural disasters that impact human developments have developed methodologies to perform risk analyses at various scales. Many of these disaster fields, such as hurricanes [87], floods [88], and earthquakes [89], have more fully developed risk assessment metrics, particularly with regards to risk to structures given certain exposure conditions from these disasters.

A common risk assessment method for other natural disasters is the development of fragility curves. Fragility curves provide a relationship describing the probability of a structure of a given building “class” experiencing a certain “level” of damage as a function of the level of some intensity measured experienced by the structure. There are several components of this function to consider. Building classes are defined as structures with a set of features which cause them to react in a distinctly different manner to the same intensity level as structures of a different class. For example, in developing fragility curves for earthquakes, the construction material of the building (e.g. concrete, wood) and the number of stories both may create distinct classes because these different building types could be damaged differently from each other, even when exposed to exactly the same level of ground motion intensity. The “level” of damage, also called the damage

state, describes distinct qualitative levels of damage, such as light, moderate, severe, or destroyed. These categorizations often relate to the expected economic impact of repairing (or rebuilding) a structure. FEMA provides normalized damage states [90]. The damage state of a building is determined based on a post-event inspection. Finally, an intensity level describes a certain feature of the disaster to which each structure is exposed (e.g. flood height in a flood [88], ground motion in an earthquake [89], or wind gust speed in a hurricane or tornado). Similar assessments can be conducted for economic impact and loss of life.

Fragility curves can be developed analytically, from experimental data, or from empirical data collected after disasters. A key difference to note when considering the application of risk assessment methods from other fields to WUI fires is that fragility curve development tends to assume a relatively even spread of buildings exposed to a range of conditions and resulting in a range of damage states. While this assumption is appropriate for other disasters, structures exposed to wildfires tend to fall either into an undamaged class or a destroyed class [56, 63]. While some buildings are partially damaged, the relative number of those buildings is much smaller than either of the other damage states. As a result, it can be difficult to have statistically significant data for the assessment of partially damaged buildings and rare to have a sufficient number of partially damaged homes to further split the “partially damaged” state into sub-classes.

2.7 Summary and Study Motivation

With regards to inclined flames, there is a large body of literature addressing various aspects of the flame spread problem. There are a number of studies that attempt to provide theoretical predictions of flame standoff and average burning rate. Although some burning rate predictions are in reasonable agreement with experimental results, most theoretical predictions over-estimate the flame standoff distance. Additionally, there are currently no correlations or theoretical predictions able to capture flame attachment length or the detachment location of the flame. Experiments on flames, both for an inclined configuration as well as under wind, have observed instabilities which influence the downstream development of flame structures. Although there are a number of studies that analyze the stability of the flow over an inclined hot plate, there are no current theories that provide predictions for the stability of a flame formed over an inclined fuel surface.

There are a large number of problems related to WUI fires that are actively being studied. While there is a fairly good understanding of how wildland fires spread into the WUI on a general scale, substantial gaps exist in our understanding of how to quantitatively model fire spread through the WUI. Relevant studies include post-fire investigations and experimental studies aimed at understanding home vulnerability to wildfire, ways to harden structures, and methods to increase community resiliency. A number of studies investigate these cases and the limitations of current wildland fire models, with respect to both reconstructing and predicting fires. A number of studies also look at landscape level risk of ignition both near communities and other assets; however, there is limited research on the risk to structures given a wildland fire. Current

risk assessment studies to that end have neglected the impacts of differing levels of fire exposure. Methods such as fragility curves are used in other disaster fields to predict the probability of damage to structures.

Chapter 3: Steady Inclined Laminar Flame Structure

The present work consider flow over an inclined plate over which a diffusion flame burns the fuel vaporized from the surface with the oxygen in the surrounding air atmosphere. It extends previous non-Boussinesq studies on the flow over an inclined hot plate. The theoretical analysis provides the steady solution of a two-dimensional flame which is used as the base flow for the subsequent temporal linear stability analysis (Chapter 4). This chapter presents the theoretical formulation and results for the base flow.

The study of the two-dimensional base flow had three main objectives. The first was to create an analytical model that could describe the structure of a steady flow developing over an inclined fuel surface. The second objective was to use this model to quantitatively model a large variety of fuels by accounting for variable mean mixture densities and non-unity Lewis numbers of the fuel. The final objective was to implement this model to calculate base flow profiles which could be perturbed in order to examine the stability of the flow.

3.1 General Theoretical Formulation

The laminar flow induced by a flame burning over a semi-infinite fuel surface inclined at an angle ϕ from the vertical is shown schematically in Figure 3.1. The flow is described in terms of Cartesian coordinates aligned with respect to the angle of the plate, including the streamwise coordinate x , the transverse coordinate y , and the spanwise coordinate z , with corresponding velocity components $\mathbf{v} = (v_x, v_y, v_z)$. The gravity vector is $\mathbf{g} = -g \cos \phi \bar{e}_x - g \sin \phi \bar{e}_y$, where g is the magnitude of the gravitational acceleration and the $\bar{e}$'s are unit vectors in the subscript direction. The differences between the topside and underside flame are a result of the transverse gravitational acceleration $-g \sin \phi$, negative on the topside ($\phi > 0$) and positive on the underside ($\phi < 0$). The fuel surface is assumed to be a vaporizing liquid fuel at the boiling temperature T_B . The conservation equations describing this flow include the continuity and momentum equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (3.1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla p}{\rho} + \frac{1}{\rho} \nabla \cdot [\mu (\nabla \mathbf{v} + \nabla \mathbf{v}^T)] + \left(1 - \frac{\rho_\infty}{\rho}\right) \mathbf{g} \quad (3.2)$$

where ρ , μ , and $\mathbf{v}$ represent the dimensional density, dynamic viscosity, and velocity of the gas, and the subscript ∞ denotes ambient air properties. The flow is characterized by small values of the associated Mach number, so that the spatial variations of the pressure are much smaller than the ambient value. In (3.2), p denotes the sum of the pressure difference from the ambient hydrostatic value and the isotropic component of the stress tensor.

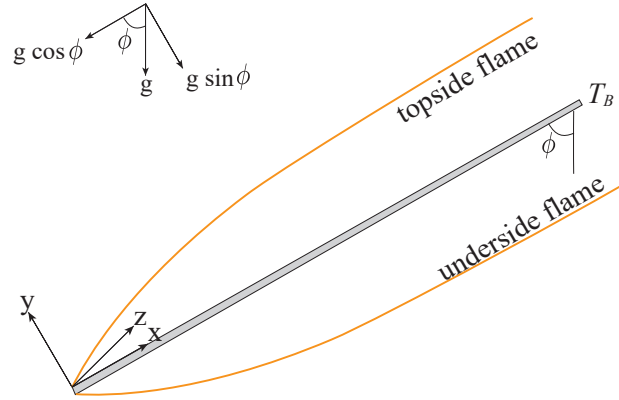


Figure 3.1: A schematic representation of the flame forming over the topside or the underside of an inclined fuel surface. The coordinate system is indicated for a topside flame; for the underside flame, the y -coordinate points in the opposite, downward, direction.

The reaction between the fuel and the oxygen in the air is taken to occur according to a global irreversible single step reaction $F + sO_2 \longrightarrow (1 + s)P + q'$, where s is the mass of oxygen consumed per unit mass of fuel burnt and q' is the amount of heat released per unit mass of fuel burnt. These thermochemical parameters appear in the equations below as $S = s/Y_{O_2A}$ and $q = q'/(c_p T_\infty)$, involving the ambient oxygen concentration $Y_{O_2A} \simeq 0.232$, the ambient temperature T_∞ , and the specific heat at constant pressure c_p , assumed to be constant. Values of S , the mass of air needed to burn a unit mass of fuel vapor, are of order $S \sim 6$ for alcohol fuels and $S \sim 15$ for alkanes, while the ratio q/S is approximately $q/S \simeq 7$ for the fuels of interest considered here.

The associated conservation equations for the reactants and energy are

$$\rho \frac{\partial Y_F}{\partial t} + \rho \mathbf{v} \cdot \nabla Y_F = \nabla \cdot \left(\frac{\rho D_T}{Le_F} \nabla Y_F \right) - w_F \quad (3.3)$$

$$\rho \frac{\partial Y_O}{\partial t} + \rho \mathbf{v} \cdot \nabla Y_O = \nabla \cdot (\rho D_T \nabla Y_O) - S w_F \quad (3.4)$$

$$\rho \frac{\partial}{\partial t} \left(\frac{T}{T_\infty} \right) + \rho \mathbf{v} \cdot \nabla \left(\frac{T}{T_\infty} \right) = \nabla \cdot \left[\rho D_T \nabla \left(\frac{T}{T_\infty} \right) \right] + q w_F \quad (3.5)$$

where Y_F and $Y_O = Y_{O_2}/Y_{O_2A}$ are, respectively, the mass fractions of the fuel vapor and of the oxygen, the latter normalized with its air value, D_T is the thermal diffusivity of the gas mixture, T is the temperature, Le_F is the Lewis number of the fuel vapor, and w_F is the mass of fuel consumed by the chemical reaction per unit volume per unit time.

The resulting boundary conditions in the farfield are

$$v_x = v_y = p - p_\infty = T - T_\infty = Y_O - 1 = Y_F = 0 \quad \text{as} \quad (x^2 + y^2) \rightarrow \infty \quad \text{for} \quad y \neq 0 \quad (3.6)$$

and on the surface are

$$\left. \begin{aligned} v_x = T - T_B = 0 \\ \rho v_y Y_F - \frac{\rho D_T}{Le_F} \frac{\partial Y_F}{\partial y} = \rho v_y \\ \rho v_y Y_O - \rho D_T \frac{\partial Y_O}{\partial y} = 0 \\ \rho v_y \left(\frac{T}{T_\infty} \right) - \rho D_T \frac{\partial}{\partial y} \left(\frac{T}{T_\infty} \right) = -l_v \rho v_y \end{aligned} \right\} \quad \text{at} \quad y = 0 \quad \text{for} \quad x > 0. \quad (3.7)$$

Vaporization of the liquid fuel is taken to occur at the boiling temperature of the fuel with latent heat of vaporization L_v . A dimensionless heat of vaporization $l_v = [L_v + c_l(T_B - T_\infty)]/(c_p T_\infty)$ is introduced to account for the energy required to raise the temperature of the liquid fuel, with specific heat c_l , from the ambient temperature T_∞ to the boiling temperature T_B .

In the limit of infinitely fast reaction rates considered here, the flame appears as a infinitesimally thin surface separating an oxygen-free near-plate fuel region from the surrounding fuel-free air. Following [8, 91] the problem is formulated in terms of coupling functions accounting for general non-unity values of Le_F . The description includes two

different mixture fractions

$$Z = \frac{SY_F - Y_O + 1}{S + 1} \quad \text{and} \quad \tilde{Z} = \frac{SY_F/Le_F - Y_O + 1}{S/Le_F + 1} \quad (3.8)$$

and a modified enthalpy

$$\xi = \frac{T/T_\infty - 1 + (q/S)(Y_O - 1)}{T_B/T_\infty - 1 - q/S} \quad (3.9)$$

satisfying the associated transport equations

$$\rho \frac{\partial Z}{\partial t} + \rho \mathbf{v} \cdot \nabla Z = \frac{1}{Le} \nabla \cdot (\rho D_T \nabla \tilde{Z}) \quad (3.10)$$

and

$$\rho \frac{\partial \xi}{\partial t} + \rho \mathbf{v} \cdot \nabla \xi = \nabla \cdot (\rho D_T \nabla \xi). \quad (3.11)$$

Here $Le = (S + 1)/(S/Le_F + 1)$ is an effective Lewis number.

The conservation equations are supplemented by the equation of state written in the low-Mach number form

$$\frac{\rho}{\rho_\infty} \frac{T}{T_\infty} = \left[Y_F \left(\frac{W_A}{W_F} - 1 \right) + 1 \right], \quad (3.12)$$

which accounts for the large density variations associated with the presence of the fuel vapor, with W_F and W_A representing the molecular masses of the fuel and air, respectively.

The presumed power law

$$\frac{\mu}{\mu_\infty} = \frac{\rho}{\rho_\infty} \frac{D_T}{D_{T,A}} = \left(\frac{T}{T_\infty} \right)^\sigma \quad (3.13)$$

with $\sigma = 0.7$ is used in the numerical integration for the temperature dependence of the transport properties.

To solve (3.10) and (3.11) coupled with (3.1) and (3.2) and supplemented with (3.12) and (3.13), T , Y_F , and Z must be related to ξ and $\tilde{Z}$. These relations can

be obtained by using the equilibrium condition

$$Y_F Y_O = 0 \quad (3.14)$$

associated with the infinitely fast reaction limit. Both reactants reach the flame with zero mass fraction, so that the flame values of the mixture fraction variables are $Z = Z_S = 1/(S + 1)$ and $\tilde{Z} = \tilde{Z}_S = 1/(S/Le_F + 1)$. Using the equilibrium condition (3.14) and the definitions (3.8) and (3.9), it follows that

$$Y_O = 0 \quad \text{and} \quad Y_F = \frac{Z - Z_S}{1 - Z_S} = \frac{\tilde{Z} - \tilde{Z}_S}{1 - \tilde{Z}_S}, \quad \frac{T}{T_\infty} - 1 = \left(\frac{T_B}{T_\infty} - 1 \right) \xi + \frac{q}{S} (1 - \xi) \quad (3.15)$$

on the fuel side of the flame sheet, where $\tilde{Z} \geq \tilde{Z}_S$, and

$$Y_F = 0 \quad \text{and} \quad 1 - Y_O = \frac{Z}{Z_S} = \frac{\tilde{Z}}{\tilde{Z}_S}, \quad \frac{T}{T_\infty} - 1 = \left(\frac{T_B}{T_\infty} - 1 \right) \xi + \frac{q}{S} \left(\frac{\tilde{Z}}{\tilde{Z}_S} - \xi \right) \quad (3.16)$$

on the air side of the flame sheet, where $\tilde{Z} \leq \tilde{Z}_S$. Equations (3.15) and (3.16) provide piecewise linear relations for the evaluation of Y_F , Y_O , and Z in terms of $\tilde{Z}$, and T in terms of $\tilde{Z}$ and ξ .

To complete the problem, boundary conditions are given in the farfield

$$v_x = v_y = p - p_\infty = \tilde{Z} = \xi = 0 \quad \text{as} \quad (x^2 + y^2) \rightarrow \infty \quad \text{for} \quad y \neq 0 \quad (3.17)$$

and at the fuel surface

$$\left. \begin{aligned} v_x &= \xi - 1 = 0 \\ -\rho D_T \frac{\partial \xi}{\partial y} &= \alpha \rho v_y \\ -\rho D_T \frac{\partial \tilde{Z}}{\partial y} &= Le_F \rho v_y (1 - \tilde{Z}) \end{aligned} \right\} \quad \text{at} \quad y = 0 \quad \text{for} \quad x > 0, \quad (3.18)$$

where $\alpha = l_v / [(q/S) + 1 - T_B/T_\infty]$. Note that the boundary condition $\xi = 1$ corresponds to the condition $T = T_B$ at the fuel surface, where $Y_O = 0$.

3.1.1 Formulation of the Solution for a Steady Flame

For the following analysis of the two-dimensional, steady, laminar flame forming over a semi-infinite fuel surface, radiation is neglected. Our interest lies in the slender boundary-layer region that develops over the fuel surface at distances x from the plate leading edge, which is large compared with the size $\delta_{\text{NS}} = [\nu_{\infty}^2/(g \cos \phi)]$ of the Navier-Stokes region [42]. An order-of-magnitude analysis of the continuity and momentum equations provides the following estimates for the boundary-layer thickness δ and the associated streamwise and transverse velocity components, u_c and v_c

$$\delta = (\nu_{\infty}^2 x)^{1/4} (g \cos \phi)^{-1/4}, \quad u_c = (xg \cos \phi)^{1/2}, \quad \text{and} \quad v_c = (\nu_{\infty}^2 g \cos \phi / x)^{1/4} \quad (3.19)$$

as they vary with x . These values are used in writing dimensionless conservation equations for the base flow. The solution is expressed in terms of the self-similar coordinate

$$\eta = y (\nu_{\infty}^2 x / g \cos \phi)^{-1/4} \quad (3.20)$$

and the dimensionless temperature and stream function

$$\Theta(\eta) = T/T_{\infty} \quad \text{and} \quad \psi = \rho_{\infty} (\nu_{\infty}^2 x^3 g \cos \phi)^{1/4} F(\eta) \quad (3.21)$$

defined such that

$$U = v_x / (xg \cos \phi)^{1/2} = F' / \bar{\rho} \quad (3.22)$$

$$V = v_y / (\nu_{\infty}^2 g \cos \phi / x)^{1/4} = \frac{1}{4} (\eta F' - 3F) / \bar{\rho}. \quad (3.23)$$

where the prime is used to denote differentiation with respect to η .

The problem reduces to the integration of (3.2), (3.10), and (3.11) written in the self-similar form

$$[\Theta^\sigma (F'/\bar{\rho})']' + \frac{3}{4}F(F'/\bar{\rho})' - \frac{1}{2}(F')^2/\bar{\rho} + 1 - \bar{\rho} = 0 \quad (3.24)$$

$$(\Theta^\sigma \tilde{Z}')' + \frac{3}{4}LePrFZ' = 0 \quad (3.25)$$

$$(\Theta^\sigma \xi')' + \frac{3}{4}PrF\xi' = 0 \quad (3.26)$$

with boundary conditions

$$F' = \tilde{Z} = \xi = 0 \quad \text{as} \quad \eta \rightarrow \infty \quad (3.27)$$

$$F' = \xi - 1 = 0 \quad \text{and} \quad \frac{3}{4}Pr\Theta_B^{-\sigma}F = \xi'/\alpha = \tilde{Z}'/Le_F(1 - \tilde{Z}) \quad \text{at} \quad \eta = 0, \quad (3.28)$$

corresponding to (3.17) and (3.18).

3.2 Numerical Method for Solution of the Base Flow

The solution of (3.24)-(3.26), independent of the inclination angle, is complicated by discontinuities in the derivatives of the density and temperature at the flame sheet. In order to overcome this difficulty, the problem is split into two domains separated by the flame surface $\eta = \eta_s$. In each domain, the system of ordinary differential equations is solved using a Chebyshev spectral method, using the MATLAB library `chebfun` [92]. Splitting the domain introduces unknown conditions at η_s , which are solved iteratively using a standard Newton-Raphson algorithm.

The location of the flame, described by the stoichiometric line $Z = Z_s$, is not known ahead of time and is therefore part of the solution. A re-scaled coordinate ζ is introduced

as

$$\zeta = \frac{\eta}{\eta_s} \quad (3.29)$$

so that the stoichiometric point always occurs at $\zeta = 1$. When we rewrite the equations (3.24)-(3.26) in terms of ζ , the variable η_s is introduced into the base flow equations, which then become

$$4 \left[\Theta^\sigma (F'/\bar{\rho})' \right]' + 3\eta_s F (F'/\bar{\rho})' - 2\eta_s (F')^2/\bar{\rho} + 4\eta_s^3(1 - \bar{\rho}) = 0 \quad (3.30)$$

$$4 \left(\Theta^\sigma \tilde{Z}' \right)' + 3\eta_s Le Pr F Z' = 0 \quad (3.31)$$

$$4 \left(\Theta^\sigma \xi' \right)' + 3\eta_s Pr F \xi' = 0 \quad (3.32)$$

where the prime denotes derivation with respect to ζ . Equations (3.30)-(3.32) are solved in separate domains: (A) the fuel side for which $0 \leq \zeta \leq 1$, and (B) the oxidizer side for which $1 \leq \zeta \leq \zeta_{\max}$ where $\zeta_{\max} \rightarrow \infty$. Because the flame conditions are unknown, these boundary conditions are assumed initially on side (A). Each domain requires seven boundary conditions which must be given in the farfield

$$F' = \tilde{Z} = \xi = 0 \quad \text{for} \quad \zeta = \zeta_{\max}, \quad (3.33)$$

at the flame

$$F = F_s, \quad F' = F'_s, \quad \tilde{Z} = \tilde{Z}_s, \quad \xi = \xi_s \quad \text{at} \quad \zeta = 1, \quad (3.34)$$

and at the fuel surface

$$\left. \begin{aligned} F' &= \xi - 1 = 0 \\ \tilde{Z}' &= \frac{3}{4} Pr Le_F \eta_s (1 - \tilde{Z}) F \Theta_B^{-\sigma} \\ \xi' &= \frac{3}{4} Pr \alpha \eta_s F \Theta_B^{-\sigma} \end{aligned} \right\} \quad \text{at} \quad \zeta = 0. \quad (3.35)$$

The boundary conditions above overdefine the fuel side problem by providing four boundary conditions both at the flame and on the fuel surface; however, the condition on F' at the flame is used to couple the domains rather than as a boundary condition. The iteration is conducted until $|\rho'_B F'_B / \rho_B - \rho'_A F'_A / \rho_A|, |\tilde{Z}'_B - \tilde{Z}'_A|, |\tilde{Z}'_B - \tilde{Z}'_A| < 10^{-5}$. The self-similar base flow is solved using the transport, thermochemical, and vaporization properties of methanol, ethanol, and heptane, given in Table 3.1.

Table 3.1: Fuel properties used in numerical integration

	W_F/W_A	l_v	θ_B	Le_F	q/S	S
Methanol	1.1	2.87	1.12	1.2	7.7	6.47
Ethanol	1.59	2.29	1.17	1.4	7.35	8.98
Heptane	3.46	1.14	1.24	1.8	7.0	15.2

The present chapter presents the results of the inclined flame theory. The first portion of the chapter presents the results for the base flow which describes the structure of the flame. These results are compared to the theory for the inclined heated plate as well as relevant experiments on inclined flames in the literature. The second half of the chapter presents the results of the stability analysis. These results are compared with the results for the stability of flow developing over an inclined heated plate. Experiments are not available in the literature on the stability of flames.

3.3 Structure of an Inclined Flame

Results for the base flow, including dimensionless profiles of the streamwise and transverse velocity, dimensionless temperature, and dimensionless density, are shown in Figure 3.2. These profiles differ considerably from those obtained previously for the

heated plate [42], which are reproduced and shown later in this chapter. The flame profiles exhibit discontinuities in slope at the flame, which is located at $\eta_s = 6.9, 7.3,$ and 8.5 for methanol, ethanol, and heptane, respectively. These discontinuities are clearest in the temperature profile.

Perhaps unexpectedly, differences in the flame location between different fuels remain relatively small, a result that can be attributed to cancellation of competing effects. For example, the large Le_F of heptane indicates that it is less diffusive than the alcohols, which would lead us to anticipate a flame that lies closer to the plate. On the other hand, the stoichiometric parameter S for heptane is considerably larger than for methanol or ethanol, which would cause the flame to lie farther from the plate than the alcohol flames. The two effects tend to cancel each other out, with the result that the heptane flame lies only slightly farther from the plate than do the alcohol flames. The most significant differences between the base flow of the heptane and alcohol flames are found in the density profiles, with the heptane flame exhibiting larger density differences than the alcohol flames, a result of the disparities in molecular weight.

One of the assumptions made in this analysis is that the Lewis number of the fuel is constant and non-unity. The effect of considering a non-unity Lewis number is shown in Figure 3.3. The “fuel” considered in comparison to heptane uses the molecular weight and thermo-chemical parameters of heptane, but assumes a unity Lewis number. The unity Lewis number implies that the thermal and mass diffusivities are equal, whereas the larger Lewis number for heptane indicates a lower mass diffusivity. This lower mass diffusivity would cause the flame to lie closer to the surface. As expected, the mock fuel with a unity Lewis number and the properties of heptane has a flame that lies farther from

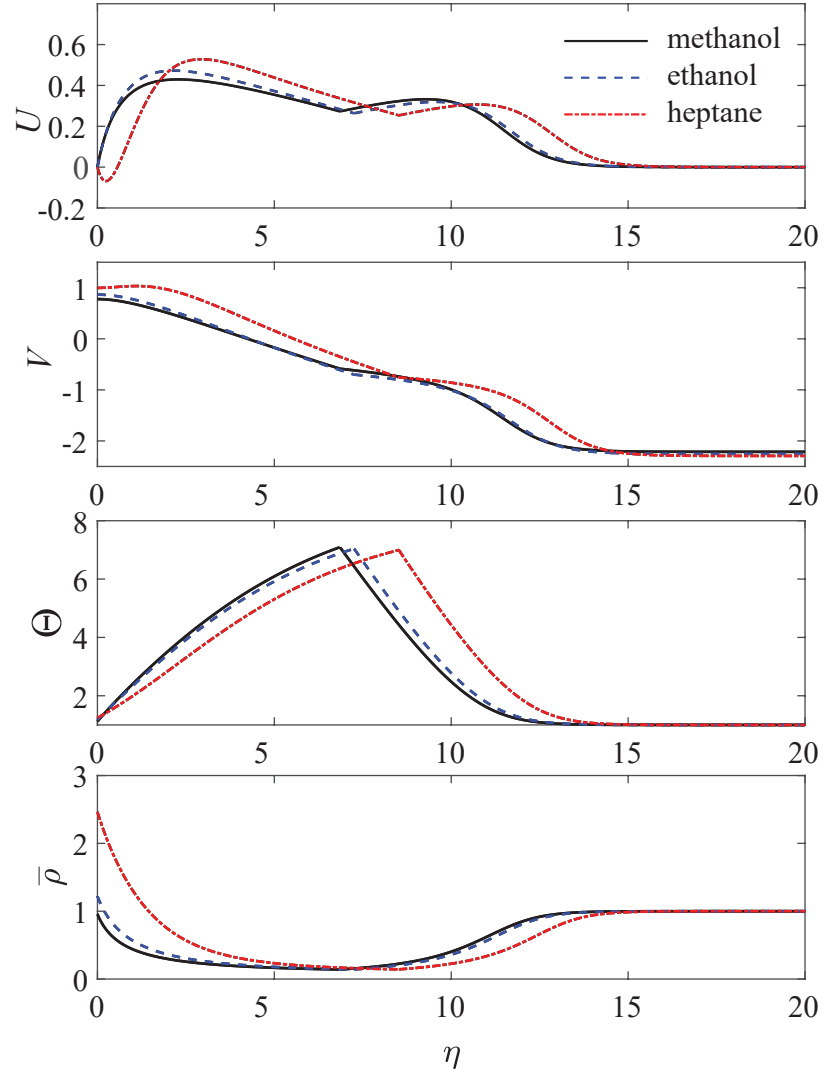


Figure 3.2: From top to bottom: dimensionless measures of streamwise and transverse velocity, following (3.22), dimensionless temperature, and dimensionless density as a function of η .

the fuel surface, at $\eta_s = 10.1$ in comparison to a heptane flame with non-unity Le_F at $\eta_s = 8.5$

Additionally, the flame temperature reached by the fuel with unity Lewis number is higher. This result can be explained by observing that the two mixture fractions become equivalent when $Le_F = 1$, and that the stoichiometric mixture fractions are used to define the flame location η_s .

3.4 Comparison of Base Flow Results with Literature

3.4.1 Inclined Heated Plate

The results for the velocity and temperature profiles of a steady flame can also be compared to the base flow profiles of the flow over an inclined heated plate. A key difference between the inclined flame and the inclined plate is that the inclined flame produces higher temperature differences than most studies on the hot plate have computed. Additionally, the maximum temperature for the inclined flame occurs away from the plate at the flame location, whereas the maximum temperature for the inclined hot plate occurs on the plate itself.

A comparison of the results for a methanol flame and an inclined isothermal plate with the wall temperature set to the boiling temperature of methanol are shown in Figure 3.4. As expected, the temperature profile of the flame shows a distinctly different profile than the temperature profile over the heated plate. The inset shows the shape of the temperature profile for the flow over the inclined heated plate. As a result of the higher temperatures produced by the flame, the velocities produced are also much higher, and

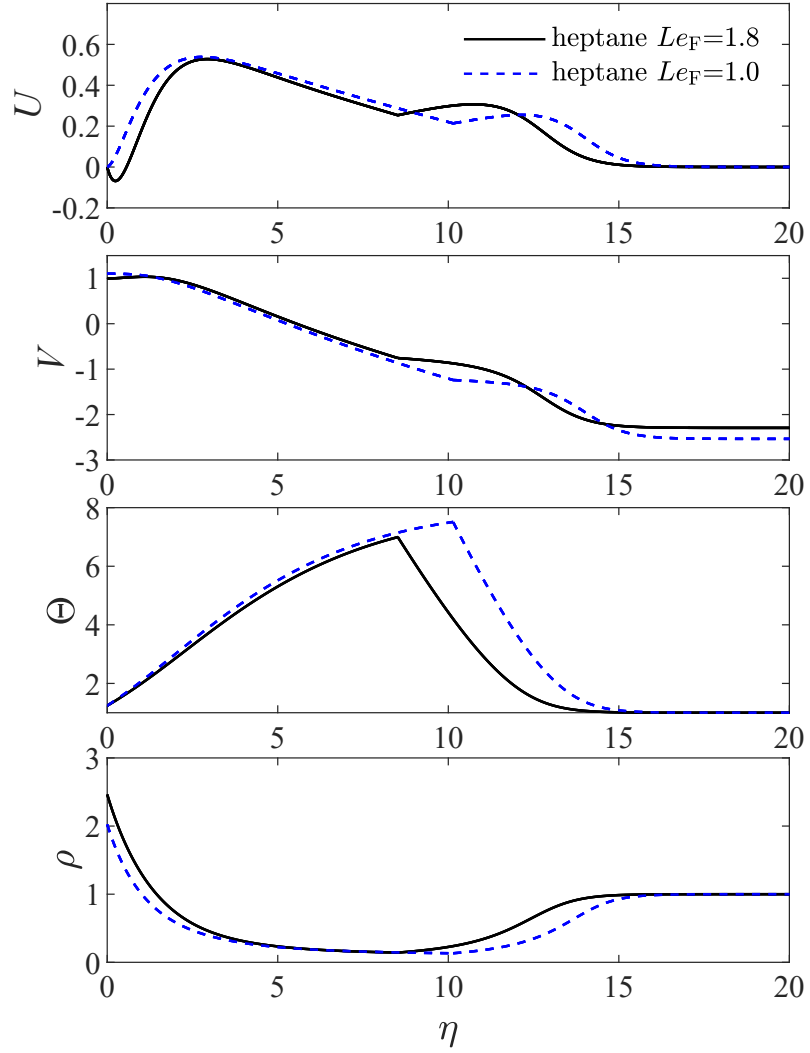


Figure 3.3: From top to bottom: dimensionless measures of streamwise and transverse velocity, following (3.22), dimensionless temperature, and dimensionless density as a function of η , comparing a flame with thermo-chemical properties of heptane and a mock fuel with the parameters of heptane, but a unity Le_F .

the shape of the velocity profile is altered due to the flame's density differences.

3.4.2 Burning Rate

Using the base flow results, an average burning rate can be calculated as

$$\dot{m}'' = -F(0)\rho_{\infty}\nu_{\infty}^{1/2}(g \cos \phi / L)^{1/4} \quad (3.36)$$

where $L = 0.10m$ here is a finite length along the plate over which the burning rate is averaged. This theoretical prediction of burning rate can be compared to burning rate data in the literature, as shown in Figure 3.5. The experiments conducted by Singh consider a steady-burning laminar methanol diffusion flame forming over a 0.08 m x 0.08 m square liquid-soaked wick. The experimental setup was also used for vertical tests [93]. Ali *et al.* [6] numerically simulated the steady burning of a 11 mm long methanol-soaked wick in 2-D. Experiments by de Ris and Orloff [4] were conducted using a 0.65 m high gas burner with sidewalls for a range of B-Numbers. The results shown here consider $B = 0.25$. Ohtani *et al.* [5] conducted experiments on PMMA of various sizes; the results shown here are for a 0.1 m x 0.1 m square. All results have been normalized with respect to the maximum burning rate for each study in order to better illuminate the trends present. Variations in fuel type and flame regime (i.e. laminar, transitional, turbulent) may account for different trends in different studies. In particular, the results of de Ris and Orloff [4] follow a different trend than the other results, likely because of their larger setup with higher proportions of radiation. The present theory calculates the average burning rate well for angles close to the vertical; however, at angles near the horizontal, burning rate becomes increasingly under-predicted. In particular, the theory cannot calculate the

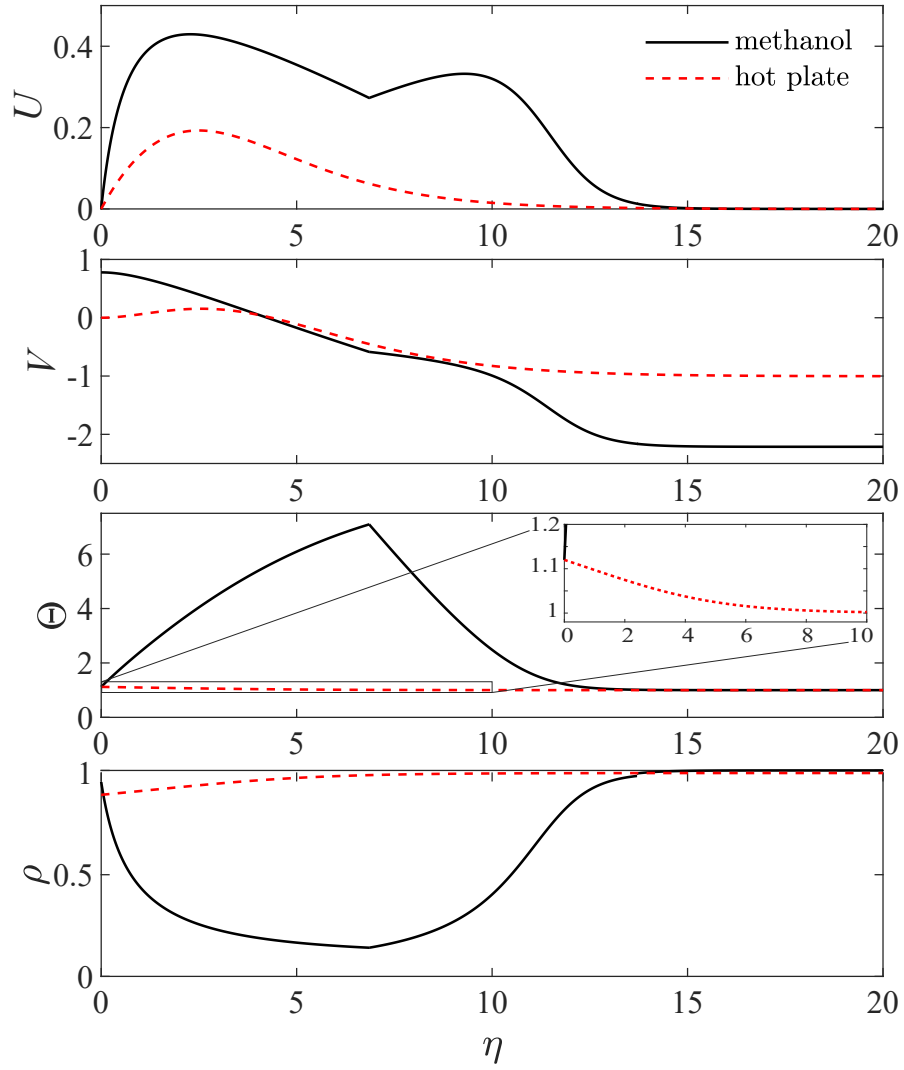


Figure 3.4: From top to bottom: dimensionless measure of streamwise velocity, following (3.22), dimensionless temperature comparing a methanol flame and a heated plate with the wall temperature equal to the boiling temperature of, and dimensionless temperature as a function of η for the same inclined plate.

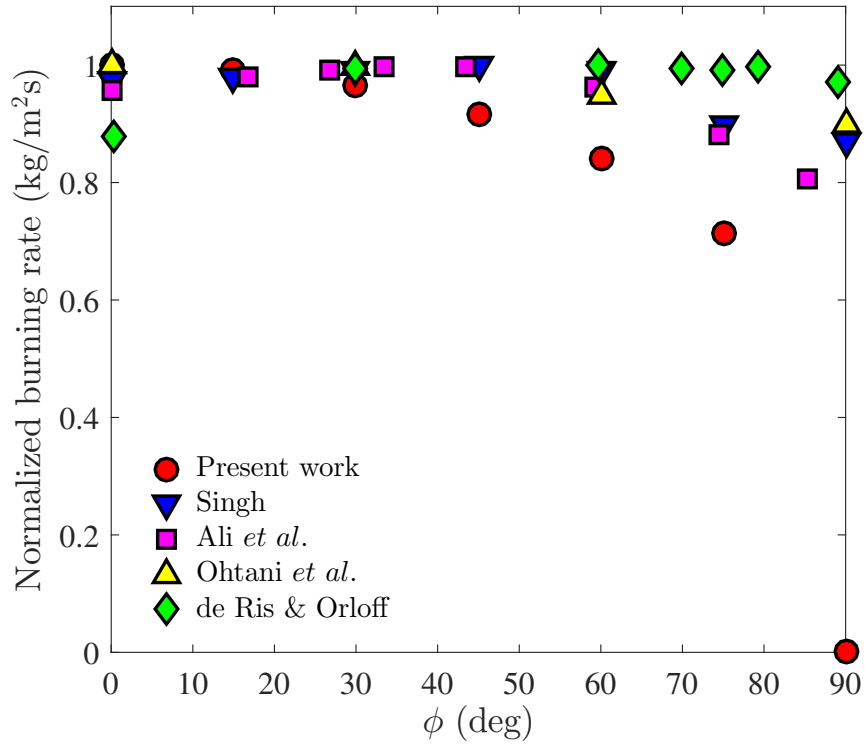


Figure 3.5: A comparison of theoretically calculated burning rate with experimental data from Singh (unpublished), de Ris and Orloff [4], and Ohtani *et al.* [5] and numerical results from Ali *et al.* [6], burning rates normalized with respect to the respective maximum burning rates from each study.

burning rate for the horizontal configuration, for which the pressure differences across the boundary layer, negligible in the self-similar inclined analysis, become significant.

3.4.3 Flame Shape

The current analysis of a steady flame predicts many flame characteristics, such as temperature profiles, velocity profiles, and flame standoff from the surface. When the theoretical predictions of flame standoff distance are compared to experimental results, as shown in Figure 3.6, comparisons work well for flames that lie in the boundary-layer; however, the theory fails to show that flames closer to the horizontal detach from the

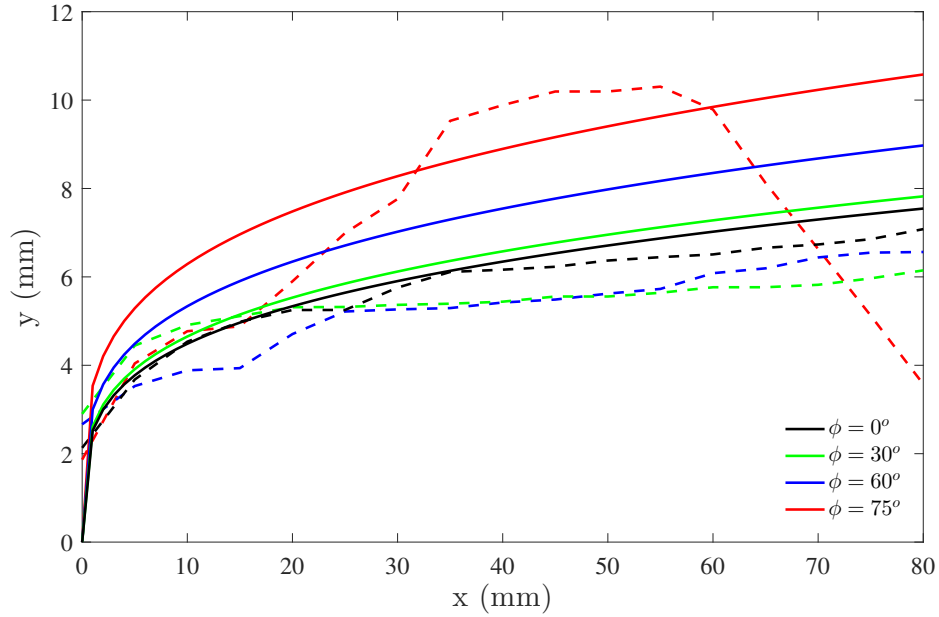


Figure 3.6: A comparison of predicted flame standoff distances (solid lines) with measured flame standoff distances from a laminar methanol diffusion flame (dashed lines) from Singh (unpublished) for a range of angles, where x is the distance along the fuel surface and y is the distance above the surface.

surface. The literature survey showed that flames lift off from the surface, particularly at angles higher than 60° from the vertical [2, 19, 31], but the predicted flames stay attached to the surface. The difference in predicted and real flame structure is clear for $\phi = 75^\circ$ in Figure 3.6. The flame standoff distances are in sufficient agreement until approximately $x = 60$ mm, at which point the experimental flame detaches from the surface. The analytical assumption of self-similarity is therefore only appropriate for flames at lower angles or for the early portion of a flame nearer the horizontal. In order to capture the flame attachment lengths and lift off locations, a revised analysis would need to be conducted.

3.5 Discussion and Limitations of Base Flow Analysis

The current analysis assumes negligible radiation, a common assumption for laminar flames. Indeed, experimentally, radiation has been found to be small in comparison to convection for small-scale flames [25] with radiation for laminar methanol, ethanol, and 1-propanol flames found to account for only 10-20% of the overall heat flux to the surface [20]. Nonetheless, a numerical study of inclined laminar methanol flames compared results with and without an optically thin radiation model and found that when radiation was neglected, the flame temperature was over-predicted by 250°C [30]. Over-prediction of flame temperature is expected to be higher for more sooty fuels, such as heptane, in comparison to methanol, for example.

Several methods of including radiation have been proposed in the literature. Kim *et al.* [29] proposed modifying either the heat of combustion or the heat of vaporization to mimic the effects of radiation. Similarly, Moreno-Boza *et al.* [94] suggested lowering the value of the heat released per unit mass of fuel burnt (q/S in our study) so that the predicted flame temperatures match experimental values in literature. There are potential difficulties with this method, particularly if there is not experimental data in a comparable configuration available. Several studies use the mass-transfer B-Number in analyses considering combustion. Although the original formulation of the B-Number does not consider radiation [95], subsequent studies have defined modified B-Numbers that include flame radiation for a transparent flame [96, 97], as well as modifications to include external radiation and consider semi-transparent flames [98]. The current problem could be reconsidered in terms of the B-Number, with a modified B-Number used to account

for radiation effects. Overall, the negligible radiation assumption is appropriate for small laminar flames, but radiation becomes increasingly important as flames are larger.

The comparison between studies on average burning rate shown in Section [3.4.2](#) indicates that the present theoretical analysis is unable to predict burning rates for the horizontal flame case. Part of the reason for the inability to predict the horizontal case is that the present analysis is limited to the inclined and vertical cases. For a burning inclined fuel surface, the pressure forces are negligible in the first approximation because of the larger influence of the buoyancy force. For a flame burning on a horizontal surface in a quiescent environment, the pressure gradient becomes of equal importance in driving the flow. In order to consider a flame burning over a horizontal surface, an additional analysis considering the effects of the pressure gradient would need to be conducted. This analysis would additionally have different expressions for the self-similar coordinate and stream function than are found for the inclined case.

Material and figures presented in the present chapter are partially reproduced from and based on the author's published work in R.S.P. Hakes, W. Coenen, A.L. Sánchez, M.J. Gollner, F.A. Williams, Stability of laminar flames on upper and lower inclined fuel surfaces, *Proceedings of the Combustion Institute* (2021) 38(3): 4515-4523, DOI: 10.1016/j.proci.2020.06.302 [[99](#)].

Chapter 4: Stability of an Inclined Flame

The base flow describes the steady structure of a laminar flame burning over an inclined surface. The flame is known to become unstable at a finite distance from the leading edge. It is expected to exhibit two modes of instability, depending on the angle of the fuel surface, a spanwise wave-type instability and stationary Görtler-type streamwise vortices. These modes of instability have been observed in experiments on the flow inclined heated plates [7, 33], see Figure 4.1; both streamwise vortices and spanwise waves have been observed experimentally in inclined flames [1], see Figure 4.2.

The stability study employed a temporal linear stability analysis. The objectives of this analysis were: first, to establish a mathematical framework to predict instabilities in inclined laminar flames; second, to investigate the effects of angle of inclination and fuel properties on the onset of instabilities. This onset is governed by the Grashof number Gr ; above a critical value of the Grashof number Gr_C , one of the instability modes begins to exhibit a positive growth rate. The characteristics of that mode and the Gr_C at which it becomes unstable determine the nature of the instability that initially develops and the position along the inclined plate at which that development occurs, for any given ϕ .

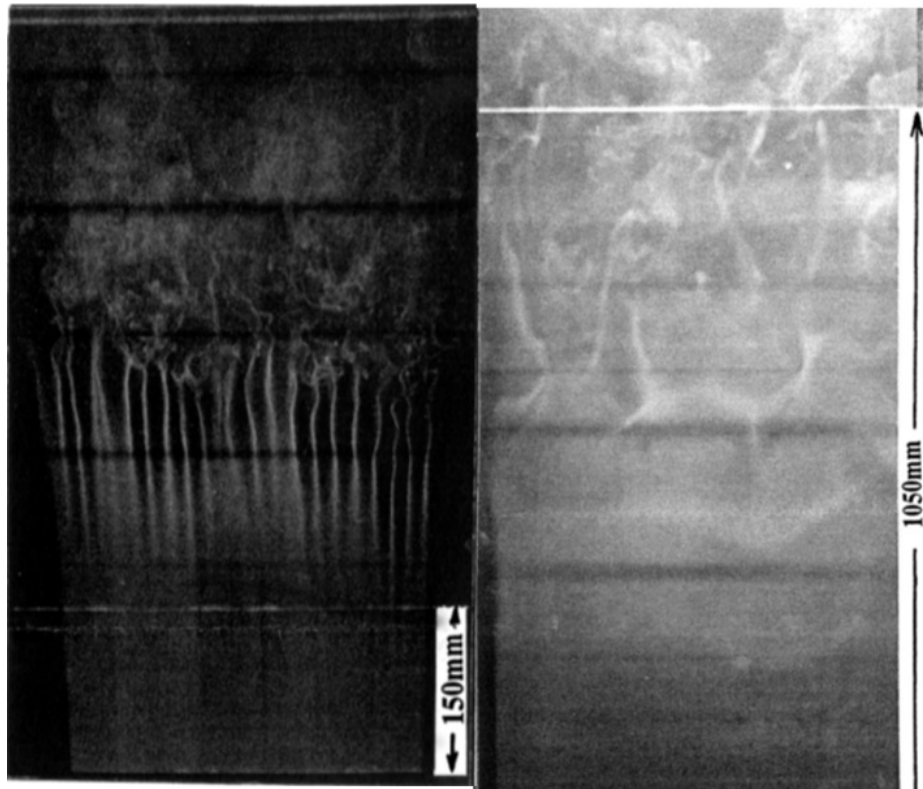


Figure 4.1: Flow instabilities observed experimentally in heated plate experiments with water used as the fluid, visualized with uranine dye; left: vortex mode, $\phi = 75^\circ$, right: wave mode, $\phi = 0^\circ$ (vertical), both images from [7], reproduced with permission from Wiley Materials. The left image shows a transition to turbulence downstream from the streaks.

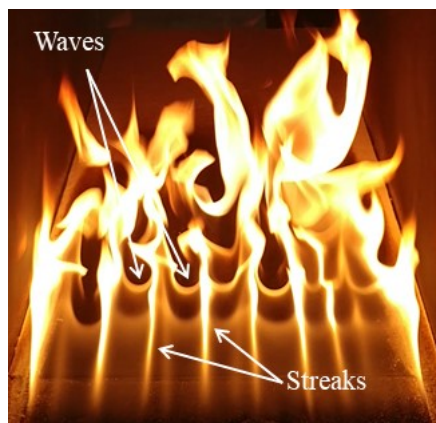


Figure 4.2: Steady streamwise streaks and traveling spanwise waves are shown over a gas burner used to generate a flame over a surface inclined 70° from the vertical with a very low ~ 0.2 m/s crossflow.

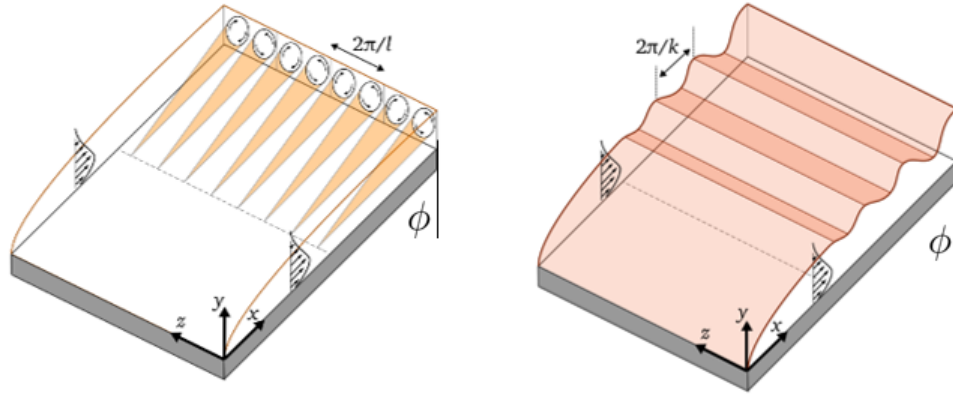


Figure 4.3: Schematic representations of (left) wave instability and (right) vortex instability showing wave numbers k and l , adapted from [8].

4.1 Formulation of the Linear Stability Analysis

The temporal linear stability of the flow to wave and vortex modes, shown schematically in Fig. 4.3, is investigated by introducing perturbations into (3.1), (3.2), (3.10), and (3.11) at a point $x = x_0$ some distance from the leading edge of the plate, such that $x_0 \gg \delta_{\text{NS}}$. The characteristic values $\delta_0 = [(\nu_\infty^2 x_0)/(g \cos \phi)]^{1/4}$ and $u_0 = (x_0 g \cos \phi)^{1/2}$ are used as length and velocity scales to nondimensionalize the problem with δ_0/u_0 correspondingly used as the time scale. Density and transport properties are scaled with their relevant ambient values. The self-similar profiles and their corresponding derivatives (denoted by a prime) are used to evaluate the base flow. The ratio of the streamwise distance to the local boundary-layer thickness defines the Grashof number

$$Gr = x_0/\delta_0 = (x_0^3 g \cos \phi)^{1/4} \nu_\infty^{-1/2} \gg 1, \quad (4.1)$$

the relevant bifurcation parameter in the stability study. After perturbations are introduced into the equations for the flow, the resulting equations are linearized for the

quasi-parallel flow and expressed in terms of normal-mode perturbations

$$e^{i(k\tilde{x}+l\tilde{z}-\omega\tilde{t})} \left[\hat{\rho}, \hat{\mu}, \hat{p}, \hat{v}_x, \hat{v}_y, \hat{v}_z, \hat{Z}, \hat{\bar{Z}}, \hat{\xi} \right] (\tilde{y}), \quad (4.2)$$

involving the dimensionless variables $\tilde{x} = (x - x_0)/\delta_0$, $\tilde{y} = y/\delta_0$, $\tilde{z} = z/\delta_0$, and $\tilde{t} = t/(\delta_0/u_0)$. The exponents k and l in the exponential factor are the dimensionless streamwise and spanwise wave numbers, where the former is related to the wave length by $k = 2\pi/\lambda$, while $\omega = \omega_r + i\omega_i$ defines the frequency ω_r and the growth rate ω_i of the perturbations. We anticipate two modes of instability, namely, a wave instability for which $l = 0$ and a vortex instability for which $k = 0$ and $\omega_r = 0$.

As in previous work [43], the slow streamwise variation of the base flow and molecular transport effects, terms in the equation not involving Gr , is accounted for when writing the linearized equations, as is needed for increased accuracy when the Grashof number is not large. This quasi-parallel assumption retains terms of order Gr^{-1} . The common strictly parallel flow assumption considers the transverse velocity component and the streamwise derivatives of the base flow to be negligible. The introduction of normal modes into the linearized equations leads to the following eigenvalue problem

$$\begin{aligned} iGr(kU - \omega)\hat{\rho} + [U/2 - (\tilde{y}/4)U' + DV]\hat{\rho} + [iGrk\bar{\rho} - (\tilde{y}/4)\bar{\rho}']\hat{v}_x + iGr(D\bar{\rho})\hat{v}_y \\ + iGr l \bar{\rho} \hat{v}_z = 0, \end{aligned} \quad (4.3)$$

$$\begin{aligned} [U(U/2 - (\tilde{y}/4)U') + U'V + 1]\hat{\rho} - (DU')\hat{\mu} + iGrk\hat{p} + [iGr\bar{\rho}(kU - \omega)]\hat{v}_x \\ + [U/2 - (\tilde{y}/4)U' + \Theta^\sigma(2k^2 + l^2) + \bar{\rho}VD - D(\Theta^\sigma D)]\hat{v}_x + [iGr\bar{\rho}U' + k(D\Theta^\sigma)]\hat{v}_y \\ + kl\Theta^\sigma \hat{v}_z = 0, \end{aligned} \quad (4.4)$$

$$GrD\hat{p} + \tan\phi\hat{\rho} - ikU'\hat{\mu} - ik\Theta^\sigma D\hat{v}_x + [Gr\bar{\rho}(\omega - kU) + i\Theta^\sigma(k^2 + l^2)]\hat{v}_y + i[\bar{\rho}(DV) - 2D(\Theta^\sigma D)]\hat{v}_y - il\Theta^\sigma D\hat{v}_z = 0, \quad (4.5)$$

$$iGr\hat{p} + kl\Theta^\sigma\hat{v}_x + l(D\Theta^\sigma)\hat{v}_y + [iGr\bar{\rho}(kU - \omega) + \Theta^\sigma(k^2 + 2l^2)]\hat{v}_z + [\bar{\rho}VD - D(\Theta^\sigma D)]\hat{v}_z = 0, \quad (4.6)$$

$$\bar{Z}'[V - (\tilde{y}/4)U]\hat{\rho} - (LePr)^{-1}(D\tilde{Z}')\hat{\mu} - (\tilde{y}/4)\bar{\rho}Z'\hat{v}_x + iGr\bar{\rho}Z'\hat{v}_y + [iGr\bar{\rho}(kU - \omega) + \bar{\rho}VD]\hat{Z} + (LePr)^{-1}[\Theta^\sigma(k^2 + l^2) - D(\Theta^\sigma D)]\hat{Z} = 0, \quad (4.7)$$

$$\bar{\xi}'[V - (\tilde{y}/4)U]\hat{\rho} - Pr^{-1}(D\bar{\xi}')\hat{\mu} - (\tilde{y}/4)\bar{\rho}\xi'\hat{v}_x + iGr\bar{\rho}\xi'\hat{v}_y + [iGr\bar{\rho}(kU - \omega) + \bar{\rho}VD]\hat{\xi} + Pr^{-1}[\Theta^\sigma(k^2 + l^2) - D(\Theta^\sigma D)]\hat{\xi} = 0, \quad (4.8)$$

with homogeneous boundary conditions in the farfield

$$\hat{p} = \hat{v}_x = \hat{v}_y = \hat{v}_z = \hat{Z} = \hat{\xi} = 0 \quad \text{as} \quad \tilde{y} \rightarrow \infty \quad (4.9)$$

and on the vaporizing surface $\tilde{y} = 0$

$$\hat{v}_x = \hat{v}_z = \hat{\xi} = 0, \quad (4.10)$$

$$(1 - \bar{\tilde{Z}})(V\hat{\rho} + iGr\bar{\rho}\hat{v}_y) - \bar{\rho}V\hat{\tilde{Z}} + (Le_{\text{F}}Pr)^{-1}[(\Theta^\sigma D)\hat{\tilde{Z}} + \bar{\tilde{Z}}'\hat{\mu}] = 0, \quad \text{and} \quad (4.11)$$

$$\alpha(\hat{\rho}V + iGr\bar{\rho}\hat{v}_y) + Pr^{-1}[(\Theta^\sigma D)\hat{\xi} + \bar{\xi}'\hat{\mu}] = 0 \quad (4.12)$$

where the base-flow functions are evaluated at $\tilde{y}$, and the symbols immediately following

D are to be multiplied by the eigenfunction prior to differentiation, as in [43].

4.1.1 Scaling for the Vortex Mode

The numerical solution can be simplified for the vortex mode because $k = \omega_r = 0$ allows $\tan \phi$ to be scaled out of the normal-mode equations by setting

$$(\check{G}r, \check{\mathbf{v}}, \check{\rho}, \check{\mu}, \check{Z}, \check{\tilde{Z}}, \check{\xi}) = (Gr, \hat{\mathbf{v}}, \hat{\rho}, \hat{\mu}, \hat{Z}, \hat{\tilde{Z}}, \hat{\xi}) \tan \phi, \quad \check{p} = \hat{p} / \tan \phi. \quad (4.13)$$

As a result, the vortex mode can be solved independently of ϕ to determine the critical value $\check{G}r_c$ of $\check{G}r$, which in turn provides the expression

$$Gr_c = \check{G}r_c / \tan \phi \quad (4.14)$$

for the inclination dependence of the vortex mode. This type of simplification is unavailable for the wave mode. This results in the following equations for the vortex mode:

$$[U/2 - (y/4)U' + DV]\check{\rho} - (y/4)\rho'\check{v}_x + \check{G}ri(D\rho)\check{v}_y + \check{G}ril\rho\check{v}_z = 0, \quad (4.15)$$

$$[U(U/2 - (y/4)U') + U'V + 1]\check{\rho} - (DU')\check{\mu} + [U/2 - (y/4)U' + \Theta^\sigma l^2 + \rho VD - D(\Theta^\sigma D)]\check{v}_x + \check{G}ri\rho U'\check{v}_y = 0, \quad (4.16)$$

$$\check{G}rD\check{p} + \check{\rho} + i[\Theta^\sigma l^2 + \rho(DV) - 2D(\Theta^\sigma D)]\check{v}_y - il\Theta^\sigma D\check{v}_z = 0, \quad (4.17)$$

$$\check{G}ril\check{p} + l(D\Theta^\sigma)\check{v}_y + [2\Theta^\sigma l^2 + \rho VD - D(\Theta^\sigma D)]\check{v}_z = 0, \quad (4.18)$$

$$Z'[V - (y/4)U]\check{\rho} - (LePr)^{-1}(D\check{\tilde{Z}})\check{\mu} - (y/4)\rho Z'\check{v}_x + \check{G}ri\rho Z'\check{v}_y + \rho VD\check{\tilde{Z}} + [(LePr)^{-1}(\Theta^\sigma l^2 - D(\Theta^\sigma D))]\check{\tilde{Z}} = 0, \quad (4.19)$$

$$\xi'[V - (y/4)U]\check{\rho} - Pr^{-1}(D\xi')\check{\mu} - (y/4)\rho\xi'\check{v}_x + \check{G}ri\rho\xi'\check{v}_y + [\rho VD + Pr^{-1}(\Theta^\sigma l^2 - D(\Theta^\sigma D))]\check{\xi} = 0. \quad (4.20)$$

4.2 Numerical Method for Solution of the Stability Eigenvalue Problem

The stability equations (4.3)-(4.8), with $\hat{\rho}$, $\hat{\mu}$, and $\hat{Z}$ written as functions of $\hat{\xi}$ and $\hat{Z}$ using (3.12)-(3.16), are discretized using a Chebyshev spectral collocation method. To that aim, the physical domain $0 \leq y \leq y_{max}$ is mapped onto the Chebyshev domain $-1 \leq \zeta \leq 1$, where the eigenfunctions are discretized in N Chebyshev Gauss-Lobatto points, $\zeta_j = \cos[(j\pi)(N-1)]$ for $j = 0, \dots, N-1$. The mapping function that was employed, $\tilde{y} = [y_c(1 - \zeta)]/[1 + \zeta + 2y_c/y_{max}]$, concentrates the discretization points near $y = 0$, with approximately $N/2$ points lying below y_c . In the present work, $N = 256$, $y_c = 200.0$, and $y_{max} = 1000.0$ provided well-converged results.

Upon discretization, the stability equations are written as the discrete generalized eigenvalue problem $Aq = \omega Bq$ for the complex eigenvalue ω , where $q = (\hat{p}, \hat{v}_x, \hat{v}_y, \hat{v}_z, \hat{Z}, \hat{\xi})$ and A and B are the discretized matrices associated with the stability equations that are dependent on k, l, Gr , and the base flow.

Note that the boundary conditions (4.10)-(4.12) are implemented by replacing the rows corresponding to $\tilde{y} = 0$ and $\tilde{y} = y_{max}$ in the matrices A and B . The eigenvalue problem is then solved using the MATLAB *eigs* function.

4.3 Stability Results

All modes are found to be stable at sufficiently small values of the Grashof number. Above a critical value of the Grashof number Gr_C , one of these modes begins to exhibit a positive growth rate. The characteristics of that mode and the Gr_C at which it becomes

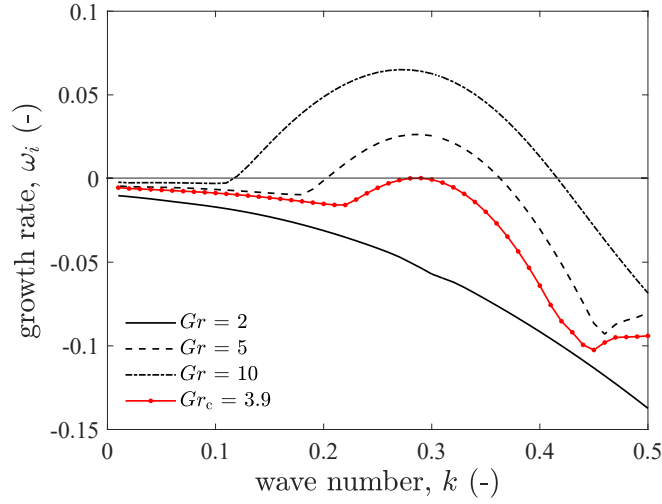


Figure 4.4: Growth rate of the wave-mode instability for a heptane flame as a function of wave number at $\phi = 0$ (vertical) for increasing Gr . Below $\omega_i = 0$, the flame is stable; for values of $\omega_i > 0$, the flame is unstable for the corresponding wave numbers.

unstable determine the nature of the instability that initially develops and the position along the inclined plate at which that development occurs, for any given ϕ . Note that all results are shown for heptane. There was little difference seen for the other fuels considered, which is consistent with experimentally observed data.

The linearized normal-mode equations are solved for a given wave number and Grashof number to determine the growth rate of the instability. As Gr is increased, the flame eventually becomes unstable for one wave number; as it is further increased, it becomes unstable for a larger range of wave numbers. Figure 4.4 shows this trend for a vertical laminar heptane flame, where the wave mode is dominant. For low Gr , the flame is stable for all wave numbers. At $Gr_c = 3.9$, the flame becomes unstable for $k = 0.29$. As Gr is further increased, a larger range of k becomes unstable.

Figure 4.5 shows the growth rate of the vortex mode instability for a heptane flame on the underside of an inclined surface at $\phi = -45^\circ$. As shown for the wave mode, at

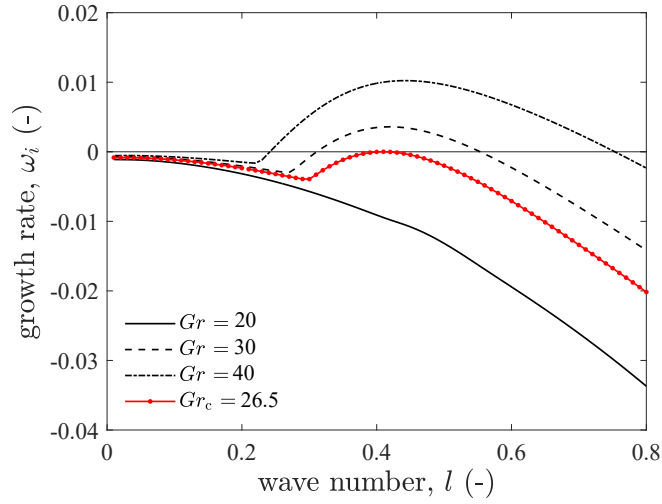


Figure 4.5: Growth rate of the vortex-mode instability for a heptane flame as a function of wave number at $\phi = -45^\circ$ for increasing Gr . Below $\omega_i = 0$, the flame is stable; for values of $\omega_i > 0$, the flame is unstable for the corresponding wave numbers.

sufficiently low Gr , the flame is stable to the vortex mode. At $Gr_c = 26.5$ the flame becomes unstable to the vortex mode for $l = 0.41$. As Gr is further increased, the flame is unstable to the vortex mode for a greater range of wave numbers.

In both Figures 4.4 and 4.5, a similar trend is visible in that there is a range of stable wave numbers and then a range of unstable wave numbers, where the initial range does not appear to become unstable for the Gr shown here. This trend is a result of the numerical analysis, which shows the most unstable eigenvalues. It is clear that for different ranges of the wave numbers, $0 < l < 0.4$ vs $0.4 < l < 0.8$, for example, in Figure 4.5 we see two different branches of eigenvalues.

In addition to investigating the growth rate of the instabilities, it is possible to determine the frequency of the wave mode, indicated by the real part of ω . The streaks shown in the vortex mode are stationary, so there is no related frequency. The frequency of the wave mode with wave number k at Gr_c for two angles is shown in Figure 4.6. For

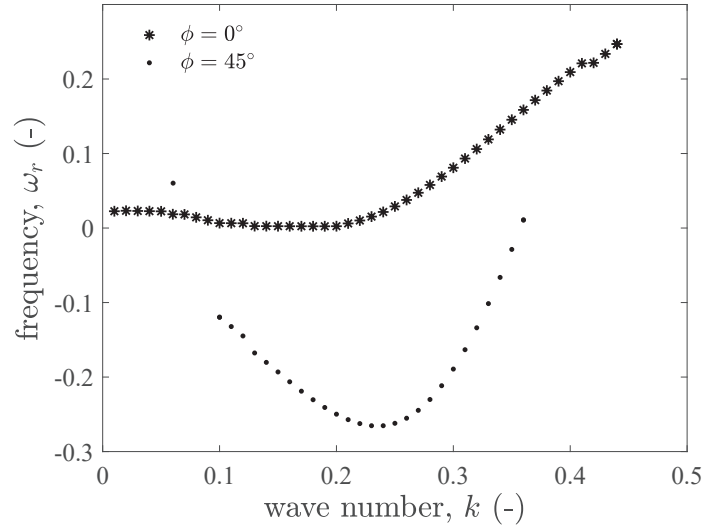


Figure 4.6: Frequency of the wave instability at the critical Gr for $\phi = 0^\circ$ and $\phi = 0^\circ$ ($Gr_C = 3.9$ and 1.18 , respectively) for a heptane flame. The vertical flame shows a positive frequency, but the other flame shows negative frequency.

$\omega_r = 0$, the temporal mode is stationary, indicating no wave movement, while a positive or negative ω_r indicates displacement either with the current or against the current, respectively. For the vertical flame, the frequency is positive for all wave numbers. However, for the flame at $\phi = 45^\circ$, the frequency is shown as negative, indicating a potential problem with the analysis. In order to determine whether these results are physical, the wave mode can instead be described by the group velocity, which represents the change in the frequency with respect to the wave number

$$v_g = \frac{\partial \omega_r}{\partial k}. \quad (4.21)$$

This process of to determine the critical Gr is repeated over the range of angles and wave numbers for each angle and mode. For the vortex mode, this only needs to be done once, as described in Section 4.1.1. Plots for each angle look fairly similar to Figure 4.4 and 4.5.

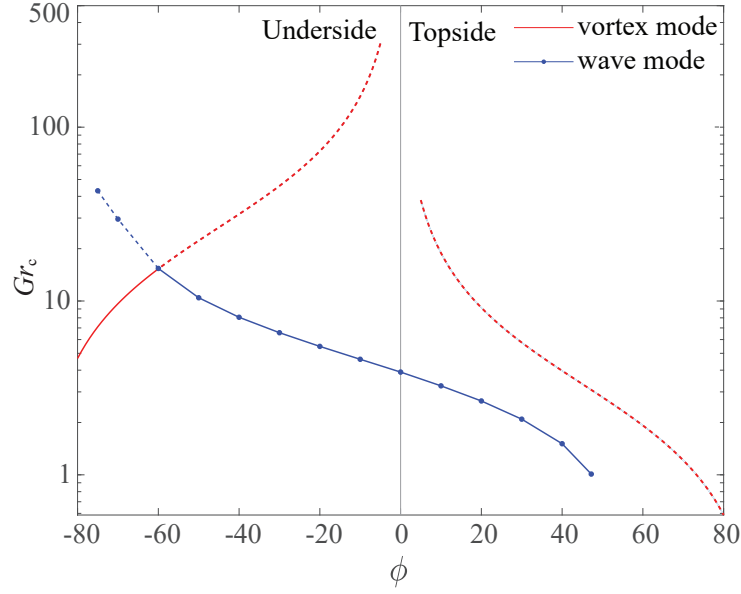


Figure 4.7: Variation of Gr_C with inclination angle for the wave mode and vortex mode for a topside heptane flame and an underside heptane flame. For the vortex mode, $\check{Gr} = 3.33$ and 26.48 for the topside and underside, respectively.

The dependence on inclination angle of the critical Grashof number of the wave and vortex instability modes is shown in Fig. 4.7 for both the topside (right) and underside (left) flame. The results for the vortex mode correspond to the prediction (4.14), with $\check{Gr}_c = 3.33$ and 26.48 for the topside and underside, respectively. Since the critical value of the Grashof number diverges as $\phi \rightarrow 0$, the flame for the vertical orientation is subject only to the wave-mode instability, with $Gr_C = 3.9$ for $\phi = 0^\circ$. The vortex mode curves are plotted only for angles below $\phi = 80^\circ$, above which the surface is near-horizontal. For the flame in the horizontal orientation, the pressure differences across the boundary layer, negligible in the self-similar inclined analysis, become significant.

For the topside flame, the wave-mode results can be calculated only as far as $\phi = 47.22^\circ$, for which Gr_C becomes exactly $Gr_C = 1$. For larger values of ϕ , the numerical analysis was unable to find stable conditions, regardless of the value of Gr .

This breakdown is attributed to the limitations of the slender-flow analysis, in that, for $Gr < 1$, the terms of order Gr^{-2} and higher that were discarded in writing the stability problem become larger than those retained. This breakdown is expected to account for the negative frequencies found for angles near $\phi = 47.22^\circ$, as shown in Figure 4.6.

Figure 4.7 indicates that the underside flame is clearly more stable than the topside flame, for both instability modes. The wave mode is the first bifurcation for the topside and also for most values of ϕ of the underside. While Gr_C decreases monotonically with increasing $|\phi|$ for the vortex mode, the value of Gr_C for the wave mode decreases for the topside flames, but increases for underside flames.

4.3.1 Comparison with Heated Plate

The results presented for the stability of the flame may be compared with the results for the stability of the flow over an inclined heated plate [43]. In that analysis, the flow is found to become increasingly unstable as the plate temperature increases. For example, at an inclination angle of 10° from the vertical, as the plate-to-ambient temperature ratio was increased from 1.03 to 3.0, the Gr_C dropped from approximately 75 to 15. The study did not consider larger temperature ratios. Nonetheless, the trend indicates that Gr_C for larger temperature ratios would be of the same order of magnitude as that found here for the stability of the inclined topside flame.

For the heated plate, there is a cross-over angle ϕ_C between the two modes of instability. Experiments with heated plates [7, 34] have found that there is a small range of angles where both instabilities can occur. Additionally, a theoretical analysis of non-

Boussinesq temperature ranges for heated plates found that there was significant change in ϕ_C as temperature was doubled. Unlike previous work on the inclined heated plate [43], the topside flame exhibits no crossover angle, at which the dominant instability switches modes. Unlike previous work on the inclined heated plate [43], the topside flame exhibits no crossover angle, at which the dominant instability switches modes. A crossover angle does occur, however, for the underside flame at $\phi = -60^\circ$; at angles closer to the horizontal, the vortex mode dominates.

4.4 Discussion and Limitations of Stability Analysis

This analysis provides critical conditions resulting in either a wave or vortex mode instability for a flame forming either on the topside or underside of an inclined fuel surface. Nonetheless, the quantitative results must be taken with caution because of the resulting order-unity values of Gr_C obtained for the topside flame. For a more accurate quantification of the flame stability, a model would need to take into account the spatial development of the instabilities. The present analysis is a first step in understanding the differences between topside and underside flames.

The current stability analysis is a local temporal analysis which investigates the stability of the flow at a given point. This analysis allows for the prediction of the onset location of the instability at a distance downstream from the leading edge. The limitation of the temporal analysis is that it provides no information on the subsequent behavior of the instability downstream of the onset location. It fails to indicate how the instabilities will develop spatially. A further analysis considering spatial stability is

needed to fully understand this problem. However, a linear spatial stability analysis will not provide more quantitatively accurate results, as it will result in the same order-unity critical conditions found in the current analysis [100]. It is likely that a DNS analysis would be necessary to represent the spatial development of instabilities.

Material and figures presented in the present chapter are partially reproduced from and based on the author's published work in R.S.P. Hakes, W. Coenen, A.L. Sánchez, M.J. Gollner, F.A. Williams, Stability of laminar flames on upper and lower inclined fuel surfaces, *Proceedings of the Combustion Institute* (2021) 38(3): 4515-4523, DOI: 10.1016/j.proci.2020.06.302 [99].

Chapter 5: Fire Reconstruction Modeling: Tubbs Fire Case Study

5.1 Introduction

The present work considers the reconstruction modeling of WUI fires using as a case study the Tubbs Fire, which occurred in Northern California in 2017. Reconstruction modeling is the use of a fire model to attempt to reproduce the conditions which occurred during a fire event. In particular, fire reconstruction may be used to attempt to gain additional information about conditions of a past fire which were not measured during the actual event. While the only available quantitative information about a past fire event is often fire perimeters at different times, a fire reconstruction model can provide insight into the local intensity of the fire, ember exposure, and the time-resolved development of the fire. Reconstruction may include predictive modeling (e.g. using only the conditions at the time of fire ignition) or may be more deterministic, using known winds throughout the fire, for example, or correcting the simulation using known interim firelines.

Wildland fires are incredibly complex, with physics occurring over a range of scales over several orders of magnitude. Fire behavior models therefore apply multiple assumptions in order to provide simulations with reasonable run times [101]. Local conditions and features, such as surface winds, fuel types, and fuel state are incredibly important for accurate fire simulations, but are often unknown at a fine enough scale to

directly reproduce an conditions before, during, and after a fire event. As a result, accurate reconstructions of wildland fire events are incredibly difficult. Additional challenges arise due to the paucity of data available for a given fire event. At best, there may be satellite IR readings of varying spatial resolution (375 m to 2 km) and varying temporal frequency (often only four times per day), in addition to official fire perimeters. Fires change over much finer spatial and temporal scales than those of the data available. Regardless of scale, there is a lack of measurement methods and available data on local fire conditions directly related to ignition, such as radiation or ember density.

Despite these difficulties, fire reconstruction modeling is important as it can help to understand the underlying behavior driving a fire event, particularly the progression of a fire between data recordings. A fire is more complex than the final area burned, and physically-based reconstruction modeling can shed light on time-resolved fire growth, local fire conditions, fire and ember exposure, and many other processes occurring throughout the fire. It can also be used, as it is in this study, to understand the conditions to which structures are exposed, critical for future fire risk analysis. It is also used for forensic reconstruction related for litigation. Finally, fire modeling – despite the limitations and uncertainty – can help to indicate the important driving factors for different aspects of a wildland fire, such as spread and ignition.

The objectives of this study were: first, to provide a reasonable reconstruction of the Tubbs fire using an operational model that is actively in use in the field. The second objective was to explicitly reproduce ember conditions from the fire event. While ember exposure is known to be critical to both fire spread and structure ignition, it is rarely explicitly modeled. The third objective is to use the model to reproduce expected

exposure conditions on a structure-to-structure level so that results from this model can be used in an analysis connecting the exposure from the fire with the damage or destruction experienced by a structure.

The Tubbs fire was chosen for modeling, first, because the spread that impacted homes occurred over a fairly short period, approximately six hours. The short time span makes it a less computationally intensive fire to model than other similarly destructive fires. Second, the Tubbs Fire is (at this writing) the second most destructive fire in California history [10], resulting in a large dataset of affected structures. Third, this fire did not create its own weather, making it feasible to model with decoupled fire and weather models.

5.1.1 Description of the Tubbs Fire Event

The Tubbs Fire (also called the Central LNU Complex) ignited at 9:45 PM local time on 8 October 2017 at the location shown in Figure 5.1, just north of Rt 128 near Calistoga [9]. 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 [80]. Due to severe Diablo winds prevailing in the southwestern direction, the fire spread over 19 km in the 5 hrs following ignition, reaching Santa Rosa in the early morning. Over the subsequent days before containment, the fire burned 36,807 acres, destroyed 5,636 structures, and caused 22 fatalities [10].

As with any fire event, there are a number of knowns and unknowns in the Tubbs fire. In terms of known data which can be used to validate results, there are infrared

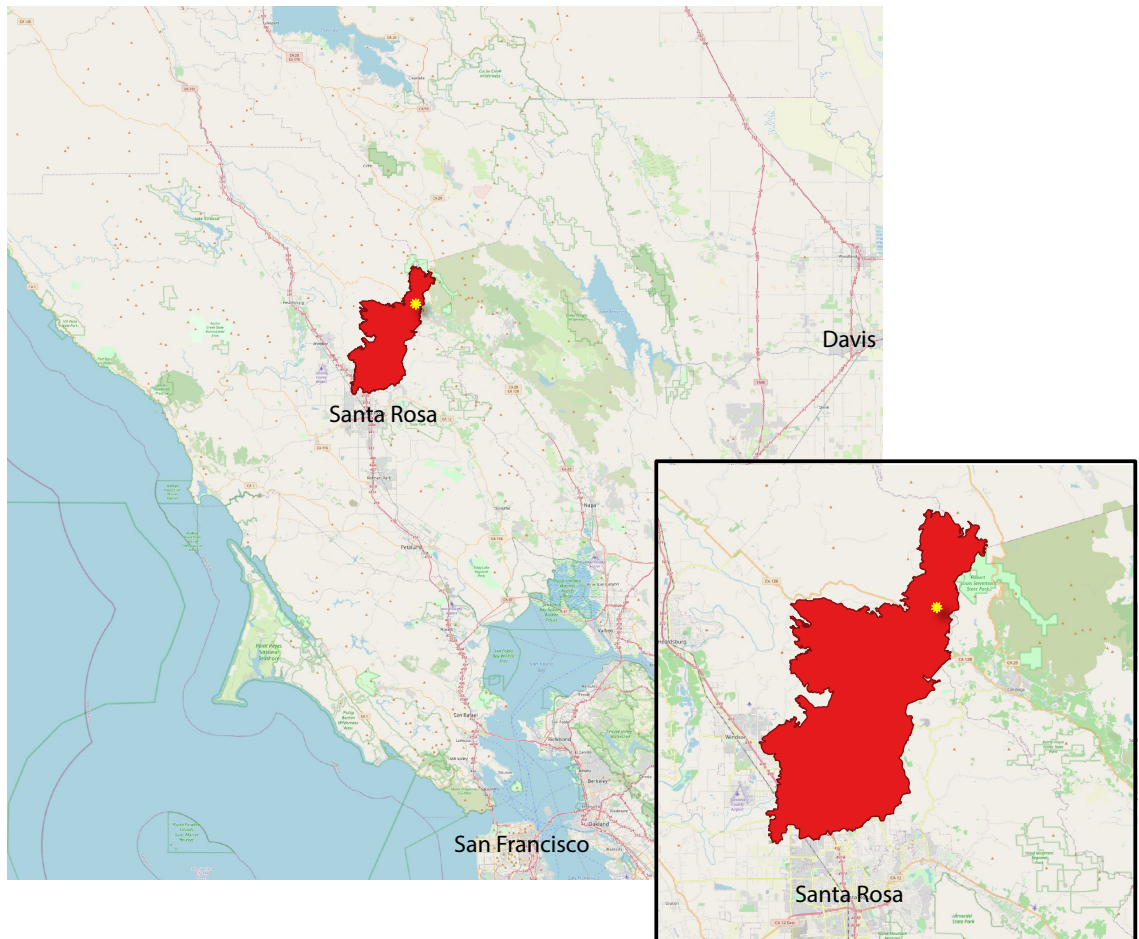


Figure 5.1: The Tubbs fire location north of the bay area and just outside Santa Rosa, final perimeter shown in red with ignition location [9] shown in yellow .

satellite reading using Visible Infrared Imaging Radiometer Suite (VIIRS) from the Suomi NPP satellite at 3:07 AM local time (PST), approximately 6.5 hr after ignition. There are no firelines available prior to this reading; official fire perimeters from CALFIRE are not recorded until 10 October 2017. There is no data available on ember exposure during the Tubbs fire. Similarly, there is no data available on flame lengths or fire intensities.

5.2 Fire Modeling Methods

Reconstruction modeling can serve a different purpose from predictive modeling. Because several features of the fire to be reconstructed are known a priori, such as weather and interim firelines throughout the event, the goal of reconstruction modeling is to match as closely as possible the actual fire event. While modeling a past fire event can be used for model validation purposes, the present study is focused on how an accurate reconstruction of a fire can be used to understand fire development and conditions that are not measured during the fire. Quantifying these conditions will provide critical knowledge for understanding the effects of a fire, particularly in the WUI.

Due to the intended application, an operational fire model, ELMFIRE (Eulerian level set method of fire spread) [81, 102, 103], that could be used in real time during a fire event, was chosen to model the Tubbs fire. ELMFIRE is used to predict annual burn probabilities in California, as well as to provide real-time forecasting of wildland fires in the United States. While it has many of the same limitations as other semi-empirical models, discussed throughout, it is used here for its relatively fast computational run time, its ability to simulate ember deposition of multiple embers, not currently available in other

models, and its implementation of Monte Carlo analysis [104] to capture the stochasticity and uncertainty inherent in wildland fire modeling.

5.2.1 ELMFIRE

ELMFIRE is an existing semi-empirical/semi-physical wildland fire spread model developed by Chris Lautenberger [81, 104], which runs thousands of simulations to produce ensemble predictions of the fire spread to account for the stochastic nature of wildland fire simulation. ELMFIRE uses an Eulerian level set method, which tracks the interface between burned and unburned areas of a fire, assuming the fireline is an interface between the two. The interface location is solved numerically with the hyperbolic partial differential equation

$$\frac{\partial \phi}{\partial t} + U_x \frac{\partial \phi}{\partial x} + U_y \frac{\partial \phi}{\partial y} = 0 \quad (5.1)$$

for ϕ , a scalar variable for which $\phi = 0$ (the isopleth or level set) corresponds to the firefront [102]. Here, U_x and U_y represent the fire spread rates in projected x and y coordinates, respectively. They are calculated using the Rothermel surface fire spread model [69], described in Section 2.5.1. The velocities are calculated by modifying the Rothermel maximum rate of spread for: wind, topographical slope, direction of the slope, elliptical wavelet model at each point along the fire front, spread rate in directions not corresponding to maximum spread, and maximum spread rate not aligned with the direction of the slope. Details of the calculations can be found in the Technical Reference of ELMFIRE [102]. The elliptical wavelet model, referred to as Huygens Principle, assumes that the fire front is elliptical and that each point along the fire perimeter

behaves as its own elliptical “wavelet” and its velocities can be calculated given the same assumptions [105]. Backing rate of spread is assumed to be spread rate with no-wind/no-slope.

The transition to crown fire spread is assumed to occur given a critical canopy cover percentage (default is 40%) and a critical fireline intensity (user set parameter, whose arbitrary value is based on Van Wagner [106]). Crown fire spread is described using the Cruz crown fire model [107], an empirical correlation which predicts crown fire ROS as a function of wind speed, moisture content (MC), and the bulk density of the canopy. Additional outputs from ELMFIRE, such as fireline intensity and flame length, are calculated as functions of the Rothermel model [69] and Byram’s equation [76].

The assumptions and limitations of ELMFIRE are partially those inherent in the underlying models used to develop it. ELMFIRE is primarily applicable for wind-driven fires, of which the Tubbs fire event is one. Unlike some other models, it does not take into account coupled fire-atmosphere interactions. The types of inputs and the specific limitations of these inputs (and their effect on the model) will be discussed in the following sections. Despite the limitations of ELMFIRE, it is used here for three reasons. First, it is able to simulate directly an ember output (rather than only integrating it into the model), a critical exposure characteristic to consider for the future risk study. Second, the computational run time is feasible for operational applications, meaning that results for this work could be replicated in real-time if desired to understand potential exposure conditions ahead of the fire. Finally, even coupled physically-based models are unable to fully reconstruct all fires [78], partially due to the fact that it is not possible to ever know all of the inputs. The potential benefits in terms of computational runtime and relevant

outputs are deemed worth the known drawbacks of the limitations.

5.2.2 Required Inputs

Modeling wildland fires requires a large number of geospatial inputs, including vegetation in the fire area, the topography of the fire area, and weather over the duration of the fire. Additional inputs include a number of user set parameters such as a spread rate adjustment factor, spotting probability, and others. Due to the complicated nature of modeling wildland fires and substantial uncertainty inherent in the inputs, input rasters are perturbed in ELMFIRE for a Monte Carlo analysis. The rasters to be perturbed, as well as the number of ensemble runs to conduct, are both user inputs. The full input deck used for the final Tubbs Fire simulation is available in [Appendix A](#).

5.2.2.1 Vegetation, Fuel, Topographical Data

ELMFIRE requires geospatial inputs which describe the vegetation in the simulation domain (represented as a fuel model), the characteristics of the fuel, and topographical information. Fuel data includes canopy cover (%), canopy height ($10\times m$), canopy base height ($10\times m$), canopy bulk density ($100\times kg/m^3$), and fire behavior fuel models associated with the vegetation. Topographical data includes topographic aspect (degrees), topographic slope (degrees), and digital elevation (m).

Vegetation data is represented in terms of a fuel model. Essentially, the fuel model provides a representation of how a given fuel complex (made up of a mixture of fuels such as litter on the ground, shrubs, trees, etc. in a cell) is expected to burn. Data contained

in the fuel model includes the fuel load (for 1-hr, 10-hr, 100-hr, live herbaceous fuel, and live woody fuel), the surface area to volume, SAV, ratio for dead 1-hr, live herbaceous and live woody fuels, the fuel depth, the dead fuel extinction MC (e.g. the moisture content at which the fuel would stop spreading under no-wind conditions [69]), and the heat content (kJ/kg) of the fuel.

Two categories of fuel models can be used: Anderson's original 13 fuel models [108], and Scott and Burgan's 40 fuel models [109]. Anderson provides models to describe three types of grassy fuels, four shrub type fuels, three timber fuels, and three logging slash fuels [108]. Scott and Burgan separate the categories of fuel models further, including models for different non-burnable fuels (including urban areas, agriculture, and water), grass fuel types, grass-shrub fuels, shrub fuel types, timber-understory fuels, timber litter fuels, and slash-blowdown fuels [109]. The classification of fuel model given the set of vegetation in an area is determined by the primary carrier of fire. An example fuel model (GR2, 102, Scott and Burgan [109]) is Low Load, Dry Climate Grass (Dynamic), a common fuel in the Tubbs Fire fuel models, which is associated with moderate flame spread and low flame lengths.

Fuel data is generally categorized using satellite imagery (primarily LANDSAT) with some ground verification [110]. Two sets of fuel data were initially considered as vegetation inputs for the present simulation: 2016 fuels at 30 m resolution from LANDFIRE [110] and fuels from summer 2017 at 10 m resolution from the California Forest Observatory (CFO) [111]. Ultimately, LANDFIRE fuels were used for all simulation results presented for this study. For both simulations, topographical data was downloaded for 2016 from LANDFIRE. For the CFO fuel simulation, the topographical

data was resampled in QGIS, an open-source geospatial information system, to match the 10 km resolution of the fuels data.

A preliminary comparison of simulations run with the CFO fuels (higher resolution) and the LANDFIRE fuels (lower resolution) showed vastly different results for fire spread. An initial simulation run with the former fuels and resolution resulted in the fire burning the full model domain. It was anticipated that this severe overprediction could be due to the way that ELMFIRE simulates ember generation. ELMFIRE has a set of user-defined input parameters (left at their arbitrary values for both initial simulations) that define the probability that a crown fire will generate embers, the probability that a surface fire will generate embers, the expected number of embers generated by a single cell, and the probability of ignition upon ember landing. To increase computation efficiency, the probability of generating embers is set low and the probability of ignition to 100%. Due to the difference in spatial resolutions, the CFO simulation has nine times as many cells as the LANDFIRE run. Since the probabilities are applied on a cell by cell based, it was anticipated that nearly an order of magnitude greater number of embers was produced. As a result, to account for the overestimation in burned area, the probability of ember generation was lowered by an order of 10. Although the modified simulation exhibited decreased fire spread compared to the initial CFO simulation, the fire spread was still drastically overestimated. Further investigation found that the CFO data showed differences in fuel model when compared with LANDFIRE, overall favoring faster spreading fuel models. Overall, the CFO data may likely improve wildland fire modeling due to its higher resolution; however, more development may be needed to ember models before it can be analogously applied.

The use of fuel models at the 30 m spatial resolution considered introduces uncertainties in three areas: wildland vegetation, urban areas, and roads. Given the large size of a single cell (900 m²), it can be expected that there is potentially substantial variation in the vegetation present. Although the fuel model is meant to represent the vegetation most likely to carry the fire, this choice assumes a single main fire carrier in a cell. It also masks the complexity of the fire spread.

One of the difficulties of applying wildland fire modeling methods to WUI areas is the underlying differences in wildland versus WUI fire spread. The fuel models used assume that urban areas are non-burnable, as shown in Figure 5.2. Therefore, urban fuels are unable to spread the fire or produce embers, both assumptions which are known to be inaccurate. One method of dealing with this assumption is to assume a different fuel model than non-burnable for urban areas, such as grassy fuel [80] or slash blowdown fuels [54]. Although this approach deals with the problem of urban areas not burning, it is also not representative of the fire spread process in urban areas. In urban areas, fire spreads primarily from structure-to-structure, rather than through the vegetation. As a result, the heat release, ember generation, and rate of spread are not accurately simulated by assuming a wildland fuel model. In the present work, urban areas are intentionally left as non-burnable to focus solely on exposure from the main fire front to structures.

A similar problem occurs for roads, which are indeed non-burnable, but which, due to the spatial resolution, are often represented spatially as much larger than they are in reality. As a result, a common problem is that the simulated fire stops at a road whereas embers or flames allow the fire to easily cross the road in an actual fire event. This limitation cannot be satisfactorily addressed using the current spatial resolution. It can

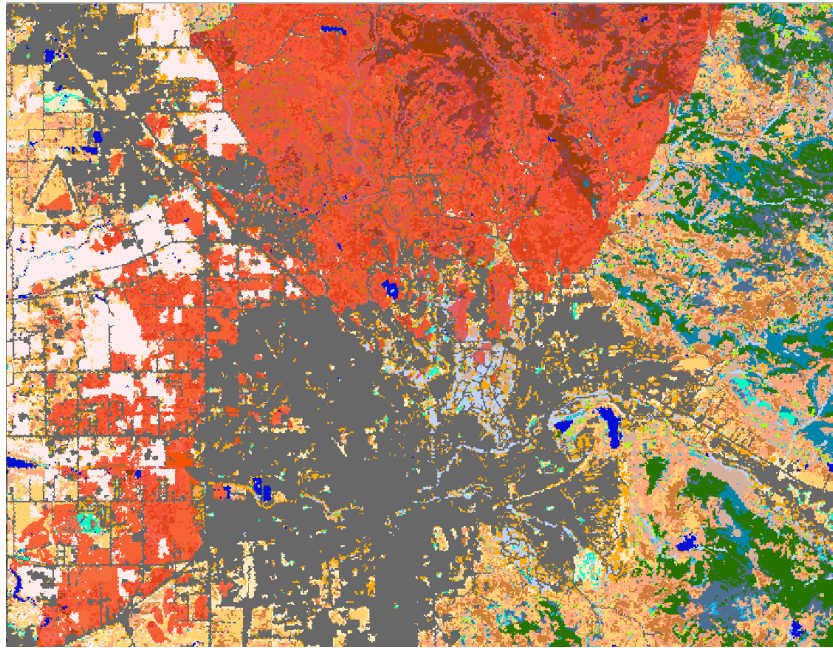


Figure 5.2: Fuel models in the Santa Rosa area, where gray is non-burnable. The red-orange overlay shows one run of the simulated fire, unable to spread into Santa Rosa.

be addressed by tweaking model parameters so that simulation results more accurately reflect the real fire event; however, it is mainly necessary to acknowledge this limitation when analyzing simulation results.

5.2.2.2 Weather Data

In addition to fuel and topographical information, ELMFIRE requires weather data to run. Note that ELMFIRE is one-way coupled: the weather affects the fire, but the fire does not affect the weather. Weather data required by ELMFIRE includes 20-ft wind speed (mph), 20-ft wind direction (degrees), 2 m air temperature (°F), 2 m relative humidity (%), 1-hr, 10-hr, and 100-hr dead fuel MC (%).

While many wildland fire models use static weather inputs, ELMFIRE utilizes temporally and spatially varying weather inputs. In this case, weather was modeled using the Weather Research and Forecasting (WRF) model, a mesoscale numerical weather prediction model. WRF models 3D weather, although ELMFIRE only requires surface winds (i.e. at 20 ft elevation). The WRF model for the Tubbs fire was initialized with conditions at the start of the fire. The model was initialized at 00:00 hours on 8 October 2017 and run through 00:00 hours on 12 October 2017. WRF utilizes a four-step decreasing resolution to account for the impacts of weather conditions and topographical features far from the fire event at a coarser resolution and increase to a finer resolution in the area of the fire model domain. Here, the full WRF domain is 180 km by 180 km. The resolution is 27 km in an outer ring, then decreases in steps to 9 km, then 3 km, and finally 1 km in the fire model domain. The resolution in the fire model domain is down-sampled



Figure 5.3: Red outline is final Tubbs fireline from CALFIRE, black dots indicate weather stations locations, blue is the wind speed at an arbitrary time from the full WRF run. WRF overlaid on map is visible to give location context.

in ELMFIRE to match the resolution of the fuels.

Results from the WRF model were compared with measured atmospheric conditions and wind speed and direction values at weather stations in the full WRF domain. There were nine National Weather Service (NWS) weather stations, which record weather data at 10 m, and 17 Remote Automated Weather Stations (RAWS), which record data at 6.1 m. An additional RAWS station in the domain (TS392) was not considered because it was unclear whether its recordings were reliable. Figure 5.3 shows the locations of the weather stations with respect to the full WRF domain, as well as the fire location.

In order to compare the WRF model with data from the weather stations, point values were extracted from the weather model at each time step at latitude-longitude locations corresponding to the weather stations. Comparisons between the model and the stations were plotted over time for wind speed, wind direction, temperature, and relative humidity. The wind speeds outputted from the WRF and used in ELMFIRE are 20-ft wind speeds, that is, the point wind speed at 20 ft above ground level. While this is the height of the RAWS stations, the NWS stations measure conditions at 10 m. Converting between 10 m wind speed and 20 ft wind speeds is commonly done in wildfire modelling by dividing the 10 m wind speed by 1.15 to get the 20-ft wind speed [112]. This convention was followed in this instance for comparability with other fire modeling and weather modeling in the field. Modeling by Coen *et al.* [113] indicates that this simplification may miss some of the small scale deviations in wind conditions.

Comparisons for wind speed, wind direction, temperature, and relative humidity are shown for one weather station in Figure 5.4. Wind speed comparisons are shown in Figure 5.5 for four weather stations around the fire area, chosen to cover measurements north, west, south, and east of the fire to indicate the variability. It is important to note that the frequency of many of the weather stations is hourly, while weather changes are expected to occur on a shorter time span. Additionally, the distance between weather stations is anticipated to be *at least* an order of magnitude larger than the variations in wind behavior [80].

Wind speed and wind direction are the most variable parameters on the time scale considered here. Overall, the WRF model primarily overestimates average wind speed or accurately predicts it. The overestimates range from < 5 mph to as high as 20 mph,

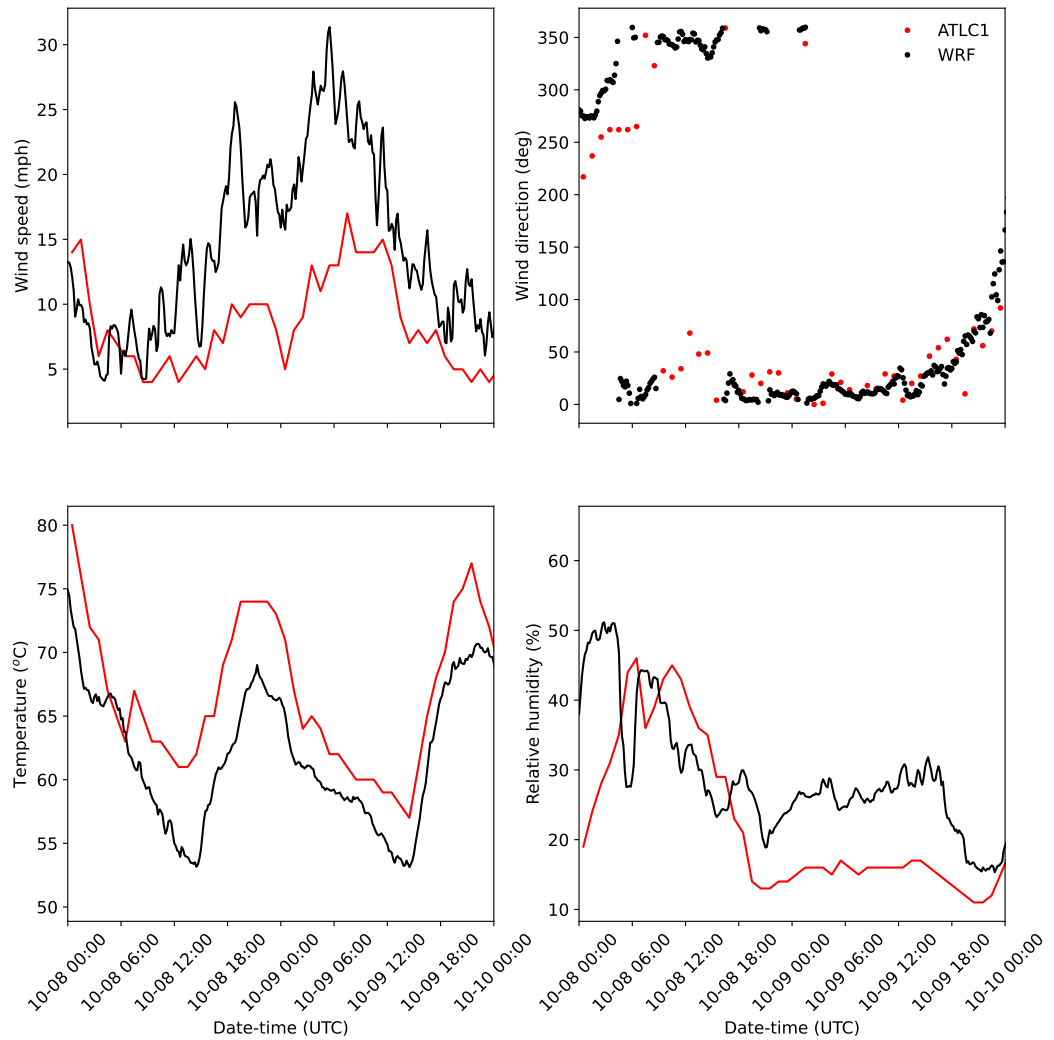


Figure 5.4: Comparison between values measured at the ATLC1 weather station and those simulated using the WRF model for (from upper left, clockwise): wind speed, wind direction, ambient temperature, relative humidity.

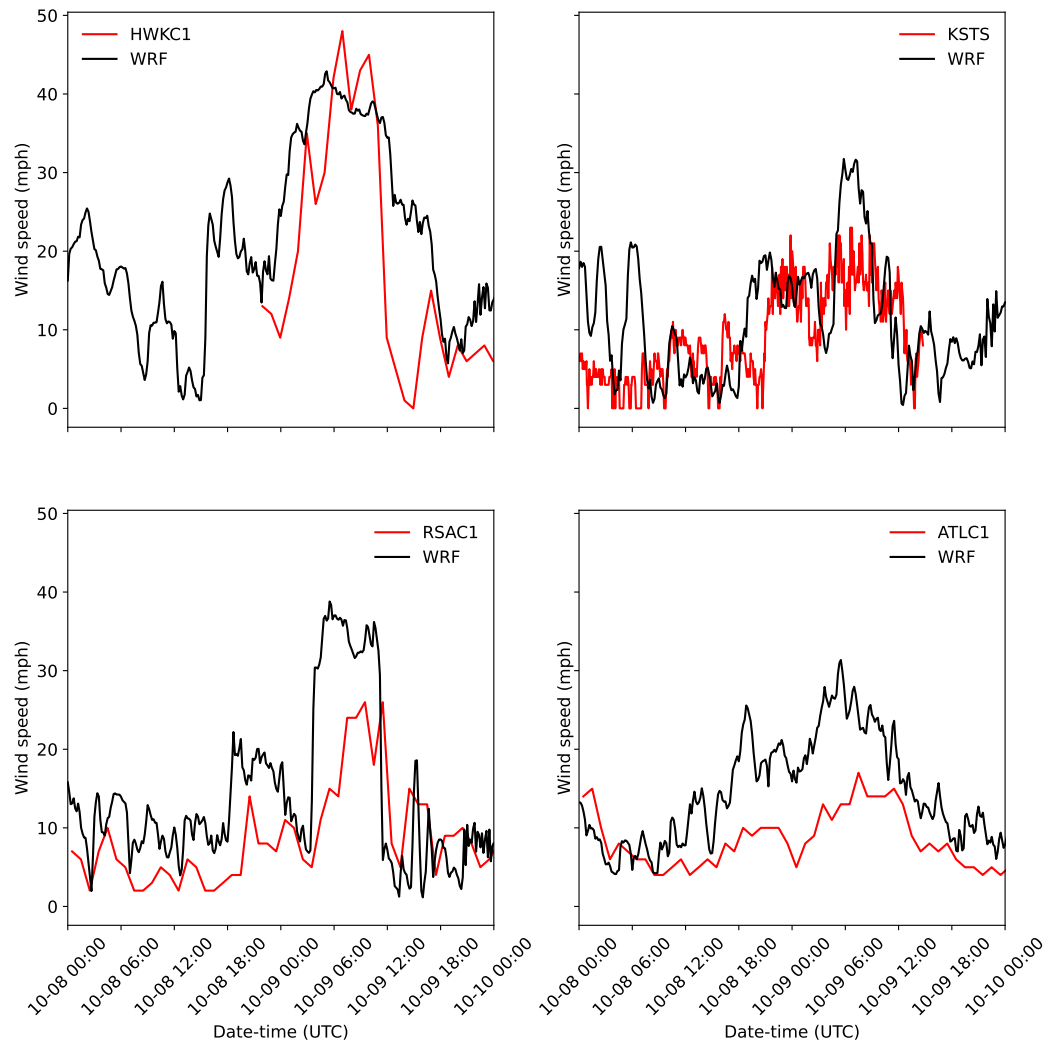


Figure 5.5: Wind speed at four of the nearest stations to the fire event, comparison between station readings and analogous WRF predictions. Near the fire, the WRF overpredicts the *average* wind speed.

usually only in spikes. There are brief periods when the WRF underestimates wind speed at a small number of stations, primarily in the time before the fire begins. In general, the WRF model provides relatively reasonable predictions of wind direction; however, it does not reliably capture brief changes in wind direction that the weather stations show. Note that all wind speeds are averaged wind speeds, not gusts.

Due to the restriction of only comparing at point locations, there is inherent difficulty in ensuring accurate representation of the winds that occurred during the actual fire event. Over the full WRF domain of 32,400 km², there were a total of 26 weather stations. Previous work [80] has indicated that the scale of wind changes in the Tubbs Fire occurred at scales an order of magnitude smaller than the distances between weather stations. Nonetheless, weather station point data is the only available data.

One of the key components of weather driving wildland fire spread is wind gusts. These are critical both for describing fire spread and for their impact on structure damage. They are important for fire spread because of the non-linear relationship between wind speed and fire spread rate. The WRF model is unable to account for wind gusts, as it averages wind speed over each time step.

5.2.2.3 Miscellaneous Inputs

ELMFIRE requires a number of additional inputs in addition to the vegetation, fuel, topographical, and weather inputs. The most relevant of these include: the surface spread rate adjustment factor (-), the initial ϕ field, and the ignition mask, if applicable. The surface spread rate adjustment factor is based on implementation of so-called adjustment

factors in FARSITE [105]. This factor allows an experienced user to tweak a single input parameter to better match fire behavior or observed fire perimeters without tweaking the more physically based aspects of the model. As described in the overview of ELMFIRE, ϕ is the level set variable, where $\phi = 0$ corresponds to the fire front, $\phi > 0$ to unburned areas, and $\phi < 0$ to burned areas. For the present simulation, there is no active fire at the beginning of the simulation, so the initial $\phi = 1.0$ (an arbitrary value greater than 0).

When reconstructing a wildland fire that previously occurred, or when forecasting a currently burning fire, it is necessary to apply an ignition mask to the domain. Without an ignition mask, ELMFIRE randomly places ignition locations across the domain for each ensemble run. This capability is possible because ELMFIRE is used to calculate annual burn probability across the state of California [114]. An ignition mask restricts the area over which random ignition can occur. For the reconstruction of the Tubbs fire, the ignition mask is a circular area of approximately 600 m in diameter near to the actual ignition location, as shown in Figure 5.6.

The ignition location for the simulation was initially set to be the exact ignition location for the fire, on the north side of Rt 128. Initial simulations using this location were unable to reproduce the spread of the fire, as the simulated fire was unable to “jump” the road (Rt 128) with the spatial resolution of the fuels. In order to better reconstruct the spread of the fire, the ignition location was moved southeast of the road, as shown in Figure 5.6. Ultimately, this alteration allowed the simulation to better match observations of the actual event.

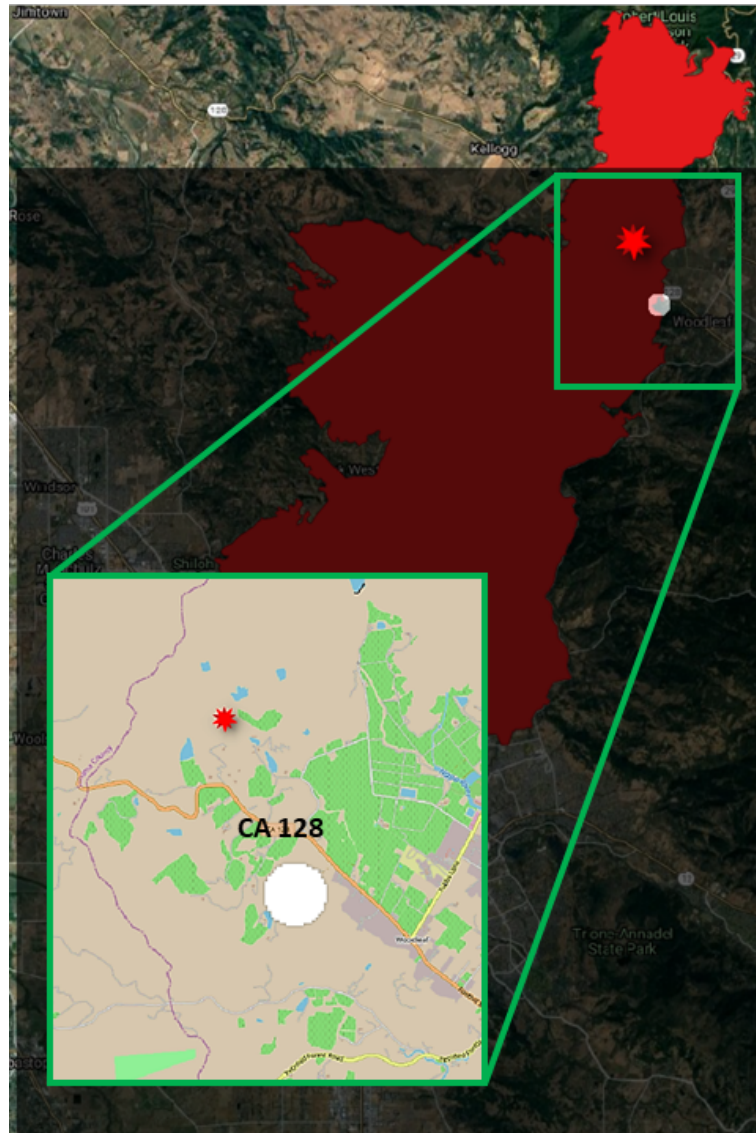


Figure 5.6: Ignition mask overlaid on Tubbs fire fire line from CALFIRE with actual ignition location marked.

5.2.3 Model Parameters and Domain

ELMFIRE uses six parameters to describe the spatial computational domain: the coordinate reference system (CRS), the cell size (m), the lower left X and Y corner of the domain in the given projection, and the overall dimensions of the domain (m), where the X domain dimension is equal to the number of pixels in the X direction multiplied by the cell size. Five additional parameters describe the temporal features of the model: the simulation start time, given as seconds past the hour of ignition, where the hour is specified in the WRF inputs; the simulation end time; the initial time step dt ; the maximum time step, specified separately, as time step is automatically adjusted; and the target Courant-Friedrichs-Lewy (CFL) condition [115], which affects the time step.

The spatial resolution of the model is set to equal the spatial resolution of the fuel data. These are chosen to be equivalent due to the already coarse resolution of the fuels. Larger cells would add to uncertainty, but data is not available at a finer resolution. The full set of spatial and temporal domain parameters are shown in Table 5.2.

Additional model parameters that must be set are the input rasters to perturb and certain conditions on the random perturbations. These conditions include wind fluctuations with values for the magnitude of random fluctuations introduced in both the wind speed and wind direction. The rasters perturbed for the Monte Carlo analysis were the wind inputs and MC inputs, as well as the spread rate adjustment factor and the wind adjustment factor (WAF). The wind and MC rasters are perturbed to account for the uncertainty in the weather model, particularly in capturing small-scale variations in wind conditions. The spread rate adjustment factor is perturbed as it is a relatively arbitrary

input parameter that has a non-negligible influence on the model results.

5.2.4 Relevant Model Outputs

ELMFIRE produces a number of outputs either at each time step for each ensemble run or for the overall length of the model for each ensemble run. The relevant model outputs considered here are: time of arrival of the fire (s), hours since burned (hr), flame length (ft), and ember flux (number of embers deposited and ignited per cell over the duration of the simulation). The first two outputs are used to compare with firelines to indicate the qualitative accuracy of the simulation in reproducing the fire event. The latter two outputs are considered as exposure metrics for the risk analysis. Their use for structure exposure will be discussed in detail in Section 6.3.

In order to capture an overall description of the fire, outputs were conditionally averaged over all ensemble members, following the methodology used in FSim [116]. The conditional averaging was done for each output and for each time step, that is for 1000 ensemble runs at each of 14 timesteps. The conditional average was taken using the `averageOverlay` function in WhiteBoxTools [117], implemented in Python. The conditional average is calculated by averaging the values (e.g. flame lengths) at a given spatial location, excluding runs that result in 0 intensity at that cell.

5.2.4.1 Flame Length

Flame length is calculated in ELMFIRE using Byram's equation [76], which defines fire intensity as a product of the fuel heat of combustion, fuel consumption, and fire rate

of spread. Flame length is then determined using a linear relationship between flame length and fire intensity provided by Thomas [118], where flame length is defined as the distance from the base of the flame to the tip of the flame. It is linearly related to fireline intensity and is considered both for its relation to fireline intensity and because different flame lengths are used to dictate what type of suppression is used during a fire.

Flame length is outputted from ELMFIRE as a raster for each ensemble member at each time step. At each timestep, the conditional average of the flame length was taken, as described above with the `averageOverlay` function in `WhiteBoxTools` [117], implemented in Python. In QGIS, all 14 timesteps of averaged flame length were layered and the maximum flame length value at each cell was taken to make a new raster of maximum flame length at each location over the full time of the simulation.

5.2.4.2 Embers

Ember generation is initiated based on user-defined inputs regarding minimum conditions for spotting. Spotting can be initiated either from crown fires or from surface fires that reach a minimum intensity (also a user-defined parameter). These parameters set a percent likelihood of initiating spotting. If spotting is initiated, then an ember is generated in that cell and its transport distance is stochastically determined using a lognormal distribution

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp \left[-\frac{1}{2} \left(\frac{\ln x - \mu}{\sigma} \right)^2 \right] \quad (5.2)$$

where x is the spotting distance, μ is the normalized mean and σ the standard deviation of the lognormal distribution, determined from a mean spotting distance and variance

calculated in ELMFIRE and related to the wind speed and fireline intensity. The basis of this distribution was derived from ground distributions of embers deposited from CFD simulations of ember transport by Sardoy *et al.* [119]

To increase computational efficiency, the ELMFIRE users guide [103] recommends setting a low probability of spotting initiation with a 100% probability of ignition upon landing. This setting effectively results in an ember “cast” which counts the embers which cause spot ignitions in each cell. There is not available data to validate this methodology. Previous iterations of ELMFIRE implemented a physically-based ember transport model based on [120, 121]; however, due to its inability to replicate fire behavior, it was removed from the model specifications.

The model outputs a count of all embers that landed at a cell and ignited over the duration of the simulated fire. A representative ember cast was calculated by averaging cell-wise the rasters from each ensemble run. As was done for flame length, the conditional average of the ember cast was calculated with the `averageOverlay` function in WhiteBoxTools [117], implemented in Python.

5.2.5 Model Error and Uncertainty

There are several sources of uncertainty and potential error in the model of the Tubbs Fire reconstruction. In wildland fire modeling, there are an enormous number of aspects of the problem over a large range of scales. Error and uncertainty can and do occur in all aspects of the problem: the inputs, the model itself, and the data to validate outputs. Many of these aspects have been touched on throughout the discussion, but are

summarized here.

Numerous uncertainties arise in the inputs used for the model. Depending on the type of inputs, the uncertainties are different. For user based inputs, there can be substantial model specification error and uncertainties given the qualitative nature of setting certain inputs (e.g. surface spread rate adjustment factor, ember parameters). For topographical inputs, most of the error is introduced as a result of coarse spatial resolution. For fuel data, there are substantial uncertainties related to classification of fuel models but also due to the coarse spatial resolution. The weather has several sources of uncertainty including the lack of sufficiently spatially and temporally resolved validation data without 3D input. Error is introduced by using a mesoscale weather model, which cannot resolve finer scale wind fluctuations. Both model and user error introduced in the WRF model will be propagated into the wildland fire model.

Additional errors arise by making input choices that attempt to account for assumptions or limitations in the model. For example, because ELMFIRE is unable to account for wind gusts, random wind perturbations are introduced. These wind perturbations introduce additional uncertainties, while attempting to minimize the known error introduced by only modeling average wind speed. Similarly, to account for the coarse grid size with which roads act as fire breaks, the ignition location is altered. While addressing the clear underestimation of fire size, the altered ignition location introduces additional error.

There are uncertainties inherent in the key models used in ELMFIRE to build a wildland fire simulation. Two key areas of uncertainty are the spread model(s) and the ember model. A key area of potential error in the spread model is the assumption of

homogeneity of fuel model within a cell. There is large uncertainty in a number of the user input parameters, including those related to initiating transition to crown fire and initiating spotting. Some of this uncertainty lies in a lack of data to validate models and a lack of understanding of the physical mechanisms driving these transitions [101].

Finally, there is substantial error in the validation of fire perimeters. Simulated fire perimeters are typically validated either against IR satellite readings or against “official” firelines, measured either via burn scars or late-night National Infrared Operations (NIIOPS) imaging flights over the fire [122]. Both of these sources of data have substantial uncertainty. The satellite data has coarse resolution, with the finest resolution at 375 m (VIIRS) and the coarsest at 1-2 km (GOES). The error in location on these measurements can vary to multiple times these distances [123]. In addition to the spatial coarseness, both satellite data and other fire perimeters have poor temporal resolution with four satellite readings daily, except at the 1-2 km resolution. The validation of fires will be discussed in more depth in the next section. Even with sufficiently resolved input data that minimizes uncertainties and well-validated models, the processes governing wildland fire spread and ignition are inherently stochastic in nature and large uncertainties are unavoidable in model inputs. Therefore, this work has followed a Monte Carlo ensemble approach to modeling fire behavior.

5.3 Model Validation

The present section considers the verification and validation of the Tubbs Fire model implemented in ELMFIRE. There are four main models implemented in

ELMFIRE: the Rothermel model for surface spread, Byram's equation relating rate of spread and fire line intensity, Cruz's model for crown fire spread, and the semi-empirical logarithmic model for ember spread. The first two models were verified by modeling a surface fire under a constant unidirectional 6.7 m/s wind. This test case is a relatively straight forward, is a common way of verifying the Rothermel model, and is available with ELMFIRE. Results are shown in Appendix A. Similar additional verification tests are available in the literature [81], as well as a validation study using the Moonlight Fire [81].

Ideally, validation of the fire model would be a process of validating the outputs discussed previously against measurements from the actual fire event. A brief discussion of validating the simulated fireline is provided here, followed by a discussion of the limitations of wildland fire model validation and how those limitations affect the ability to validate the outputs of the Tubbs Fire simulation.

Tubbs Fire simulated results were compared with satellite data from the Suomi NPP satellite which provides VIIRS data at 375 m resolution and with official firelines from CALFIRE. The VIIRS data provides hotspots, within which there may be fire. There is high uncertainty associated with this data; however, this satellite data has the best spatial resolution available. The CALFIRE data is a 2D fire line, and the comparison is done qualitatively. A number of studies [54, 68, 79, 124, 125] have investigated quantitative measures of evaluating the matching between simulated and actual fire lines. Summaries of quantitative assessment of fire perimeter matching can be found in [126, 127]. Despite the wide array of methods available, investigations have found [126] that qualitative comparison still provides a comparably reliable and effective validation of simulation

results. The process of fireline comparison was repeated iteratively throughout the modeling process to improve the inputs and settings provided to the model.

There are a number of challenges to the feasibility of validating wildland fire models. Due to the dearth of well-resolved data on the extent of the fire, the VIIRS data and CALFIRE firelines are actually the most complete data sources available for validation. There is no data available on flame length, ember density, or fire intensity during the fire event. This lack is reflective of the overall state of available data for wildland fire model validation. The validation of the Moonlight Fire referenced previously [81] similarly uses only fire perimeter data for validation.

5.4 Fire Modeling Results

The relevant results of the Tubbs Fire simulation are presented. First, the simulated fire perimeters are shown with respect to observations from the event. Then, two primary model outputs will be considered for the subsequent study of the relationship between exposure and structure damage. The results of these outputs – flame length, to represent the fire front, and embers – are shown here in comparison to the fireline to understand how well the model is reconstructing the actual fire spread.

5.4.1 Validation with Fireline Data

The results of the model are plotted with the first CALFIRE fireline (4:00 PM on 10 October 2017), shown in Figure 5.7, and with the VIIRS hotspot data (3:07 AM on 9 October 2017), shown in Figure 5.8. The result shown from the model is the hours

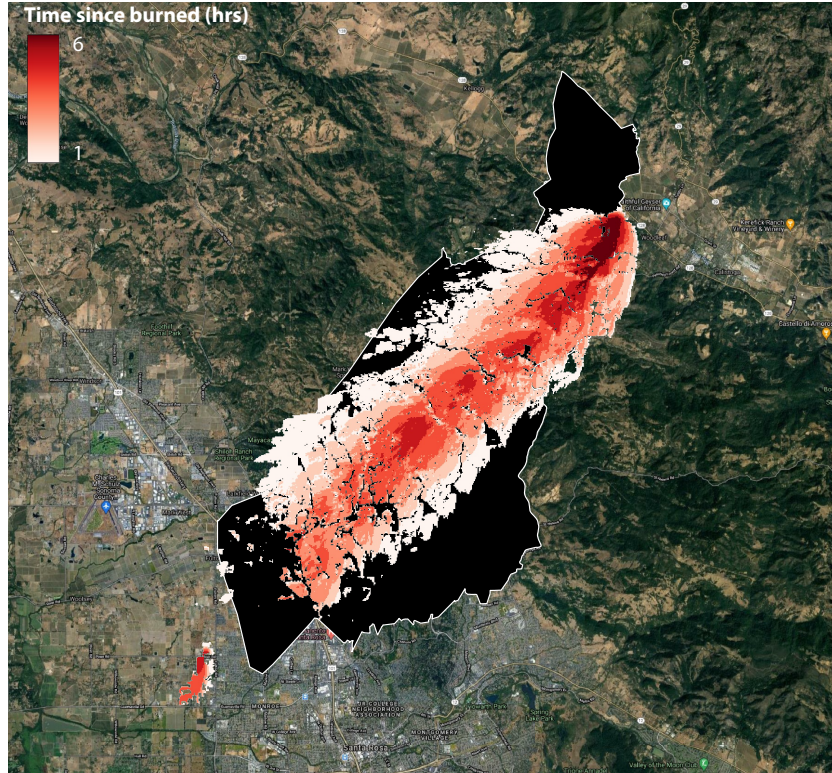


Figure 5.7: First official CALFIRE fire perimeter (4:00 PM, 10 October 2017) shown in black with the fire progression shown as hours since burned in white to red.

since burned, averaged over 1000 ensemble members. The model results are shown for 3:30 AM, which is close to the VIIRS time; however, it is more than a day before the CALFIRE fireline. This fireline is the first official fireline available for the fire. Since it is not the same timestamp as the simulation, it is used to compare the results in the area of the first few hours of spread.

Despite the time difference, it is a reasonable comparison because the majority of the fire spread occurred in the first day and a half of the fire. Figure 5.9 shows the fireline used in Figure 5.7 in comparison with the final fireline recorded for the fire event by CALFIRE. It is worth noting that the final fireline shows corrections when compared

with the initial fireline, particularly along the southwestern front in Santa Rosa. After the initial fireline shown, spread occurred primarily along the northern backing fire and the western flank.

Overall, a few features of the simulation results are important to note. First, the ignition point of the simulation is east of the actual ignition point, causing the initial spread to also be farther east, which may account for the initial overprediction on the eastern flank. Additionally, the model underestimates fire spread and fire area throughout the six hours simulated. Some of this underprediction is likely due to the impacts of non-burnable fuels, both roads and urban areas (particularly Santa Rosa), which acted as fire breaks in the simulation.

When compared with both the VIIRS and the CALFIRE fireline, the simulation underpredicts the most on the southeastern flank (when considering that the final area of the final front is considered non-burnable). It is unclear what is responsible for the underprediction; however, it can likely be attributed to the weather simulation. As shown in the plots comparing the WRF and the weather stations, the WRF was unable to capture some of the shifts in wind which occurred during the fire. Additionally, Coen *et al.* [113] note that, in the Tubbs Fire, there was high local variability in wind velocity, which is not captured in mesoscale weather models. The other major area of underprediction is the backing fire at the north end of the fire. This result is expected, given the limitations of ELMFIRE and implementations of the Rothermel model of fire spread.

The Tubbs Fire simulation shows no spread into Santa Rosa, particularly the Coffey Park area which is in the bottom southwest corner of the fireline. This neighborhood was almost completely destroyed in the Tubbs Fire. The inability of the model to simulate fire

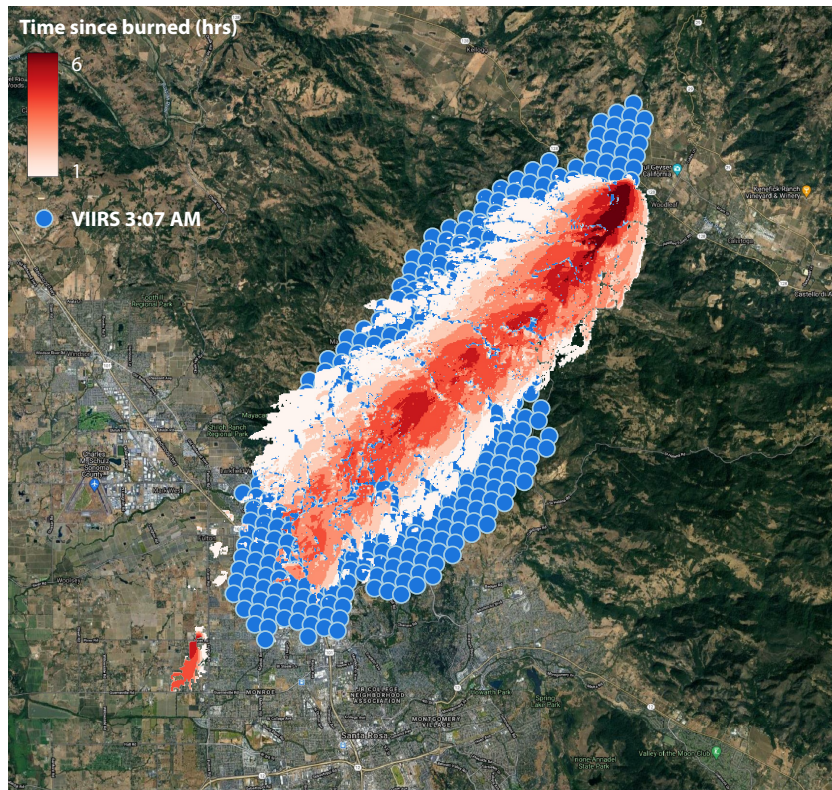


Figure 5.8: VIIRS measurement of hot spots at 3:07 AM on 9 October 2017 in blue with the fireline shown as hours since burned in white to red.

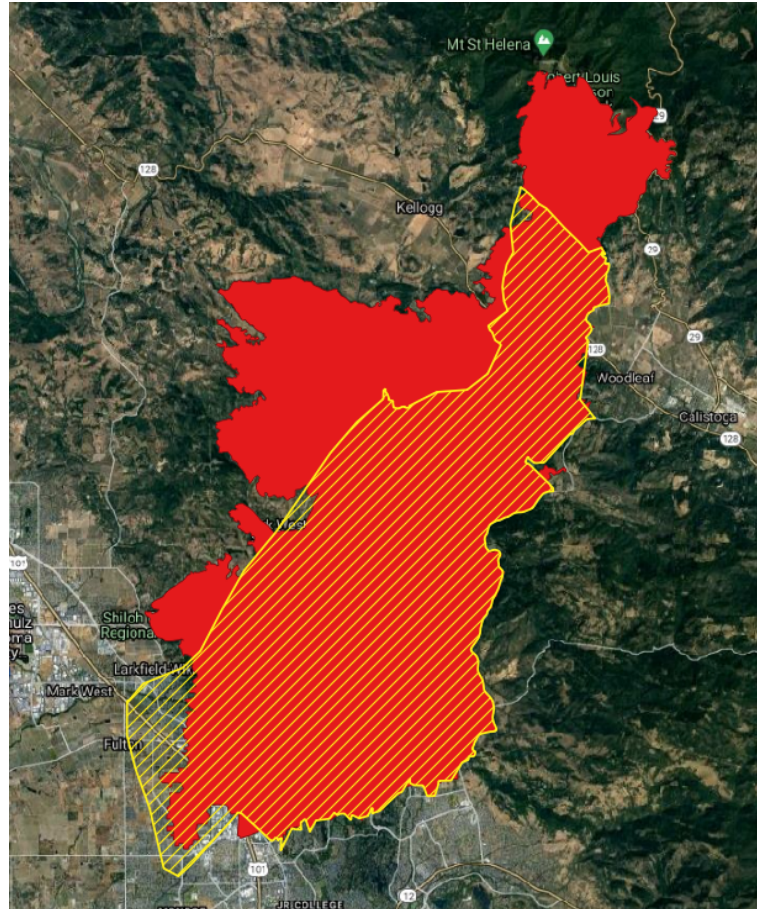


Figure 5.9: Final CALFIRE fireline (9:30 PM, 25 October 2017) for the Tubbs fire is shown in solid red, with the first fireline (4:00 PM, 10 October 2017) overlaid in hashed yellow. The latter is the fireline used for model validation.

into this area is a key limitation of our ability to apply wildland fire models to WUI areas and a focus of Chapter 6.

5.4.2 Flame Length

Figure 5.10 shows the development of the fire at four different time steps, represented by the conditionally averaged flame length. Results for the averaged maximum flame length over the full simulation are shown in Figure 5.4.2. It can be seen that, similar to the previous figures, the flame length underestimates spread along the eastern flank and into Santa Rosa. However, these results also show flame length occurring far south of the actual fire line. This may be explained by the averaging over all time steps and all ensemble members. The process averaged all the ensemble members at a given time step, then took the maximum at each cell and layered these over the full time of the simulation. This maximum flame length is considered for the maximum exposure that a structure may experience. Although the spread into the area south and west of the actual fire line is unrealistic, it shows an interesting example of the effect of spatial resolution on fire spread. The roads are clearly shown as areas without spread. Here, it is important to note that the spread of the flame front is not *by itself* currently able to replicate the spread of the actual fire.

5.4.3 Embers

The results for the ember cast are shown in Figure 5.12 with respect to the same CALFIRE fire perimeter from early in the fire. The color-coding on the ember cast shows

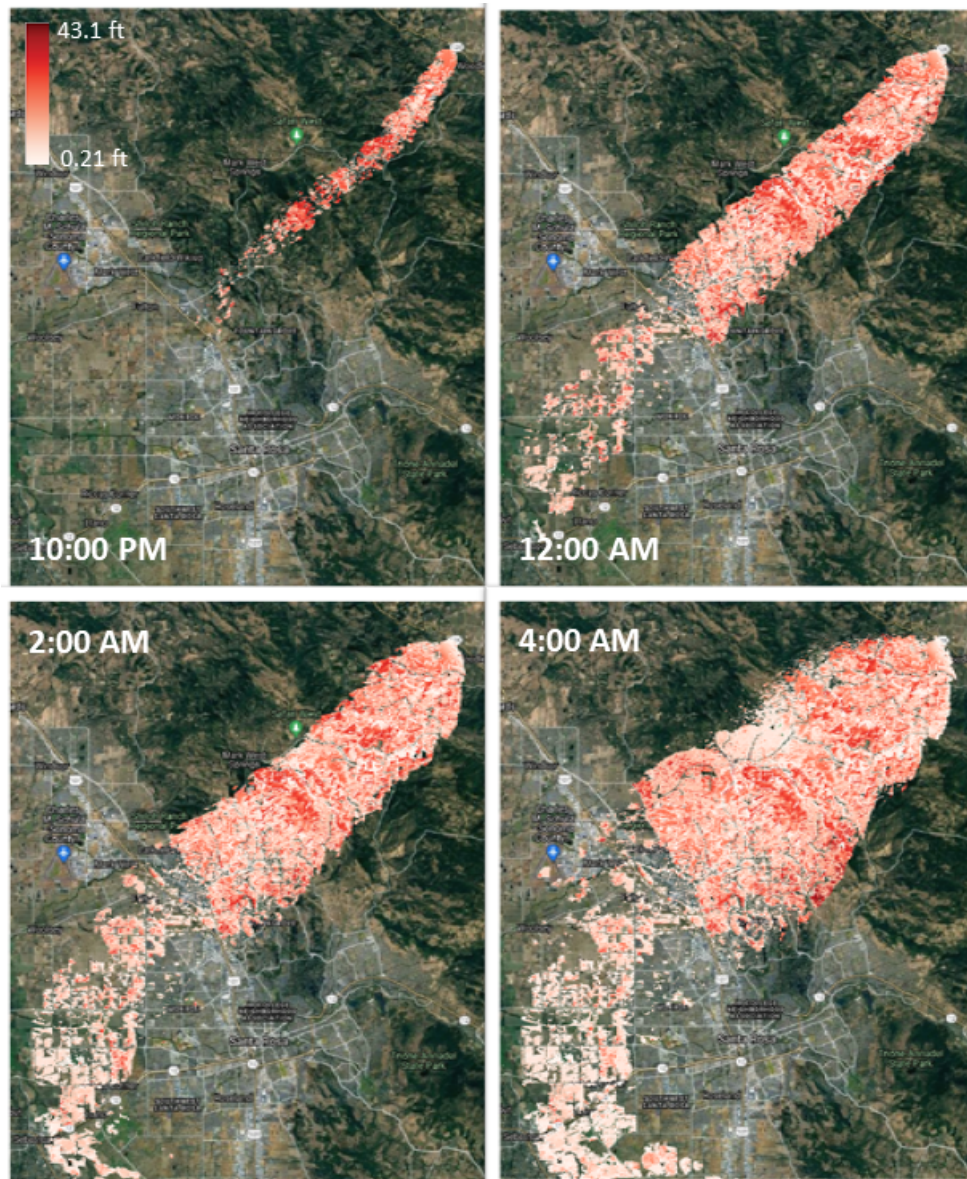


Figure 5.10: Ensemble averaged predictions of flame length at four time steps: 10:00 PM (30 min after the fire began) and every two hours thereafter.

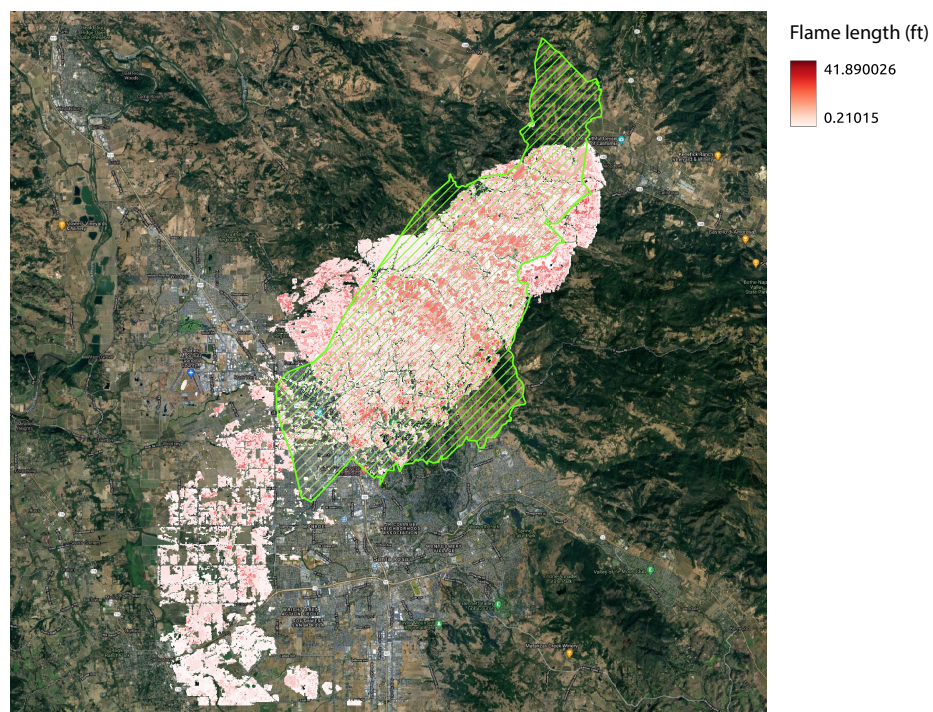


Figure 5.11: Maximum flame length at each location over the first six hours of the Tubbs fire, with variation from white to red, shown with respect to the first CALFIRE fire perimeter, in green hash marks.

the density of embers. The density of embers is shown quantitatively as the number of embers that were deposited on a single cell and later ignited throughout the time of the simulation. These values are more appropriately considered qualitatively, since there is no validation data available to indicate the number of embers that are deposited and cause spot fire ignition in a cell. The apparent streaks indicate that the density of ember distribution is aligned with the approximate southwestern wind direction. The central area of the ember coverage is, in general, the area with higher ember density, while the areas on the edges of the fire experience lower ember densities. This distribution is expected based on the dependence of the ember transport on both wind velocity and a logarithmic distribution.

One of the key features to notice about the ember output is the comparison with the fire area shown in the previous figures. Figure [5.7](#) and [5.12](#) showing the fire perimeter and the flame length, respectively, showed that the simulation underestimated the flanks, especially the eastern flank, and was unable to spread into Santa Rosa, likely due to the non-burnable fuel model. Unlike the fire itself, the embers spread over a wider area, almost fully covering the area where burning occurred. In the subsequent chapter, the relationship between ember coverage and structure destruction will be investigated. Inclusion of the embers here plays a key role in being able to reproduce the fire, as the fire front alone is unable to reproduce the observed results. Notice, in particular, that the embers spread over the Coffey Park area that was missed by the main fire front but was nearly completely destroyed in the actual fire.

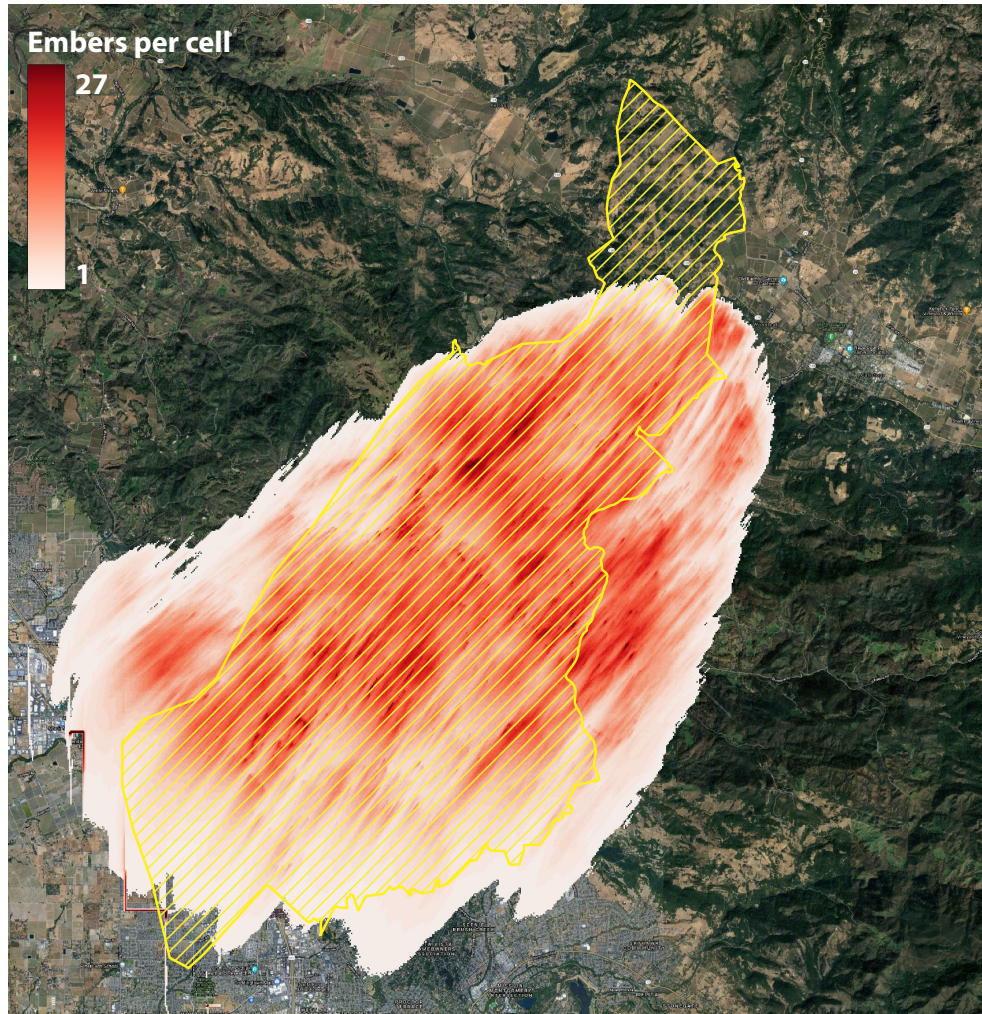


Figure 5.12: Ember cast over the first six hours of the fire as simulated by ELMFIRE compared with first CALFIRE fireline. While the extent of the fire, as shown in previous figures, underestimates the fire area, the embers provide more complete coverage of the fire area. Note that embers are shown as the number per 30 m by 30 m.

5.5 Discussion and Limitations of Fire Modeling

The reconstruction model of the Tubbs fire highlights the current capabilities of modeling as well as the limitations for current fire modeling for reconstruction purposes. There are three major sets of limitations: input data, the model itself, and validation data.

The Tubbs Fire example showcases the limitations of current fuel data. Fuel data has three major limitations: spatial resolution, treatment of urban areas, and whether it is up-to-date (i.e. if the fire was in 2017, how long has it been since fuels were catalogued?). Anything from urban development to large fires can impact the vegetation in an area and will influence the behavior of a future fire in that area. LANDFIRE, the most commonly used source for fuel data in the United States, has a resolution of 30 m, too coarse to accurately represent most roads, and provides updates only every few years. While other fuel data, such as CFO, is being introduced, it is not yet sufficiently reliable for all use cases to replace LANDFIRE. Ultimately, effective reconstruction modeling will require finer spatial resolution and more frequent mapping to capture aspects of fire behavior affected by roads and changing landscapes.

The treatment of WUI fuels in wildland fire models is still in its early stages. At the moment, the typical approach is to assign WUI fuels (e.g. structures) as either a non-burnable fuel or to assign to them a wildland fuel model (e.g. grass, downed slash). Both approaches have their drawbacks and advantages. While the latter approach allows the fire to spread into WUI areas, it does not capture the way that rate of spread changes in a WUI area due to the difference in ignition mechanisms of structure-to-structure spread as opposed to spread through porous vegetative fuels. Despite the advantages of applying a

fuel model to WUI fuels, the current spatial resolution is too coarse to resolve individual (particularly residential) structures. Ultimately, better understanding of and modeling of ignition and fire spread in the WUI will be necessary to improve models for reconstruction modeling.

The comparison between the actual and simulated fire perimeters of the Tubbs fire indicate that there is still room for improvement on the models used. ELMFIRE is based on the Rothermel model of fire spread; however, even fully physically-based models are unable to fully reproduce all fires. The current iteration of the Rothermel model, while valuable, has substantial room for improvement, particularly in its treatment of slopes and wind, two key aspects governing the spread of fires through the wildland (and the WUI). Currently, modeling does not capture the effects of transient heating or complex three-dimensional flame structures, discussed in the two previous chapters. Improvements are continuing to be made to better understand the underlying physics governing fire spread.

In addition to flame spread, a major limitation of current wildland fire models is the models used for ember generation, transport, and subsequent ignition. The most effective models, like that used in ELMFIRE, assume a logarithmic distribution of embers as a function of wind. The advantage of these models is that they are able to account for fire spread and areas impacted by the fire that flame spread does not. The ember cast from the Tubbs Fire simulation showed embers reaching locations that the flames did not, particularly locations known to have experienced substantial structure damage and destruction. While the current ember model is empirically based, it does not describe the physical processes occurring. As a result, there are a number of limitations to these models. The most glaring of these is in the density of embers projected, orders of

magnitude lower than actually experienced in a fire. Some of this underestimate may be due (at least in ELMFIRE) to the way ELMFIRE implements generation probability vs ignition probability to save computational time; however, clearly the manipulation of these parameters indicates a need to better understand ember transport. The improvement of these models will rely partially on the gathering of validation data for ember models, currently practically nonexistent.

Finally, the methods of comparing the simulations and actual fires shown here are based on commonly used methods of comparing fires based on fire perimeter. Part of the rationality for this validation method is the severe lack of sufficiently resolved temporal or spatial validation data. The “best” data currently available is a combination of satellite data and official fire perimeters. Ultimately, validation data on flame lengths, ember casts, local rates of spread, spotting and more will be critical in validating reconstruction models of past fire events. A further focus on fire reconstruction methods and, more widely, wildfire model validation is needed but will likely require a long-term concerted effort from the fire modeling community.

Table 5.1: Weather stations with latitude, longitude coordinates, temporal frequency of measurements, and minutes after the hour of measurements (listed as first measurement if frequency is finer than one hour).

Station	Type	Location (Latitude, Longitude)	Frequency	Minute
ATLC1	RAWS	38.475, -122.265	hourly	:29
BBEC1	RAWS	38.028, -122.702	hourly	:11
BKSC1	RAWS	38.738, -122.145	hourly	:59
COWC1	RAWS	39.126, -123.073	hourly	:01
HGLC1	RAWS	39.209, -122.810	hourly	:36
HPDC1	RAWS	39.031, -123.081	hourly	:15
HWKC1	RAWS	38.735, -122.837	hourly	:56
KAPC	NWS	38.207, -12.279	5 min	:00
KCCR	NWS	37.992, -122.052	5 min	:00
KDVO	NWS	38.142, -122.555	20 min	:15
KEDU	NWS	38.531, -121.786	20 min	:15
KELC1	RAWS	38.912, -122.706	hourly	:57
KNXC1	RAWS	38.862, -122.417	hourly	:09
KO69	NWS	38.258, -122.605	20 min	:15
KSTS	NWS	38.5, -122.817	5 min	:00
KSUU	NWS	38.267, -121.95	hourly	:58
KUKI	NWS	39.128, -123.200	5 min	:00
KVCB	NWS	38.378, -121.959	5 min	:00
LKRC1	RAWS	38.806, -122.741	hourly	:05
MDEC1	RAWS	37.928, -122.587	hourly	:36
NVHC1	RAWS	38.112, -122.550	hourly	:31
ONOC1	RAWS	37.865, -122.221	hourly	:33
PIBC1	RAWS	37.95, -121.884	hourly	:28
PLEC1	RAWS	37.934, -122.118	hourly	:28
RSAC1	RAWS	38.478, -122.712	hourly	:29
WISC1	RAWS	39.019, -122.412	hourly	:36

Table 5.2: Spatial and temporal domain settings.

Setting	Value
Cell size	30 m
Lower left corner, X coordinate	-11054.813
Lower left corner, Y coordinate	320429.408
Domain, X dimension	21000
Domain, Y dimension	27000
t_{start}	1800 s (past 9:00 PM)
t_{stop}	25200 s (4:30 AM)
Initial time step	1.0 s
Maximum time step	15.0 s
Target CFL	0.45

Chapter 6: Coupling Fire Exposure and Structure Losses

6.1 Introduction

The present study investigates the relationship between local fire exposure, structure characteristics or vulnerabilities, and structure losses during the 2017 Tubbs Fire to understand the risk associated with structure loss. Current hazard and risk assessment of wildland fires focuses primarily on fire risk at a landscape scale, used for land and resource management [15]. This study focuses instead on developing a methodology for addressing risk at a community or structure scale, for which previous studies have neglected to include the fire conditions to which a structure is exposed [16, 17]. The present work fills this gap by extracting fire conditions from reconstruction modeling of past fires.

Other disaster fields, including earthquakes, floods, and hurricanes, have developed standardized risk metrics used to describe the probability of destruction to a structure based on the intensity of the exposure (e.g. speed of winds, height of flood water). The present study builds on methods used in other disaster fields to construct fragility curves for the Tubbs Fire. In particular, this study investigates appropriate exposure types and intensity levels for wildland fires, as well as which structure and community characteristics can be used to define building classes and which more directly influence

the intensity measures.

The objectives of this study are: first, to use the Tubbs Fire as a case study to develop a framework for risk assessment of the WUI at the structure level; second, to determine appropriate measures and levels to describe exposure from fires; third, to elucidate the impacts of structure characteristics on structure survival; and finally, to quantify trends between fire exposure, structure damage, and structural vulnerabilities.

For structures in the WUI, the vulnerabilities of a structure may consist of properties such as building features, spacing between structures, local fuel-clearing (defensible space), or a combination of these features quantified, for instance, by year built. Fire intensity measures should consider the known spread pathways of WUI fires: radiation, direct flame contact, and embers. Ember deposition is critical as the majority of structures are lost in WUI fires due to ember ignition [57]. Due to the lack of intensity measurement during a fire, the results of the reconstruction modeling are used to simulate the local exposure to each structure from the wildland fire. The risk analysis framework will be based on reconstruction results, pre- and post-fire structure characteristics and damage levels, and a comparison between structure damage and exposure levels.

6.2 Destroyed Structure Data

A critical aspect of this problem is knowing the damage that a structure sustained as a result of fire exposure. Data on pre- and post-fire structure characteristics and post-fire structure damage is available for the Tubbs Fire (and many other fires) through home damage inspection (DINS) reports produced by CALFIRE [128]. The DINS reports

preferentially include damaged and destroyed structures. Although a small selection of undamaged structures are recorded, the inspections do not cover the full spectrum of structures exposed to a fire. In order to be able to draw any 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. As a result, this dataset has been supplemented by collecting data from the city of Santa Rosa in Sonoma County [129] and Napa County [130] to determine the locations of structures not included in the inspection reports. This data is also supplemented with the Microsoft building footprints database [131].

6.2.1 Damage States of Structures

The damage state of a structure refers to the level of damage a structure experienced as a result of the fire and can range from no damage (i.e. the structure is in the same condition as it was before exposure) to complete destruction. Damage levels are used in risk analyses as a metric to describe the impact of an event on a given structure. Ultimately, combined with fire exposure levels and structure/community characteristics, they are used to develop predictions of the probability of exceeding a given damage level conditioned on a certain level of intensity for a certain building class.

The data provided for the Tubbs Fire follows a prior methodology for splitting damage levels, which was updated in 2018 to be consistent with FEMA classifications for other disasters. The damage levels reported for the Tubbs Fire include: Survived, 1-9% damage, 10-25% damage, 26-50% damage, 51-75% damage, and Destroyed. To be

consistent with FEMA standards [90], the 51-75% damage classification is included in the Destroyed data category for this analysis. This modification reflects that this level of damage usually results in a home having to be completely rebuilt.

For the CALFIRE structure data, damage states are assigned to structures consistent with the DINS report. For the supplemental data from the cities and Microsoft, all structures are assumed to be undamaged, since they were not included in the DINS report. Supplemental data is included for all structures within the fireline, as well as structures within 150-750 m (dependent on whether the area is urban or rural) of the fireline. The table below shows the number of structures in each damage state, once the supplemental data is added.

Table 6.1: Number of structures from the Tubbs fire in the original five CALFIRE DINS damage states.

Damage State	Number Structures
Survived	2946
1-9%	186
10-25%	74
26-50%	32
Destroyed	5651

Given the comparatively small number of structures in the 1-9%, 10-25%, and 26-50% damage states, these three damage states are combined into a new single “Partially Damaged” state. This combination is consistent with previous work that has looked at home destruction [132]. With the updated three damage states, the number of structures is: 2946 Undamaged, 292 Damaged, and 5651 Destroyed. Figure 6.1 shows the full dataset of structures exposed to the Tubbs fire, color-coded by damage state, with respect

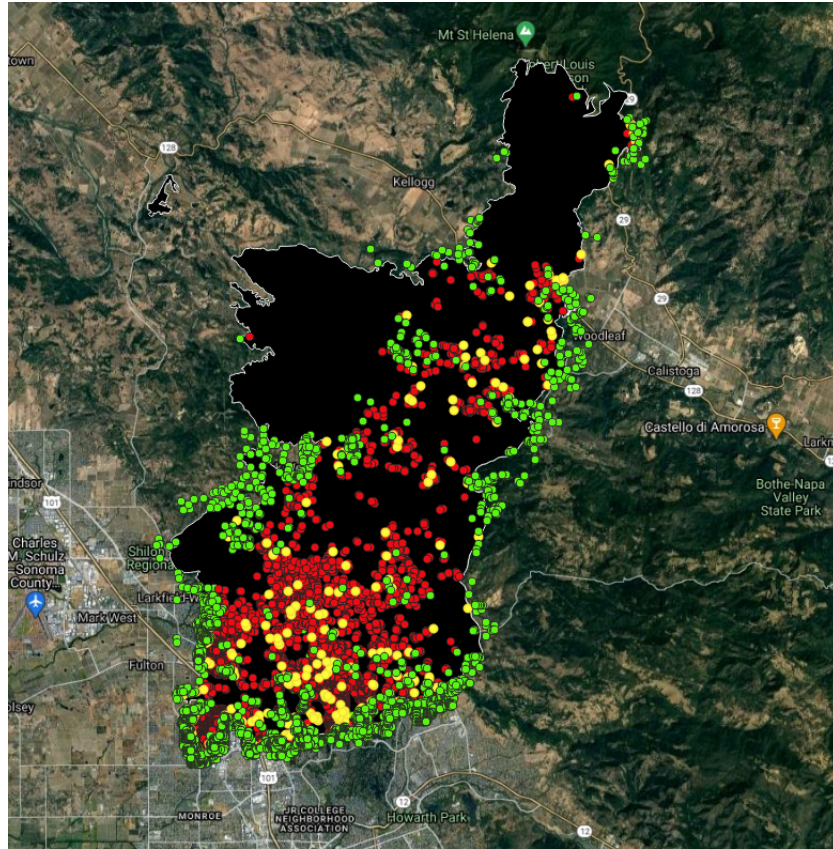


Figure 6.1: Structures exposed to the Tubbs fire (green = undamaged, yellow = partially damaged, red = destroyed) shown with respect to the final CALFIRE fire line.

to the final fire perimeter of the event.

6.2.2 Structure Vulnerability Data

It is expected that the probability of a structure exceeding a given damage state when exposed to an intensity metric will vary based on certain structural characteristics. There are a number of characteristics that may impact structure vulnerability, including the distance between structures, the distance from a structure to surrounding vegetation, the year built of a structure (due to changing building code recommendations), and more. The effects and significance of different structure characteristics on the probability of

damage will be investigated in the following risk analysis.

The DINS reports identify and log a selection of structure characteristics expected or known qualitatively to have an impact on structure survival. These characteristics include the defensible space around a structure, where defensible space is the area cleared of contiguous vegetation [133], the type of roof, windows, and siding, the community where a structure is located, the local topography, coverings of vents and eaves, and the construction material of decks. These characteristics were supplemented with additional home and community characteristics anticipated, based on previous literature and post-fire investigation reports, to affect the likelihood of home survival. These characteristics included the presence of a fence, particularly a wood fence, connecting to the house; the year built of the house, relevant due to code changes for building in the WUI in California; the distance to the nearest structure (N1); and the local density of structures.

Where possible, characteristics identified in the CALFIRE DINS reports were determined to the additional undamaged homes not included in the DINS. These characteristics included defensible space, roof construction, and the presence of a deck or porch. These characteristics were determined using historical data viewed on Google Earth and Google Street View within two years before the fire. It was not feasible with the available imagery to supplement data sets on windowpane type, enclosure of eaves, or vent screens.

In the DINS reports, defensible space is categorized as 0-30 ft, 30-60 ft, 60-100 ft and >100 ft. However, these distances were modified for all structures (including those originally categorized by CALFIRE) to 0-5 ft (a range included in some defensible space recommendations), 5-30 ft, 30-60 ft, 60-100 ft, and >100 ft. Within a single distance

category, defensible space was separated into dense or sparse to account for situations such as a single line of trees near a commercial building which is otherwise clear of vegetation.

Local structure density was determined using the heatmap functionality in QGIS which counts the structures within a given radius. Year built is included in the analysis to understand the effectiveness of code changes implemented for new construction. In particular, in 2008, California introduced Chapter 7A of the Building Code to specifically address code changes for WUI fire hazards. Previous studies and reports (unpublished and [64]) have found differences in rates of home survival for those homes built in 2008 and later.

Structure-to-structure distance was calculated using the QGIS function `Nearest Neighbor Analysis`, which measures the distance to the nearest point in the layer. While other analyses of structure features considered structures as points, structure-to-structure distance was calculated using the building footprints from Microsoft [131]. Previous studies and post-fire investigations [59] have found that the distance between structures, particularly in suburban and urban areas where structures are organized near one another, can influence fire spread from structure to structure.

Table 6.2 shows the full set of characteristics related to structural and community vulnerabilities. For certain features, it was not possible to fill out the details of a characteristic for every structure. For example, the Microsoft dataset used for the structure-to-structure distance calculation did not include the full set of structures. Certain characteristics, such as vent coverings, could not be determined from historical imagery and, thus, could not be expanded for structures not included in the DINS reports. As a

Table 6.2: Structure and community characteristics with their possible values or categories and the number of structures within the dataset for which a specific characteristic is available.

Characteristic	Structures	Potential values
Community	6017	Fountaingrove, Coffey Park, Riebli, Larkfield-Wikiup, Franz Valley, Mark Valley, Calistoga
Defensible Space	7060	0-5 ft, 5-30 ft, 30-60 ft, 60-100 ft, >100 ft (dense and sparse)
Year built	8705	Range 1870-2016
Structure type	6015	Residence, Outbuilding, Commercial
Roof construction	6994	Fire resistant, Combustible
Window panes	4020	Multi-pane, Single-pane
Exterior siding material	6972	Fire resistant, Combustible
Eaves	1964	Un-enclosed, Enclosed, No eaves
Deck/porch construction	6958	Composite, Masonry, Wood, No deck/porch
Vent screen present?	3427	Yes, No
Local topography	6017	Flat ground, Slope, Ridge top, Chimney, Saddle
Structure-to-structure distance	7713	Range

result, the number of structures with the relevant characteristic is listed.

6.3 Exposure Data

In order to understand the relationship between structure characteristics and damage, it is imperative to know the conditions to which a structure was exposed. Without knowledge of the intensity of the fire, it is not possible to quantitatively draw conclusions about what structure characteristics will influence, and to what degree, the damage state

of a structure.

Fire spreads into the WUI via radiation, direct flame contact, and ember exposure. As discussed previously, the majority of structure ignitions in the WUI are attributed to ember ignition [57]. Thus, a measure of ember exposure is included in the intensity types considered for the risk analysis. Additionally, radiation is considered as another pathway to structure ignition. While the model does not directly output radiation, other outputs can be used to represent the impact of the main firefront on ignition. Here, flame length (linearly related to fireline intensity by Byram's Equation [76], which can in turn be related to radiation) is considered as another intensity metric.

The outputs for embers and flame length are discussed in the previous chapter in Section 5.2.4; here, their application to risk assessment is considered. Ember exposure is simulated as the average number of embers deposited on a given cell *which ignite* throughout the duration of the simulation. The “number” of embers is quantitatively relatively meaningless as no data is available to validate the model. As a result, rather than providing the ember exposure in terms of quantitative values, the embers will be split into qualitative exposure levels.

ELMFIRE produced average ember counts of 0-27 ember ignitions for each cell. The relationship between the structure exposure for a given density of embers and damage state is shown in Figure 6.2. The percentage of structures is calculated as the percentage of buildings in a given damage state exposed to a given number of embers (e.g. if 300 buildings are exposed to 10 embers, the percentage is proportion of those buildings that are in each of the three damage states).

Previous work on fragility curves for earthquakes recommends splitting the

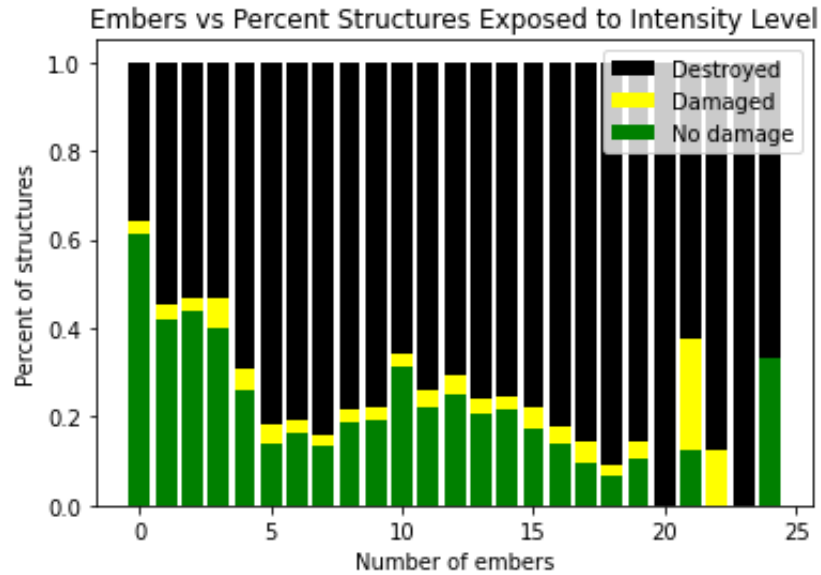


Figure 6.2: Percentage of structures in a particular damage state vs. the number of embers impacting and igniting in the cell.

intensity measure into discrete levels. To separate embers into discrete levels, different groupings of embers were considered, two of which are shown in Figure 6.3. On the left, embers are bucketed into groupings of two embers per “ember level”, while on the right, embers are bucketed into groupings of five embers per level. As the larger grouping (five embers) appears to capture the trends in both the two ember grouping and in the ungrouped embers, the five ember bucket was used to create ember intensity levels of: None, Low, Medium, High, and Severe.

Maximum simulated flame lengths ranged from 0-47 ft, as shown in Figure 6.4. While embers were grouped based on qualitative trends, flame lengths were grouped to be consistent with flame length range guidelines influencing suppression recommendations [134]: 0-4 ft, 4-8 ft, 8-11 ft, >11 ft. To account for the large range of flame lengths above 11 ft, that category was further split into 11-20 ft and >20 ft. It can be seen that the majority of flame lengths occur in the range below 20 ft. Note that only the maximum

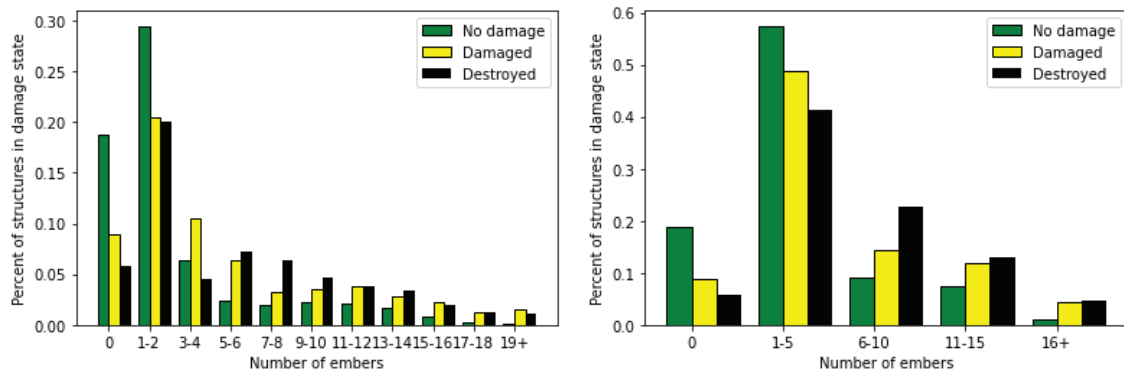


Figure 6.3: Percentage of structures in a particular damage state vs. the number of embers impacting the cell, with embers segregated into buckets to more clearly show trends.

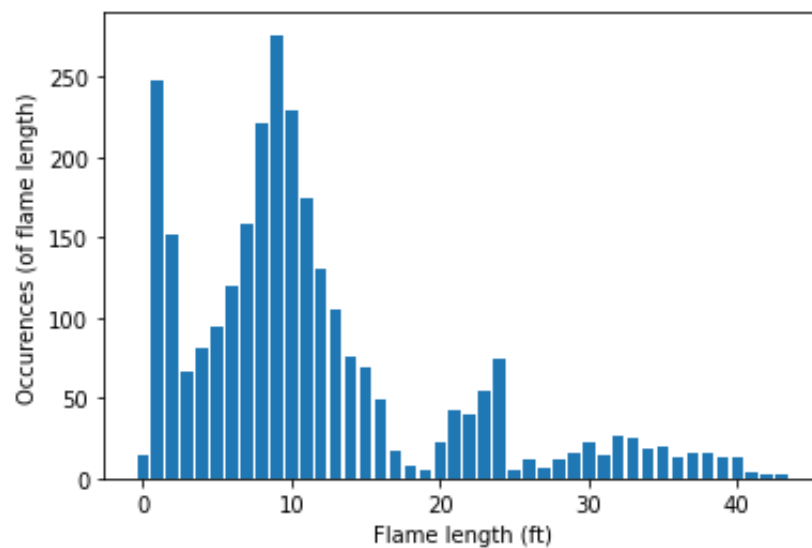


Figure 6.4: Distribution of flame length for the full simulated fire.

flame length for the entire simulation at a given cell is considered. This choice is made based on the assumption that the maximum flame length will occur when the fire is present (thus eliminating the need to match firelines to individual structures) and that a structure is most likely to be ignited at maximum flame length.

Two measures of flame length were considered in the risk analysis: the flame length occurring in the same cell as a structure and the maximum flame length occurring within a given distance from the structure ($s = 60$ m). The latter measure was considered due to the possibility of radiation outside a cell influencing structure ignition, as well as the relatively low number of structures whose cells were “burned” in the simulation (approximately 25%). Figure 6.5 shows the community of Coffey Park which experienced major destruction. Despite the destruction in the actual event, the simulation shows that most structures did not experience local flame lengths. The inclusion of nearby maximum flame length is also to account for the likelihood that flame length results in smaller unsimulated flames that can cause ignition (i.e. direct flame contact ignition).

The following figures, Figures 6.6 and 6.7, show the maximum flame length distribution over the fire area and the ember ignition distribution over the fire area, respectively, with locations of structures color-coded by damage state, where black indicates Destroyed, yellow indicates Damage, and green indicates Survived/Undamaged.

6.4 Risk Analysis Methods

Existing wildland fire spread models, including ELMFIRE, do not account for structures. Thus, the exposure results from the model are overlaid onto the structure

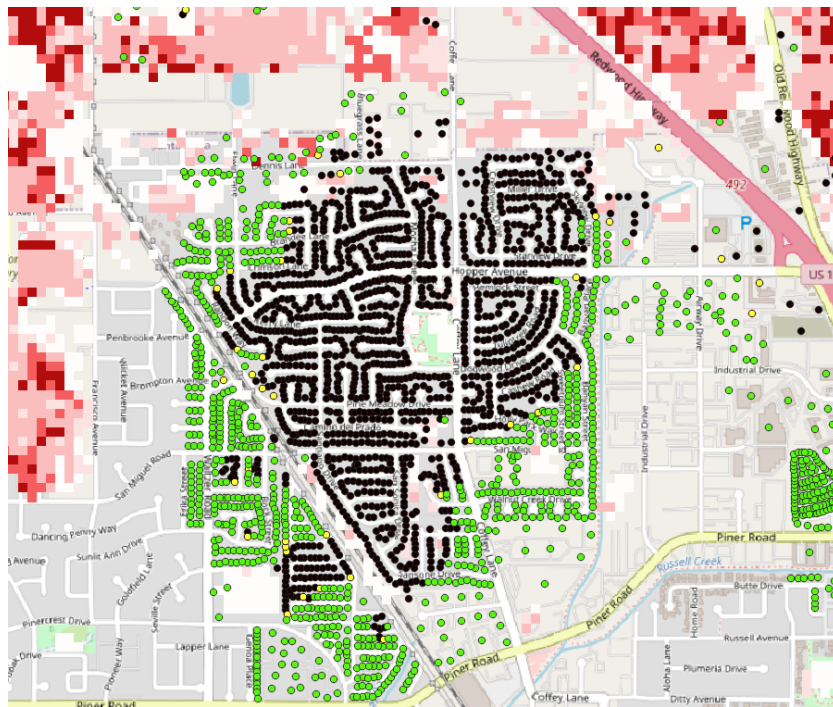


Figure 6.5: The community of Coffey Park showing undamaged (green), damaged (yellow), and destroyed (black) structures. Flame length is overlaid indicating the lack of modeled flame exposure to the community despite significant destruction, thereby indicating ignition via embers.

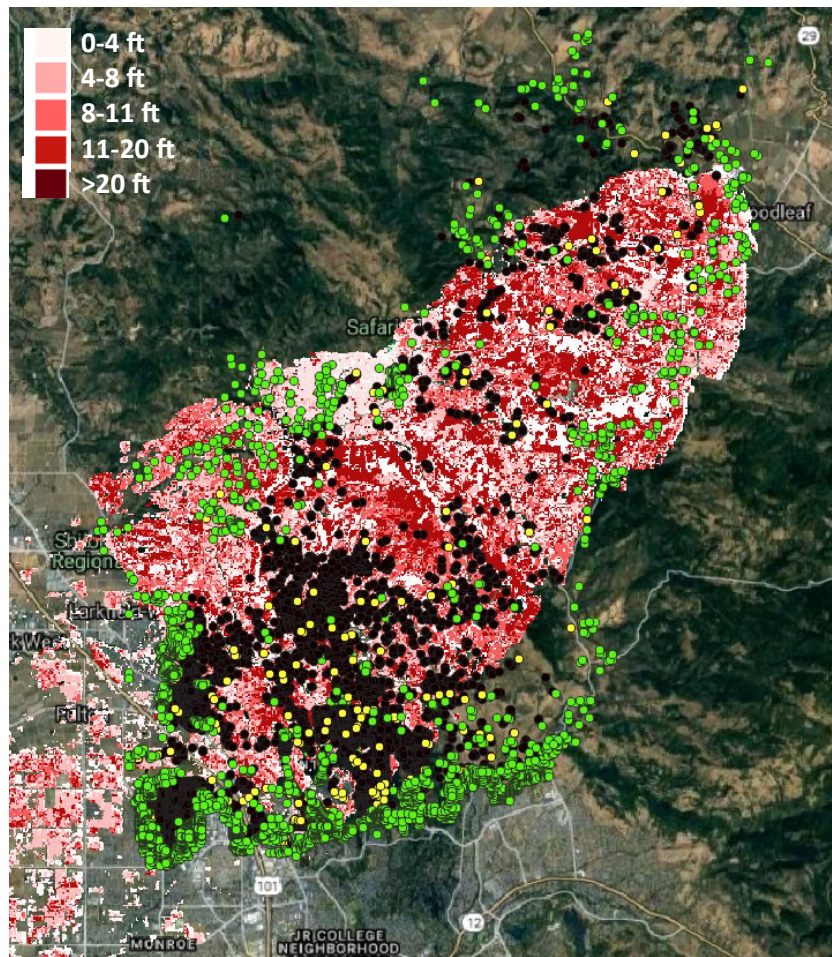


Figure 6.6: Distribution of maximum averaged flame lengths for the full simulation of the Tubbs Fire with structures exposed to the fire plotted on top, color-coded by damage state (green = undamaged, yellow = damaged, black = destroyed). Structures on the southeastern flank are not exposed to the main simulated fire front.

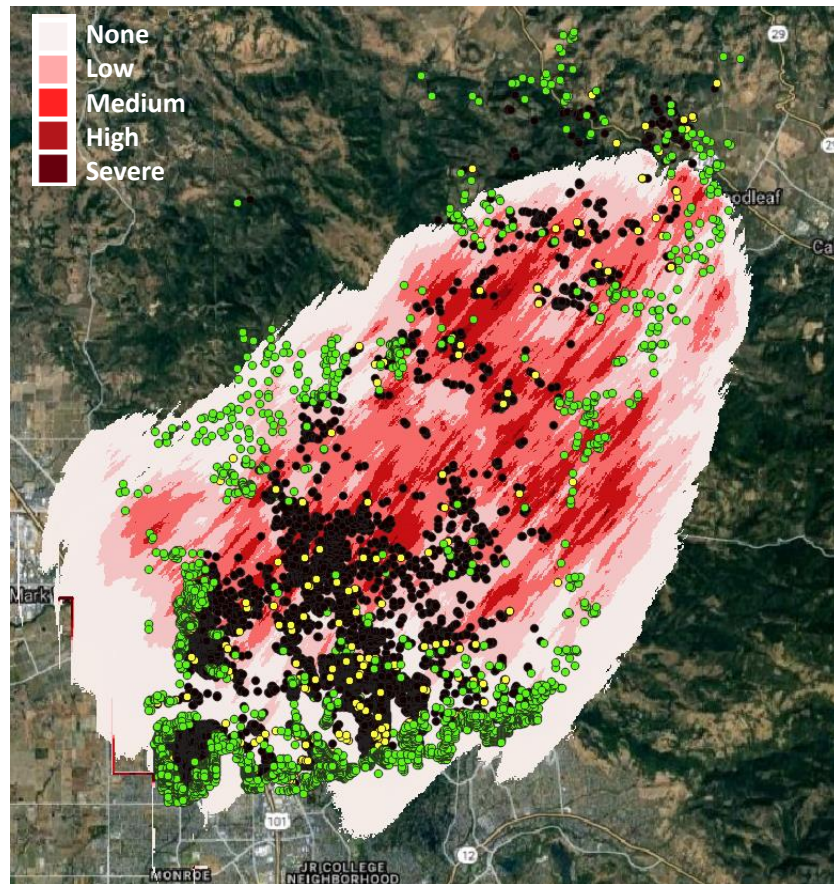


Figure 6.7: Distribution of embers for the full simulation of the Tubbs Fire with structures exposed to the fire plotted on top, color-coded by damage state (green = undamaged, yellow = damaged, black = destroyed). Embers are deposited and ignited in areas which are not exposed to the simulated main fire front.

data to connect intensity level in a cell with the structures in that cell. Due to the coarser resolution of the simulation, it is possible to have multiple structures in the same 30 m by 30 m cell.

The first objectives of this study are to determine reasonable intensity characteristics and which structure characteristics are of relative importance. To that end, two analyses are conducted. The first is an exploration of the data set to understand the qualitative influences of various structure and community characteristics. The second is the development of fragility curves to model the probability of a structure achieving a certain damage state, given a certain exposure level.

6.4.1 Development of Fragility Curves

Fragility curves provide a measure of the probability of a structure exceeding a certain damage state given a certain level of intensity (e.g. ember density or flame length). 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.

There are three aspects of risk that are needed to produce fragility curves: a measure of intensity with discrete levels, discrete damage states that a structure may reach, and building classes. Part of the intention of this work is to determine intensity measures and levels that are representative of a WUI fire scenario. The two intensity measures

discussed, ember density and flame length, are used to represent two pathways of ignition in the WUI. The preliminary work on exposure and structure features discussed in the previous section is used to inform possible intensity levels for each measure of intensity, as well as to inform what building characteristics could be included in building classes.

The damage states and intensity measures are used to construct fragility curves for all buildings and for different configurations of building classes. The inclusion of community characteristics, such as the local density of structures, is considered for their potential effect on the fragility curves. In general, the development of the different fragility curves follows the same overall methodology of fitting the empirical data with a statistical model to determine the probability distribution of the damage.

The fragility curves are fitted using a generalized linear model (GLM), which takes the form of:

$$Y = \beta_0 + \beta_1 x_1 + \dots + \beta_n x_n \quad (6.1)$$

where $X = [x_1 + x_2 + \dots + x_n]$ is the explanatory variable, β_0 is the intercept, $\beta_1, \dots, \beta_n$ are the weights of the explanatory variables, and Y is the response variable for which

$$Y = \begin{cases} 0 & \text{for } DS < ds_i \\ 1 & \text{for } DS \geq ds_i \end{cases} \quad (6.2)$$

with DS the damage state of a given structure, and $ds_i = ds_0, ds_1, ds_2$ for Undamaged, Damaged, and Destroyed damage states. Each structure in the database has values for Y and X , which are used for the fitting of the GLM.

There are three components of a GLM [89]: the random component, which is a probability distribution of the response variable; the systematic component, expressed in

terms of a linear predictor

$$\eta = \nu_0 + \nu_1 IM \quad (6.3)$$

which relates the mean response variable and the exposure, IM , through the model parameters ν_0 and ν_1 ; and the link function

$$g(E[Y|X]) = g(\mu) = \eta \quad (6.4)$$

which relates the mean response variable, $\mu = E(Y|X)$ (the expectation of the response variable conditioned on the explanatory variables), to the linear predictor, η .

The response variable is modeled using a binomial probability density function

$$Y = \binom{n_j}{y_j} \mu^{y_j} [1 - \mu]^{n_j - y_j} \quad (6.5)$$

The explanatory variables are considered to be the intensity measures as well as select community features, which are included 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.

Three link functions applicable to binomial distributions are considered: the logit distribution

$$\eta = \log[1/(\mu^{-1} - 1)] \quad (6.6)$$

the probit distribution

$$\eta = \Sigma^{-1}(\mu) \quad (6.7)$$

and the complementary log-log distribution

$$\eta = -\log[-\log(1 - \mu)]. \quad (6.8)$$

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. The GLM is fitted using the `glm` function in the Python `statsmodels` package.

6.5 Results of Risk Analysis

Results present two methods of coupling fire exposure conditions with structure destruction. The damage plots provide insight into the relationship between individual community or structure characteristics, the damage state of a structure, and the level and type of exposure it experienced. These results can help indicate which features might be used to define different building classes, as well as describe the effects of different exposure levels. The fragility curves describe the statistical relationship between exposure levels and damage states, for all structures or for specific classes of buildings.

6.5.1 Damage Plots

The Tubbs Fire was characterized by major destruction in specific communities, the most widely cited being Coffey Park. In initially investigating structure damage, it can be helpful to look at the impacts of exposure on different communities to understand the influence of different exposure mechanisms on rural vs urban communities. A map of indicated communities is available in the Damage Inspection Report of the Tubbs Fire [135]. It can also help to determine which structural or community characteristics might be worth further investigation. Figure 6.8 shows the number of destroyed structures in

seven communities exposed to the Tubbs Fire with respect to the exposure levels they received of both embers and flame length. Note that community is a feature from the CALFIRE reports and was not filled out for added structures in the data set, so this data is mainly discussed from the perspective of structure destruction.

In most communities, more structures received ember exposure than fire exposure. It is possible that structures that received ember exposure also received flame length exposure; no separation is made here. This result is consistent with investigations that find that embers ignite more structures than the main fire front. However, interpreting this result is complicated by the fact that the simulation does not spread into urban areas, such as the Santa Rosa communities, and the fact that the simulation does not simulate structure ignition. As a result, the present analysis is missing flame exposure from nearby structures, expected to play an important role in structure-to-structure fire spread. As these new tools are developed, possibly informed by this work and others, and applied to developing WUI fire spread models, future analyses can be improved.

Another key result is that there are destroyed structures shown that receive *no* level of that intensity (shown for both ember and flame exposure). It is unknown from these specific results whether these structures (e.g. the ones that received no ember exposure) received other types of exposure (e.g. flame length). Additionally, ember and flame length exposure likely do not capture the full spectrum of ways that structures ignite. In particular, they do not account for structure-to-structure fire spread. Additionally, the number of structures in a community exposed to embers and the number exposed to flame length is not equal. While Franz Valley and Mark West had relatively equivalent numbers of structures receiving both embers and flame exposure, other communities had larger

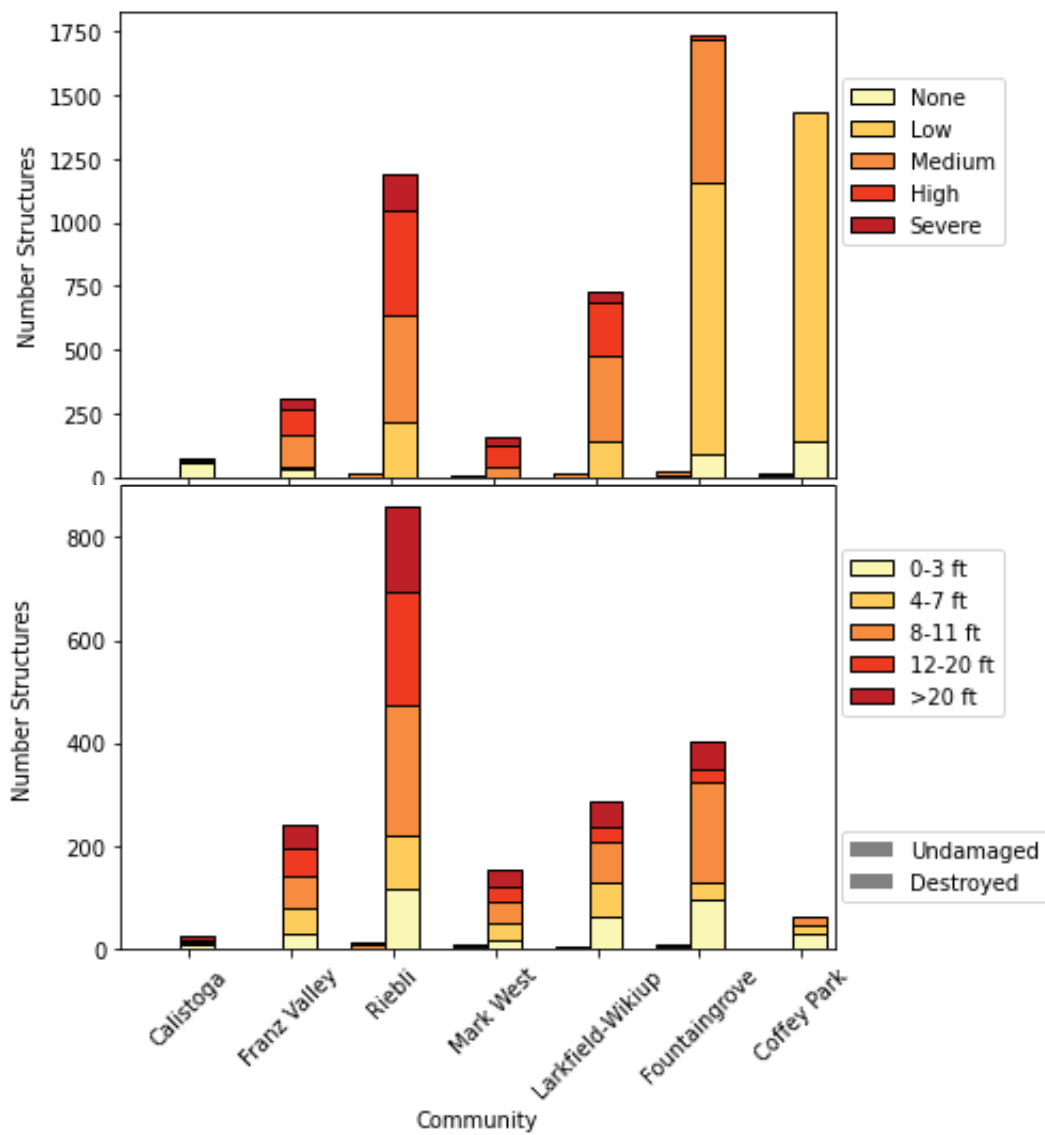


Figure 6.8: Comparison of the number of structures impacted by flame length (bottom) vs. ember exposure (top) in different communities impacted by the Tubbs fire.

numbers of structures receiving ember exposure than flame exposure. As a result, it is possible that structures showing no exposure level are destroyed by intensity types not represented here.

There are interesting differences in ember and flame length exposure to destroyed structures. In looking at the flame length figure, notice that proportionally more destroyed structures experience large flame lengths (8 ft and over). On the other hand, communities like Coffey Park and Fountaingrove show the majority of destroyed structures only exposed to low ember levels. These results show that even a single ember ignition can be sufficient to cause structure destruction. Although the analysis shows simulated *exposure*, there is no way to indicate or determine the actual method of *ignition*. While exposure may be used to represent likely ignition paths, there is inherent uncertainty due to the lack of data on ignition mechanism.

Three additional features describing structure and community characteristics will be discussed: the year built of the structure, the defensible space around the structure, and the distance to the next nearest structure. Year built is considered as it represents construction changes over time, as well as code changes in reaction to previous wildland fires. Although year built does not isolate individual structure characteristics, it can give an overall picture of the effectiveness of mitigation efforts and can verify unpublished studies that have found the 2008 code change to be correlated with increased likelihood of structure survival.

In Figure 6.9, for structures exposed to analogous low ember conditions, there was increased likelihood of destruction for structures built from 1968 and onward until the code changes of 2008. Structures exposed to higher flame lengths were primarily

destroyed whereas those exposed to lower flame lengths were sometimes destroyed and sometimes survived. Overall, a greater number of undamaged structures were exposed to no embers. Regardless of exposure mechanism, the proportion of survived to destroyed structures was higher for structures built after the implementation of 2008 code changes for certain exposure conditions. These code changes included the creation of Chapter 7A which addresses construction features such as fire resistant roofing.

Results for showing the effect defensible space for structures exposed to embers are shown in Figure 6.10 for all structures within the fireline. Structures outside of the fireline are currently excluded. Here, defensible space is split into five distance categories, with the 0-5 ft range further divided into sparsely or densely vegetated. This split is made due to the large number of structures (over 5000) with vegetation in the nearest defensible space category. Other categories have too few structures for splitting into sparse and dense to be statistically significant.

Overall, there are fewer structure with large defensible space and these are primarily destroyed. Previous studies have found that structure destruction is different in urban vs rural areas. It is expected that the structures shown here with defensible space above 30 m are rural structures. Many of these structures are exposed to higher ember loads or may experience ignition via direct flame contact by dead leaves or other features that would not appear in satellite imagery as vegetation. A comparison of structures with little defensible space finds that more structures were destroyed that had dense (rather than sparse) vegetation in the 0-5 ft range. In particular, the proportion of destroyed to survived structures with 0-5 ft defensible space is higher for dense than sparse. When exposed to higher ember loads, the structures with dense vegetation were preferentially

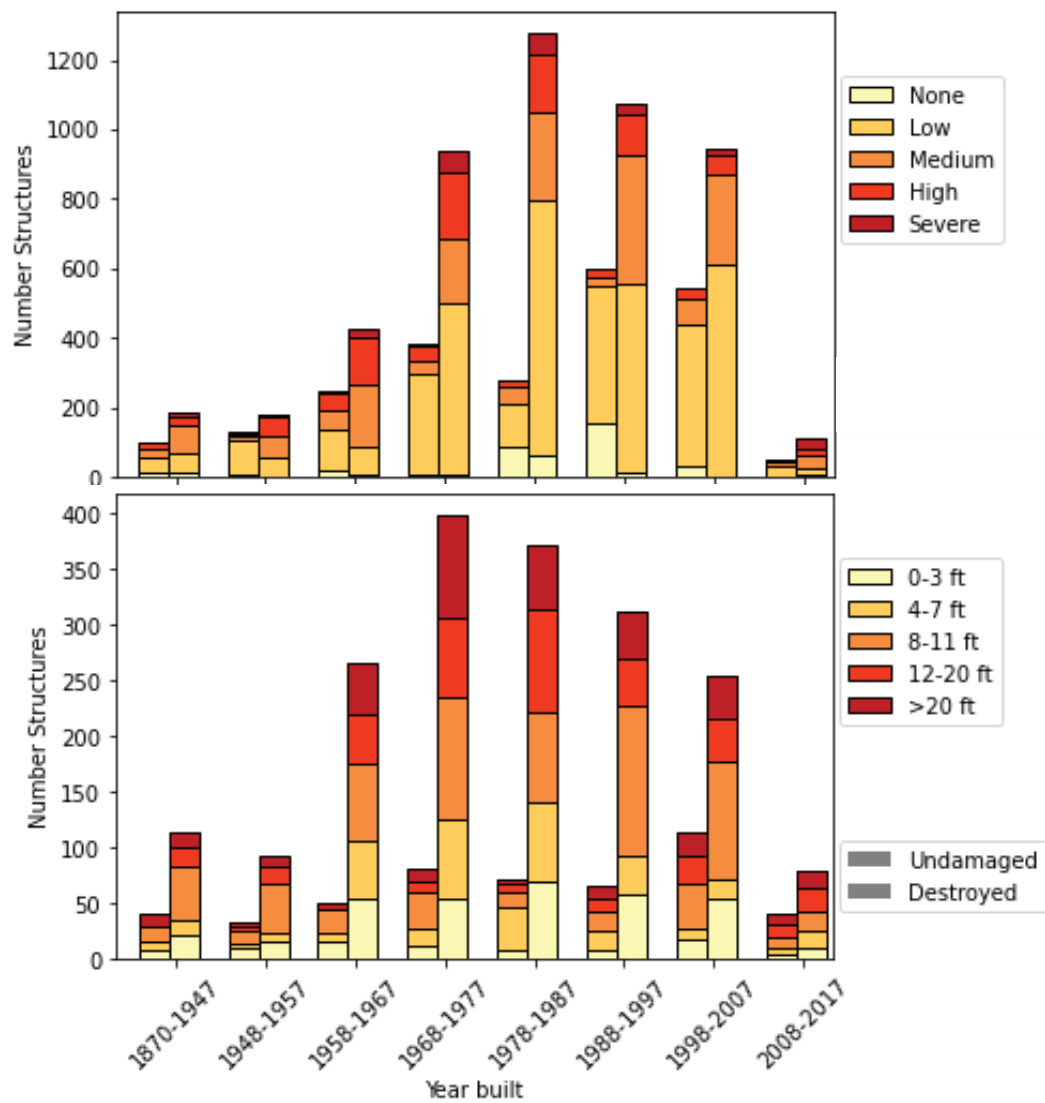


Figure 6.9: Top: A comparison of structures exposed to embers vs. year built. Bottom: A comparison of structures exposed to flames vs. year built of the structure.

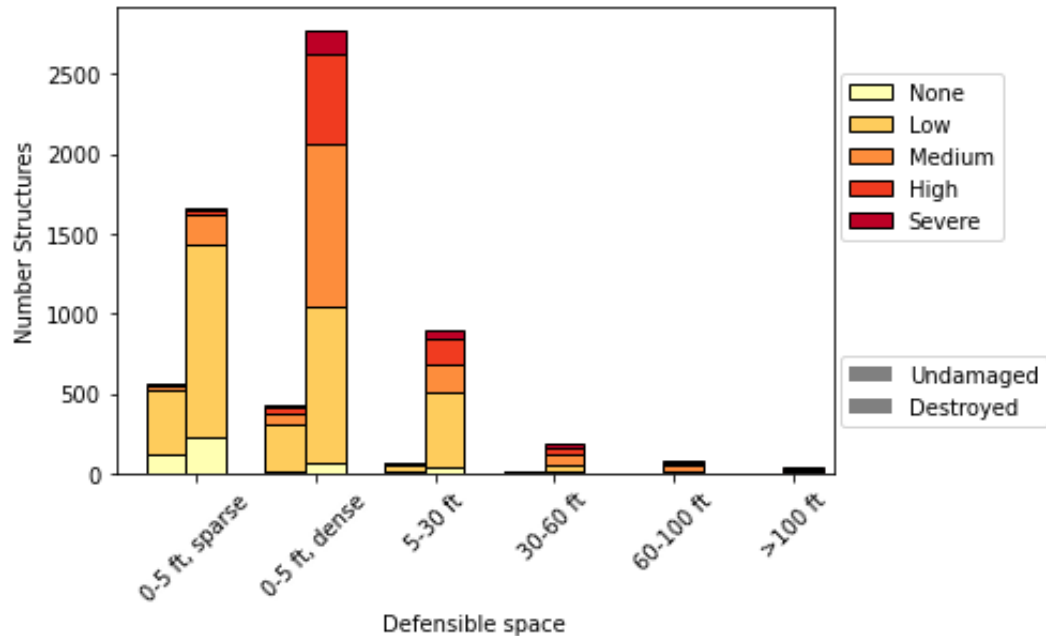


Figure 6.10: A comparison of undamaged and destroyed structures exposed to embers at different defensible space distance.

destroyed; for low ember loads, there was a smaller difference in the dense and sparse vegetation.

There are several metrics to describe spatial arrangement of the structures in a community. Results for the distance to the nearest structure, or the local structure-to-structure distance, are shown in Figure 6.11. On the x-axis, distance is split into a ranges of distances of different sizes due to the large distribution of structure-to-structure distance in the full database, as well as the most frequent structure-to-structure distances that occur in urban vs rural areas. A distance of 2 m is generally the minimum distance between single family residences, which accounts for the split shown at 2 m. Because of the large number of structures for which the nearest structure is less than 10 m away, these distance were split into three groupings to investigate whether they exhibited different behavior when exposed to embers.

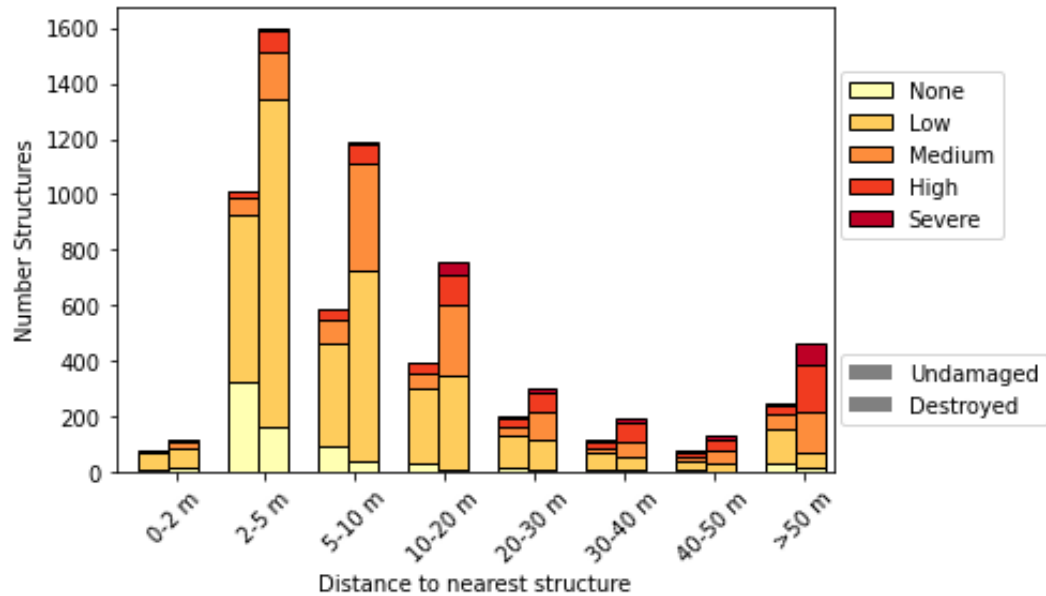


Figure 6.11: A comparison of undamaged and destroyed structures exposed to embers at different structure-to-structure distances.

For the small number of structures with another structure 2 m or fewer away, ember exposure appears to have little influence on likelihood of destruction. Trends are relatively similar for structures whose nearest structure is in the 2-20 m range. For all distances, any ember exposure results in a higher likelihood of destruction. However, in the near ranges, this trend is most apparent for low and medium ember levels. For the far ranges, high and severe ember levels are correlated with an increased likelihood of destruction.

Overall, a few main conclusions can be highlighted from the damage plots. First, low levels of ember exposure have a noticeable impact on increasing the likelihood of destruction. Second, the relative influences of embers and flame length are different. Whereas embers have a major impact with even small numbers, flame lengths have more impact for flames above 8 ft. Third, there are select scenarios (such as larger defensible space and farther structure-to-structure distance) for which the proportion of structures

destroyed to survived is higher for higher ember loads than for lower ember loads. Additional damage proportion plots for different structure characteristics are included in Appendix B. The plots presented for structure-to-structure distance, year built, and defensible space are also shown in this appendix, normalized by the number of structures in each category.

6.5.2 Fragility Curves

There was negligible difference between the link functions in the statistical fitting, so a link function of logit was used for all GLMs used to create the fragility curves in the following section. A table of the full set of GLMs for the fragility curves shown in this section can be found at the end of this section in Table 6.3.

To understand the relationship between exposure and damage, fragility curves with all structures for each intensity measure were produced. These curves were produced both for the full range of each intensity measure, as shown in Figures 6.12 and 6.13, and for the grouped levels of intensity used in the damage plots, as shown in Figures 6.14 and 6.15. This comparison was done to investigate the effectiveness of the intensity levels for fragility curves and prediction of damage and destruction.

Figure 6.12 shows an increase in the probability of both damage and destruction as the number of embers ignited in a cell increases. In particular, this relationship is stronger for embers than for flames (shown in Figure 6.13). When comparing Figures 6.14 and 6.15 using discrete intensity levels with Figures 6.12 and 6.13 using the raw exposure data, similar trends are apparent: probability of damage and destruction increases with

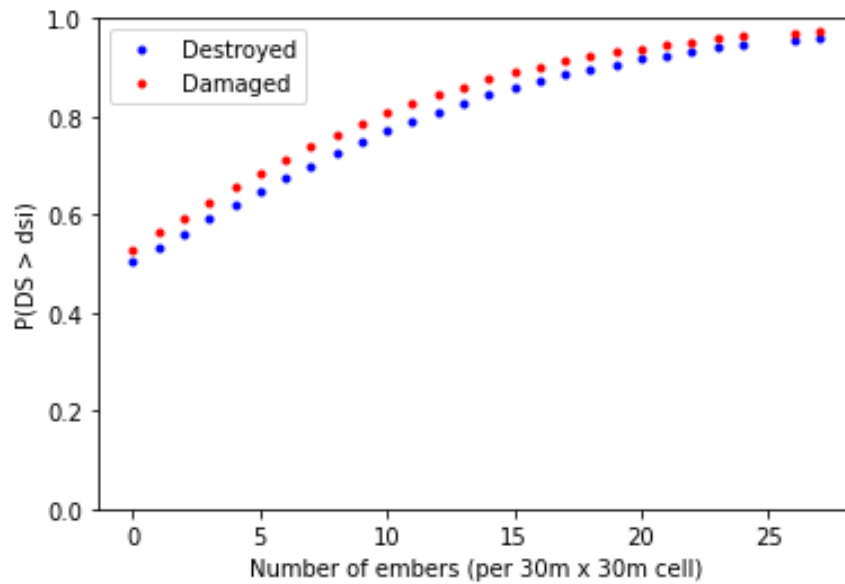


Figure 6.12: Fragility curves showing the probability of damage (red) or destruction (blue) at different raw ember densities for all structures in the Tubbs Fire.

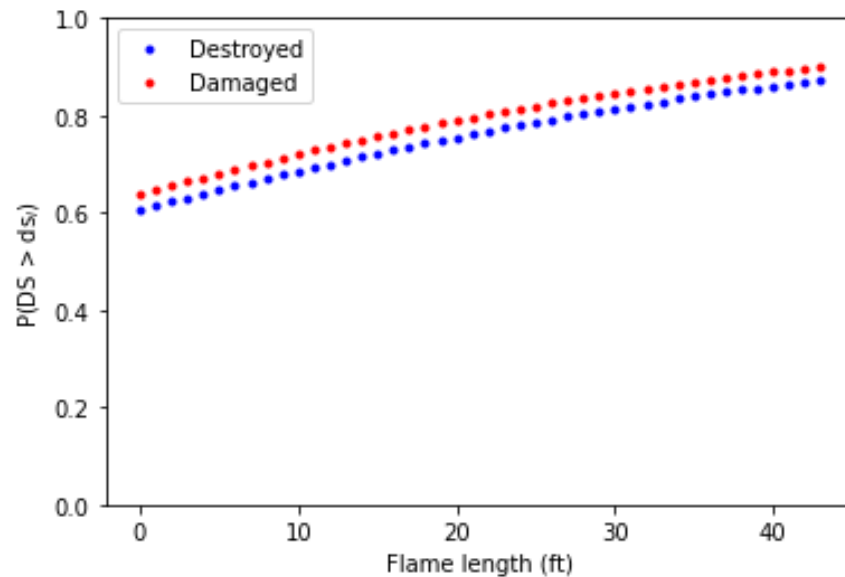


Figure 6.13: Fragility curves showing the probability of damage (red) or destruction (blue) at different raw flame lengths for all structures in the Tubbs Fire.

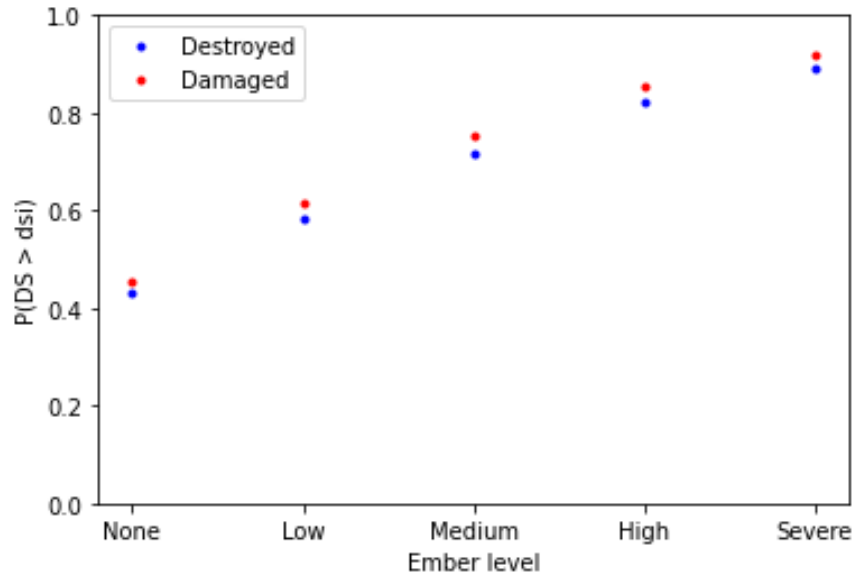


Figure 6.14: Fragility curves showing the probability of damage (red) or destruction (blue) at different discrete ember levels for all structures in the Tubbs Fire.

increasing intensity. Comparatively, the ember level plot does not show the same leveling off at higher levels; however, this is due to the grouping of all embers above 16 into a single level. The leveling off shown in the main plot shows that this grouping of a larger range of embers into a single level is able to capture the severe intensity behavior. The flame length shows a relatively similar trend with both the raw values and the discrete intensity levels.

It is important to note, for both the ember and flame length figures, that the probability of either damage or destruction should be 0 for no intensity. The prediction of some probability of damage at 0 exposure can be explained by the fact that the current exposures do not fully describe all mechanisms of exposure that a structure may experience. First, the structures that have no exposure to the main fire front may be exposed to embers (as in Coffey Park, Figure 6.5) and vice versa. Second, the simulated flame lengths only include flames from vegetative fuels as the fire model does not

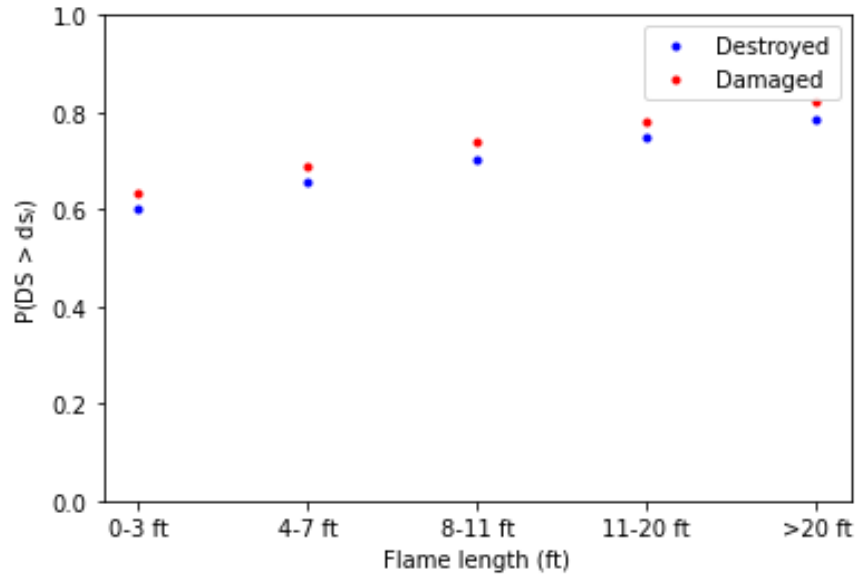


Figure 6.15: Fragility curves showing the probability of damage (red) or destruction (blue) at different discrete flame length levels for all structures in the Tubbs Fire.

include structures. However, nearby burning structures would expose their neighbors to substantial flame lengths, currently missed in this analysis. Similarly, the implementation of the model for exposure conditions is unable to account for additional embers generated from burning structures. The last points are salient as structure-to-structure spread is known to be a critical aspect of spread in the WUI.

Fragility curves were produced to investigate the same structural and community characteristics shown in the previous section in an effort to elucidate possible building classes. These characteristics are: year built of the structure, defensible space, and structure-to-structure distance. For these fragility curves, only the probability of destruction (rather than damage) is considered, as damage and destruction have thus far followed very similar trends.

Figure 6.16 shows fragility curves for structures built before 2008 (in blue) and after 2008 (in red), analogous with major code changes in the CA building code. It can

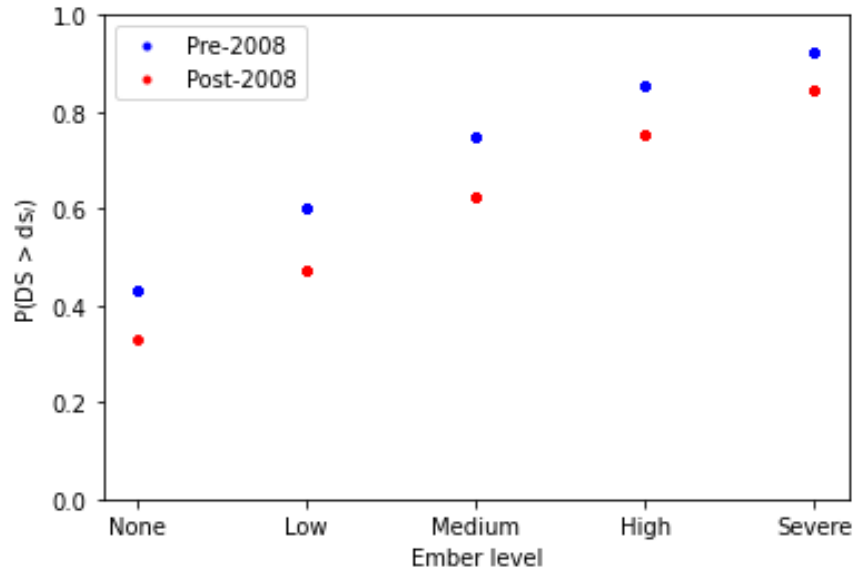


Figure 6.16: Fragility curves showing the probability of destruction for structures built pre-2008 (blue) or post-2008 (red) at different discrete ember levels.

be seen that the probability of destruction is approximately 10% higher at every ember exposure level. These results qualitatively agree with the damage plots.

Figure 6.17 shows defensible spaces in the 0-30 ft range. There was insufficient data and relationship for the larger distances to draw statistically significant conclusions ($p > 0.05$). The data for defensible space is skewed towards destroyed structures due to the exclusion of structures outside the fireline. As a result, the probabilities observed are quite high. Nonetheless, different relationships between probability of destruction and ember exposure level are clear for different defensible space conditions. The 5-30 ft range has a relatively smaller relationship with increasing embers, while the 0-5 ft range, when densely vegetated, increases nearly 40% in probability of destruction.

Figure 6.18 shows fragility curves for structure-to-structure distances, grouped by 10 m increments. The grouping of 0-10 m is included because p -values were not significant for 0-2 m or 5-10 m. Closer structure spacing in general results in a high

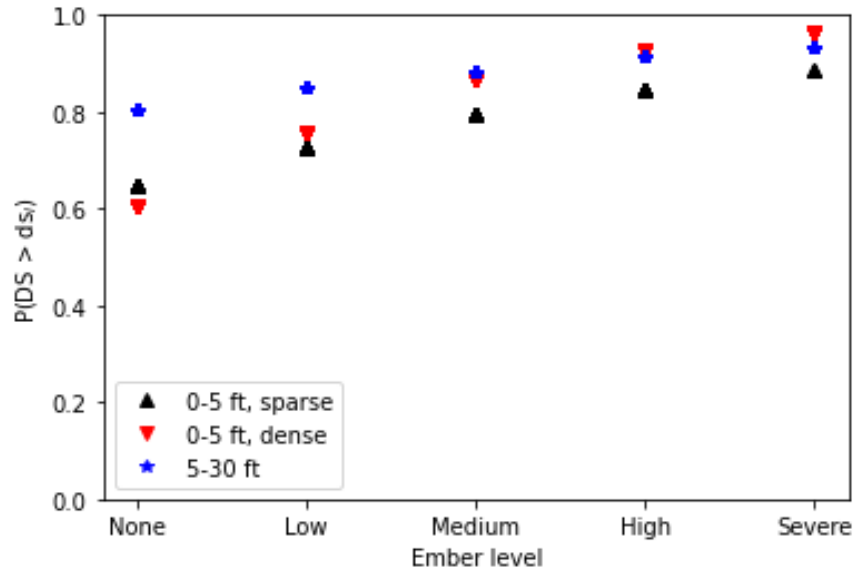


Figure 6.17: Fragility curves showing the probability of destruction for structures based on defensible space at different discrete ember levels.

probability of destruction; however, at high and severe ember loads, the probabilities begin to collapse, with a 20% difference at lower exposure and less than a 10% difference at the highest exposure.

Overall, the fragility curves are able to condense and clarify trends shown in the damage plots, as well as indicate which trends are of statistical significance. Curves for specific characteristics show for which building conditions intensity level plays a more substantial role in probability of destruction.

6.6 Discussion and Limitations

The analysis of exposure conditions, structure characteristics, and damage states shows a clear relationship between exposure and destruction. In particular, as exposure increases, the probability of structure destruction also increases, for both types of

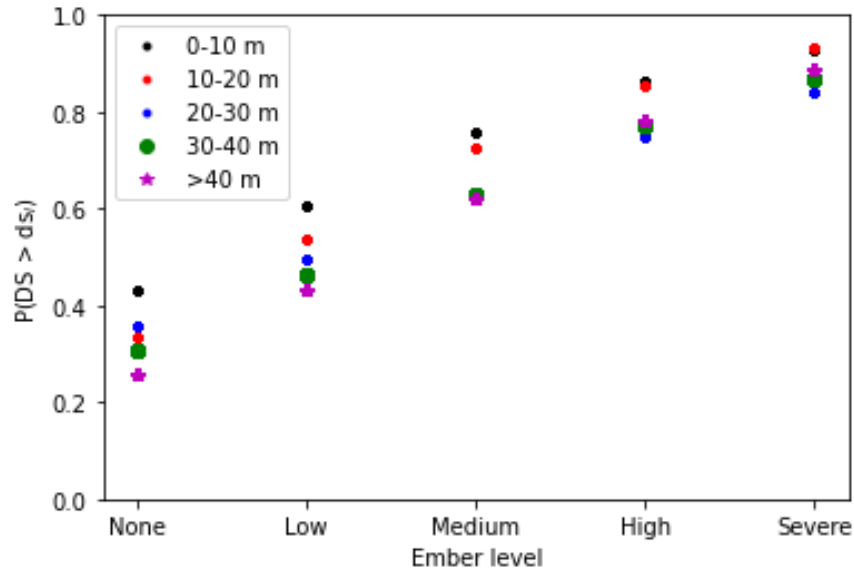


Figure 6.18: Fragility curves showing the probability of destruction for structures based on distance to the nearest structure at different discrete ember levels.

exposure considered. While previous work [86] highlights that ember and fire exposure are both important in determining structure damage, the present work elucidates the relationship between exposure and destruction across a range of intensity conditions. Likewise, post-fire investigation reports cite embers are a major driver of structure ignition. This work confirms those qualitative observations.

Both the damage plots and the fragility curves show key differences in correlation between embers and destruction, and that between flames (representing the main fire front) and destruction. Structures require only low ember exposure to reach Damaged and Destroyed states (i.e. a single ember per cell is often sufficient), while the majority of structures exposed to the main fire front only reach those same damage states when exposed to higher flame lengths (>8 ft). Additionally, fragility curves show that embers have a greater influence on the increasing probability of destruction than flames do. 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.

In a more general way, this work highlights that it is imperative to include exposure conditions when investigating the risk to structure from wildland fire. Previous work [16, 17] has used both local topography and fuel models to represent exposure. However, as shown in Figure 6.19, local topography is not a reliable metric to determine exposure. Here, it can be seen that the local topography around a structure does not correlate with exposure conditions. While flat ground is less likely to receive severe ember loads, the other topographies (with sufficient structures to be significant) experience widely varying ember and flame exposure conditions.

Another metric that has been used previously in lieu of exposure conditions is the local fuel model. In general, the limitations associated with fuel models discussed in the previous chapter are expected to propagate when applied to additional analyses. Moreover, the limitations of urban fuel models make fuel model an unusable substitute for exposure in urban areas. As can be seen in Figure 6.20, which shows the community of Coffey Park, the majority of the fuels are non-burnable (shown in black). The lighter gray and white show infrequent occurrences of other fuel models. Most of the community is modeled as non-burnable, while most of the structure were in fact destroyed. This example highlights the inability of fuel models to represent exposure levels. While some previous works [54, 80] have applied burnable fuel models to urban areas, these assumptions are merely substitutions for the non-burnable fuels and, thus, experience the same inability to represent varying exposure.

Recall from Figure 6.5 that most structures in Coffey Park, shown with the fuel models in Figure 6.20, experienced no exposure from the main fire front. Instead, these

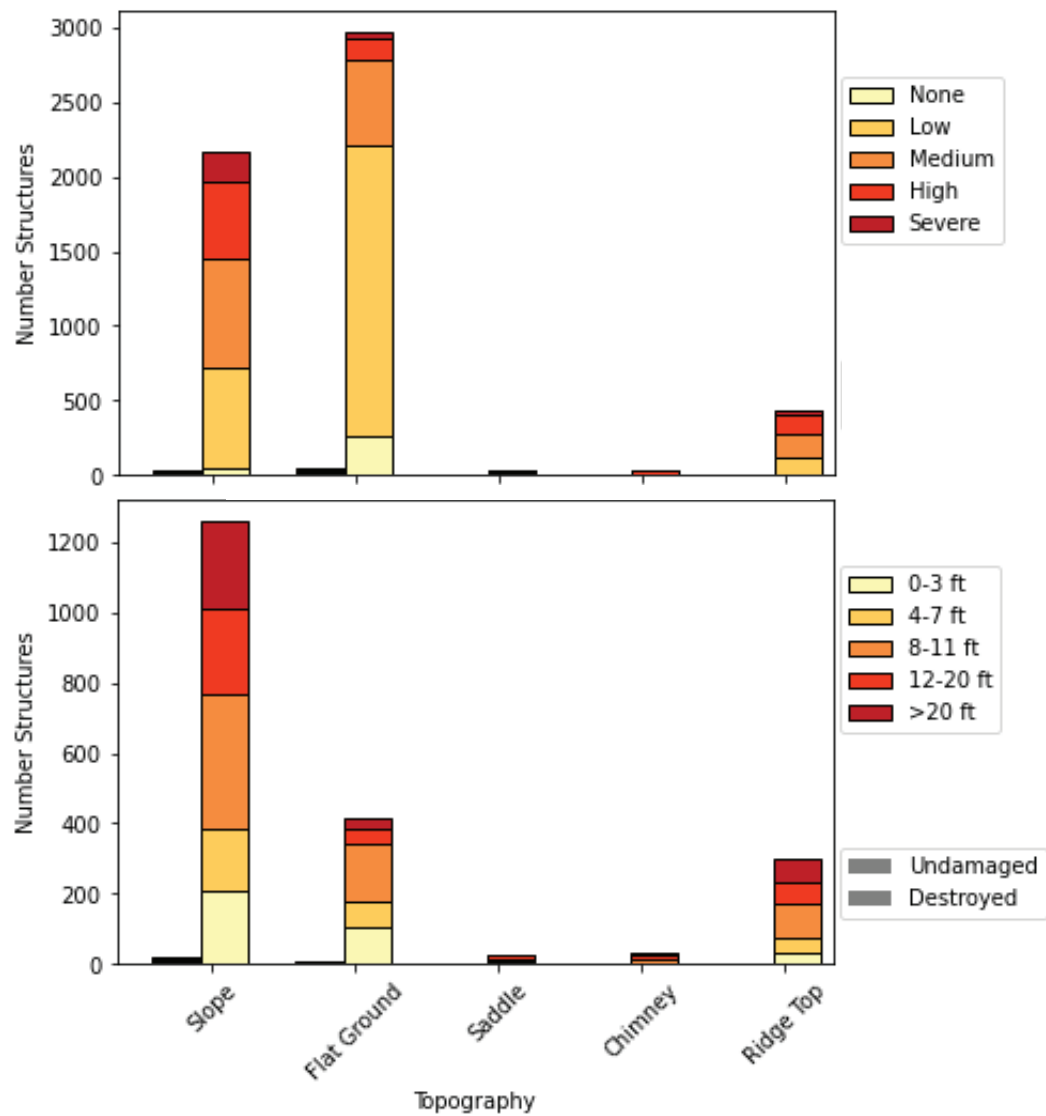


Figure 6.19: Intensity levels of embers (top) and flame length (bottom) simulated for different local topographies.



Figure 6.20: Coffey Park, structures color-coded by damage state (green = undamaged; yellow = partially damaged; red = destroyed) overlaid on the area fuel models, where black represents non-burnable fuels and lighter grays and white represent a variety of burnable fuel models. Most of Coffey Park is shown to be non-burnable, including areas with destroyed structures.

structures experienced mainly ember exposure. This result indicates how important it is to model ember deposition to capture the destruction that occurs in a wildland fire that the main fire front is unable to replicate. As risk assessment continues to be developed at the structure level, it will be critical to include both types of exposure to capture structure ignition behavior and the effects of additional structure characteristics. An important next step in this work will be to nuance this analysis with additional structure characteristics, particularly as more data becomes available on structure conditions before a fire. Ultimately, including additional features and investigating additional fires should help to extend this developed methodology to a more predictive capacity.

Table 6.3: Equations for GLMs for fragility curves presented in the figures in this chapter, where Y is defined in Eq 6.2, X_1 is raw ember numbers per cell, X_2 is raw maximum flame length in the cell, X_3 is discrete defined ember levels, and X_4 is discrete defined flame length levels.

Figure	Description	GLM
6.12	All damaged structures, raw ember values	$Y = 0.1203 + 0.1309X_1$
6.12	All destroyed structures, raw ember values	$Y = 0.0124 + 0.1193X_1$
6.13	All damaged structures, raw flame length values	$Y = 0.5687 + 0.0378X_2$
6.13	All destroyed structures, raw flame length values	$Y = 0.4316 + 0.0348X_2$
6.14	All damaged structures, ember levels	$Y = -0.1774 + 0.6460X_3$
6.14	All destroyed structures, ember levels	$Y = -0.2707 + 0.5982X_3$
6.15	All damaged structures, flame length levels	$Y = 0.5534 + 0.2427X_4$
6.15	All destroyed structures, flame length levels	$Y = 0.4179 + 0.2218X_4$
6.16	Pre-2008 destroyed structures, ember levels	$Y = -0.2772 + 0.6859X_3$
6.16	Post-2008 destroyed structures, ember levels	$Y = -0.7097 + 0.6063X_3$
6.17	Destroyed structures, 0-5 ft sparse defensible space, ember level	$Y = 0.6048 + 0.3674X_3$
6.17	Destroyed structures, 0-5 ft dense defensible space, ember level	$Y = 0.4343 + 0.7171X_3$
6.17	Destroyed structures, 5-30 ft defensible space, ember level	$Y = 1.4050 + 0.3146X_3$
6.18	Destroyed structures, N1 = 0-10 m, ember level	$Y = -0.2711 + 0.7066X_3$
6.18	Destroyed structures, N1 = 10-20 m, ember level	$Y = -0.6828 + 0.8239X_3$
6.18	Destroyed structures, N1 = 20-30 m, ember level	$Y = -0.5807 + 0.5574X_3$
6.18	Destroyed structures, N1 = 30-40 m, ember level	$Y = -0.8233 + 0.6801X_3$
6.18	Destroyed structures, N1 = >40, ember level	$Y = -1.0611 + 0.7791X_3$

Chapter 7: Conclusions and Scope for Future Work

7.1 Conclusions

The thesis has presented work on an analytical study of the structure and stability of inclined laminar flames, an exploration of reconstruction modeling applied to a case study of the Tubbs Fire, and the application of modeling to assess risk and the relationship between exposure conditions and structure destruction in the WUI. The key results of each of these studies is presented here, along with areas of needed or interesting future work.

7.1.1 Structure and Stability of Inclined Laminar Flames

The results of the linear stability analysis indicate that instabilities in the flame may contribute to some of the morphological differences observed between flames forming on the topside and the underside of an inclined fuel surface. The underside flame is seen to be more stable than the topside flame. These results are consistent with differences observed experimentally, which previous work on the base flow structure of the flame has been unable to explain. Instabilities in both configurations are predicted to begin near the leading edge of the plate, which is also qualitatively consistent with experimental observations for flames, but is a distinct difference from the stability of

the flow forming over an inclined heated plate. Despite qualitative comparisons, the paucity of experimental work on instabilities arising in inclined flames does not allow for a quantitative validation of analytical predictions. Additionally, the quantitative results must be taken with caution because of the resulting order-unity values of Gr_C obtained for the topside flame. For a more accurate quantification of the flame stability, a model would need to take into account the spatial development of the instabilities. The present analysis is a first step in understanding the differences between topside and underside flames.

7.1.2 Tubbs Reconstruction Modeling

The objective of this study was to use wildland fire modeling to reconstruct the Tubbs Fire event. Despite the major limitations of wildland fire modeling in general, and WUI fire modeling in particular, the first six hours of the Tubbs fire were reproduced reasonably well using the model ELMFIRE. A methodology for fire reconstruction was presented here and should be replicated and expanded for additional fires. While it is not possible to perfectly reproduce a fire given the extensive uncertainties and lack of available validation data, it is possible to reconstruct a fire sufficiently well to investigate risk associated with fire exposure.

The reconstruction of the Tubbs fire found that the model was sensitive to fuel type (particularly, to the fuel model) as found in the comparison between the LANDFIRE fuels and the CFO fuels. Similarly, the model was found to be sensitive to wind conditions, specifically wind speed and direction. While the weather model used generally over-

predicted average wind speeds, it was unable to capture wind gusts. The inability to capture wind gust is a limitation of the implementation of weather in operational wildland fire models, as rate of spread is nonlinearly related to wind velocity.

Ember spotting was included explicitly both in the model and in the outputs, the first time it had been presented as such. Typically, spotting is included indirectly as an effect on rate of spread calculations or is only able to capture a single ember per cell. While the ember model shown here could not be physically validated, it clearly outlined areas of qualitatively greater and lesser ember density and deposition as a function of varying wind velocity. The ember outputs clearly lined up with destruction. This result is critical, as looking at *only* the fire itself is unable to capture the overall fire event. The inclusion of embers is an important step for wildland fire model reconstruction, as the underestimates shown here are not a unique problem.

Additional limitations of wildland fire modeling were highlighted. The inability to model WUI fuels and ignition resulted in an inability to model fire spread into the WUI. However, the ability to include embers partially balanced out this limitation for the risk application. The fire model was used to produce exposure conditions that could be used for a risk assessment to structures damaged in the fire.

7.1.3 WUI Structure Risk

The methodology of developing fragility curves using past destruction data combined with reconstructive modeling for risk assessment was developed into a framework to apply to wildland fires. This work uniquely considered the impacts of

both fire and ember exposure, a critical component of understanding risk which has been neglected in most previous studies of community-scale wildland fire risk. Results found both damage and destruction to structures to increase with increasing fire exposure (as expected), with a higher dependence on ember exposure than flame length, consistent with wildland fire investigation reports. Importantly, this dependence has been quantified for the scenarios studied within the Tubbs Fire, as well as the influence of different structure features on this dependence, and a framework developed to assess other fires in the future.

Comparison of ember and fire exposure shows that more structures are exposed to embers and that lower levels of ember exposure result in destruction, whereas higher levels of flame length are generally required for structure destruction. The impact of high ember exposure on structures with different characteristics is highlighted for structures with dense 0-5 ft vegetation or far structure-to-structure distance. Present results verify the effectiveness of the 2008 CA building code changes in reducing the probability of destruction. This work highlights that it is critical to include exposure conditions when assessing structure and community level risk. While topography and fuel models have been used as proxies for exposure in previous studies, this work highlights that a single local topography can experience a full spectrum of exposure levels, while the limitations of fuel models, particularly in urban areas, make them an inappropriate description of likelihood of ignition.

7.1.4 Summary of Scientific Contributions

A summary is provided here of the primary scientific contributions made throughout the course of this work. First, an analytical model has been developed which describes the steady structure of a laminar diffusion flame both on the bottom and topside of an inclined fuel surface. A linear stability analysis was applied to this problem which identified the onset locations of both wave and vortex mode instabilities, which modify the downstream flow and may have implications on heating and flame spread.

In the latter half of this work, a fire reconstruction was developed which uniquely identified both fire and ember exposures, with the latter being neglected in most reconstruction models despite its key role in exposure to WUI structures. Using results from the reconstruction analysis, a fragility curve analysis was employed which provided relationships between both fire and ember exposure and structure destruction. These curves were assessed for different home conditions, highlighting the importance of implemented building codes and defensible space in reducing the risk of structure destruction.

7.2 Scope for Future Work

7.2.1 Inclined Laminar Flames

There are three important avenues for future work. First, careful experiments are needed to validate the theoretical results and assess the validity of the underlying assumptions. In particular, the predictions of instability onset, the wave length of the

vortex instability, and the frequency of the wave instability should be compared over a range of topside and underside angles. Experiments must be conducted in a quiescent environment and with a sufficiently small flame to stay in the laminar regime, with a wide enough wick to avoid three-dimensional edge effects.

Second, additional experimental work could consider the relationship between instability development and liftoff of the flame from the top surface of the plate to determine whether an instability can help trigger liftoff. The liftoff phenomenon is observed experimentally for topside flames. Comparisons of instability predictions with experimentally measured liftoff conditions could ultimately indicate how helpful stability analyses can be in estimating when liftoff may occur.

Finally, there is substantial room for future theoretical or computational improvements on the current model. In particular, future work should consider a base flow which is not self-similar, as well as the spatial development of instabilities. Additionally, future work may want to consider the effects of radiation, neglected in the current analysis. The inclusion of radiation will allow for more realistic flame temperature predictions. Given the limitations of the linear stability analysis, a direct numerical simulation may be a more appropriate method to describe the stability of the inclined flame.

7.2.2 Tubbs Reconstruction Modeling

The present study highlighted a number of the limitations of reconstruction modeling. There are several levels of future work, from modeling this single fire to a

more general development of wildland fire and WUI fire spread modeling.

On the scale of an individual fire, future work should consider comparing the results of different models and assessing their sensitivity to input data. One source of uncertainty in wildfire modeling is related to the error inherent in the model used [85]. As discussed in both Section 2.5 and Chapter 5, there are a number of limitations present in operational models, including ELMFIRE. A preliminary attempt at reconstructing the Tubbs Fire using the model FSim, which is similar to FARSITE and assumes the Rothermel model for forward fire spread, produced entirely unrealistic results with the fire spreading in a different direction than it actually did. Future work might also consider expanding model comparisons to physics-based models.

Due to the high dependence on user input parameters, future work should consider implementing a sensitivity study on the various parameters. In the present model, attempting to increase the resolution of fuels resulted in unrealistic fire spread. While this is likely partially due to the bias toward faster spreading fuels in the finer scale dataset, it is likely also influenced by user parameters that have been optimized for 30-m spread. This dependence is particularly true for ember-related models and parameters which have very limited, if any, validation data available.

On a larger scope, the limitations of the present Tubbs Fire reconstruction model are limitations in wildland fire and WUI modeling in general. There is a dearth of data available to validate wildland fire models, and the available data often has coarse temporal or spatial resolution or both. In particular, embers play a major role both in spreading fires and ignition structures; however, there is currently little to no data on the number of embers which are deposited during a wildland fire. How deposition changes for WUI

fires and the influence of wind and vegetation types are all currently unknown.

7.2.3 WUI Structure Risk

There are a number of avenues for future work on the problem of describing risk to structures from a wildland fire. The current work considers two mechanisms of exposure: ember exposure and flame length. Future studies might 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 were considered individually here; however, another study has found that some characteristics are only significant when combined with others [86]. Future work should consider interactions between features.

This framework should be expanded and applied to other fires to determine whether the fragility curves developed for the Tubbs Fire can describe other historical fire events. In particular, the Tubbs Fire had a relatively high ratio of destroyed buildings to total exposed structures. Investigating other fires may find bifurcations in the relative importance of structure and community characteristics depending on the severity of the fire. Ultimately, such analysis should highlight critical choices that home owners, developers, and fire managers can make to reduce risk from both low and high severity fires.

The results here could also be applied to a first order statistical model describing structure-to-structure fire spread. Ultimately, an interesting application of this work would

be towards the development of WUI spread models. The understanding of structure risk based on exposure and characteristics could help in the development of the ignition aspect of a future WUI model, complementing envisioned future work on reconstruction modeling applications.

Appendix A: ELMFIRE Tubbs Fire Model

A.1 Input Deck ELMFIRE Simulation

Input deck for simulation using LANDFIRE fuel data

```
&INPUTS
FUELS_AND_TOPOGRAPHY_DIRECTORY = './fuels_and_topography'
ASP_FILENAME                    = 'asp'
CBD_FILENAME                    = 'cbd'
CBH_FILENAME                    = 'cbh'
CC_FILENAME                     = 'cc'
CH_FILENAME                     = 'ch'
DEM_FILENAME                    = 'dem'
FBFM_FILENAME                   = 'fbfm40'
SLP_FILENAME                    = 'slp'
ADJ_FILENAME                    = 'adj'
PHI_FILENAME                    = 'phi'
IGNITION_MASK_FILENAME         = 'ignition_mask'
WEATHER_DIRECTORY              = './weather'
DT_METEOROLOGY                 = 1800.
WS_FILENAME                    = 'ws'
WD_FILENAME                    = 'wd'
M1_FILENAME                    = 'm1'
M10_FILENAME                   = 'm10'
M100_FILENAME                  = 'm100'
DEAD_MC_IN_PERCENT             = .TRUE.
LIVE_MC_IN_PERCENT             = .TRUE.
USE_CONSTANT_LH                = .TRUE.
LH_MOISTURE_CONTENT            = 30.0
USE_CONSTANT_LW                = .TRUE.
LW_MOISTURE_CONTENT            = 60.0
USE_CONSTANT_FMC               = .TRUE.
FOLIAR_MOISTURE_CONTENT        = 90.0
```

/

```
&OUTPUTS
OUTPUTS_DIRECTORY           = './outputs'
CONVERT_TO_GEOTIFF         = .FALSE.
DTDUMP                      = 9999999.
DUMP_TIMINGS                = .TRUE.
DUMP_BINARY_OUTPUTS        = .TRUE.
DUMP_EMBER_FLUX             = .FALSE.
DUMP_TIME_OF_ARRIVAL       = .FALSE.
DUMP_CROWN_FIRE            = .FALSE.
DUMP_SPREAD_RATE           = .FALSE.
DUMP_FLAME_LENGTH          = .FALSE.
/
```

```
&COMPUTATIONAL_DOMAIN
A_SRS                      = '+proj=lcc +lat_0=35.5
                             +lon_0=237.3 +lat_1=35.5
                             +lat_2=41.5 +x_0=0 +y_0=0
                             +R=6371200 +units=m
                             +no_defs'
COMPUTATIONAL_DOMAIN_CELLSIZE = 30.0
COMPUTATIONAL_DOMAIN_XLLCORNER = -11054.813
COMPUTATIONAL_DOMAIN_YLLCORNER = 320429.408
COMPUTATIONAL_DOMAIN_XDIM      = 21000.000
COMPUTATIONAL_DOMAIN_YDIM      = 27000.000
/
```

```
&TIME_CONTROL
SIMULATION_TSTART    = 1800.0
SIMULATION_TSTOP     = 25200.0
SIMULATION_DT        = 1.0
SIMULATION_DTMAX     = 15.0
TARGET_CFL           = 0.45
/
```

```
&SIMULATOR
CROWN_FIRE_MODEL      = 2
ALLOW_NONBURNABLE_PIXEL_IGNITION = .FALSE.
MAX_RUNTIME           = 99999.
BANDTHICKNESS         = 3
WIND_FLUCTUATIONS     = .TRUE.
DT_WIND_FLUCTUATIONS  = 30.
WIND_DIRECTION_FLUCTUATION_INTENSITY = 0.15
WIND_SPEED_FLUCTUATION_INTENSITY    = 0.1
```

```

DEBUG_LEVEL                      = 1
RANDOMIZE_RANDOM_SEED             = .TRUE.
UNTAG_CELLS_TIMESTEP_INTERVAL    = 10
UNTAG_TYPE_2                     = .TRUE.
UNTAG_TYPE_3                     = .TRUE.
/

&MONTE_CARLO
METEOROLOGY_BAND_START           = 1
METEOROLOGY_BAND_STOP            = 25
NUM_METEOROLOGY_TIMES            = 25
METEOROLOGY_BAND_SKIP_INTERVAL   = 26
ALLOW_MULTIPLE_IGNITIONS_AT_A_PIXEL = .TRUE.
EDGEBUFFER                       = 30.
NUM_ENSEMBLE_MEMBERS             = 1000
RANDOM_IGNITIONS                  = .TRUE.
SEED                             = 2020
USE_IGNITION_MASK                = .TRUE.
WIND_DIRECTION_FLUCTUATION_INTENSITY_MIN = 0.15
WIND_DIRECTION_FLUCTUATION_INTENSITY_MAX = 0.15
WIND_SPEED_FLUCTUATION_INTENSITY_MIN    = 0.0
WIND_SPEED_FLUCTUATION_INTENSITY_MAX    = 0.1
NUM_RASTERS_TO_PERTURB              = 7

RASTER_TO_PERTURB(1)             = 'ADJ'
SPATIAL_PERTURBATION(1)          = 'GLOBAL'
TEMPORAL_PERTURBATION(1)         = 'STATIC'
PDF_TYPE(1)                      = 'UNIFORM'
PDF_LOWER_LIMIT(1)               = -0.5
PDF_UPPER_LIMIT(1)               = 0.5

RASTER_TO_PERTURB(2)             = 'WS'
SPATIAL_PERTURBATION(2)          = 'GLOBAL'
TEMPORAL_PERTURBATION(2)         = 'STATIC'
PDF_TYPE(2)                      = 'UNIFORM'
PDF_LOWER_LIMIT(2)               = -5.0
PDF_UPPER_LIMIT(2)               = 5.0

RASTER_TO_PERTURB(3)             = 'WD'
SPATIAL_PERTURBATION(3)          = 'GLOBAL'
TEMPORAL_PERTURBATION(3)         = 'STATIC'
PDF_TYPE(3)                      = 'UNIFORM'
PDF_LOWER_LIMIT(3)               = -7.5
PDF_UPPER_LIMIT(3)               = 7.5

```

```

RASTER_TO_PERTURB(4)      = 'M1'
SPATIAL_PERTURBATION(4)   = 'GLOBAL'
TEMPORAL_PERTURBATION(4)  = 'STATIC'
PDF_TYPE(4)               = 'UNIFORM'
PDF_LOWER_LIMIT(4)        = -0.01
PDF_UPPER_LIMIT(4)        = 0.01

RASTER_TO_PERTURB(5)      = 'M10'
SPATIAL_PERTURBATION(5)   = 'GLOBAL'
TEMPORAL_PERTURBATION(5)  = 'STATIC'
PDF_TYPE(5)               = 'UNIFORM'
PDF_LOWER_LIMIT(5)        = -0.01
PDF_UPPER_LIMIT(5)        = 0.01

RASTER_TO_PERTURB(6)      = 'M100'
SPATIAL_PERTURBATION(6)   = 'GLOBAL'
TEMPORAL_PERTURBATION(6)  = 'STATIC'
PDF_TYPE(6)               = 'UNIFORM'
PDF_LOWER_LIMIT(6)        = -0.01
PDF_UPPER_LIMIT(6)        = 0.01

RASTER_TO_PERTURB(7)      = 'WAF'
SPATIAL_PERTURBATION(7)   = 'GLOBAL'
TEMPORAL_PERTURBATION(7)  = 'STATIC'
PDF_TYPE(7)               = 'UNIFORM'
PDF_LOWER_LIMIT(7)        = -0.05
PDF_UPPER_LIMIT(7)        = 0.05
/

&SPOTTING
ENABLE_SPOTTING            = .TRUE.
ENABLE_SURFACE_FIRE_SPOTTING = .TRUE.
SURFACE_FIRE_SPOTTING_PERCENT(:) = 0.1
CRITICAL_SPOTTING_FIRELINE_INTENSITY = 1000.0
STOCHASTIC_SPOTTING        = .TRUE.
SPOTTING_TYPE               = 2
SPOTTING_DISTRIBUTION_TYPE  = 'LOGNORMAL'
MEAN_SPOTTING_DIST_MIN      = 5.0
MEAN_SPOTTING_DIST_MAX      = 10.0
NORMALIZED_SPOTTING_DIST_VARIANCE_MIN = 250.0
NORMALIZED_SPOTTING_DIST_VARIANCE_MAX = 600.0
SPOT_WS_EXP_LO              = 0.4
SPOT_WS_EXP_HI              = 0.7
SPOT_FLIN_EXP_LO            = 0.2
SPOT_FLIN_EXP_HI            = 0.4

```

```

MEMBERS_MIN                      = 1
MEMBERS_MAX_LO                   = 2
MEMBERS_MAX_HI                   = 5
GLOBAL_SURFACE_FIRE_SPOTTING_PERCENT_MIN = 0.1
GLOBAL_SURFACE_FIRE_SPOTTING_PERCENT_MAX = 1.0
CROWN_FIRE_SPOTTING_PERCENT_MIN    = 1.0
CROWN_FIRE_SPOTTING_PERCENT_MAX    = 2.0
PIGN_MIN                         = 100.0
PIGN_MAX                         = 100.0
/

&CALIBRATION
CALIBRATE                        = .TRUE.
CALIBRATION_TARGET_FILENAME     = 'calibration'
NUM_CALIBRATION_TIMES           = 1
CALIBRATION_TIMES(1)            = 16600.0
/

&MISCELLANEOUS
MISCELLANEOUS_INPUTS_DIRECTORY = '/home/elmfire/elmfire/
                                inputs/misc'
FUEL_MODEL_FILE                 = 'fuel_models.csv'
PATH_TO_GDAL                    = '/usr/bin'
SCRATCH                         = './scratch'
/

&SUPPRESSION /

```

A.2 ELMFIRE Test Case

Below are shown the results of a test case to qualitatively show the basic models underlying ELMFIRE. Figure [A.1](#) shows the time of arrival in seconds of a surface fire on flat terrain under a constant 6.7 m/s south wind. The time of arrival shows that the fire spread substantially faster in the direction of the wind and slowest in the backing direction.

Figure [A.2](#) shows the fire line intensity for the same test case. Recall that Byram's

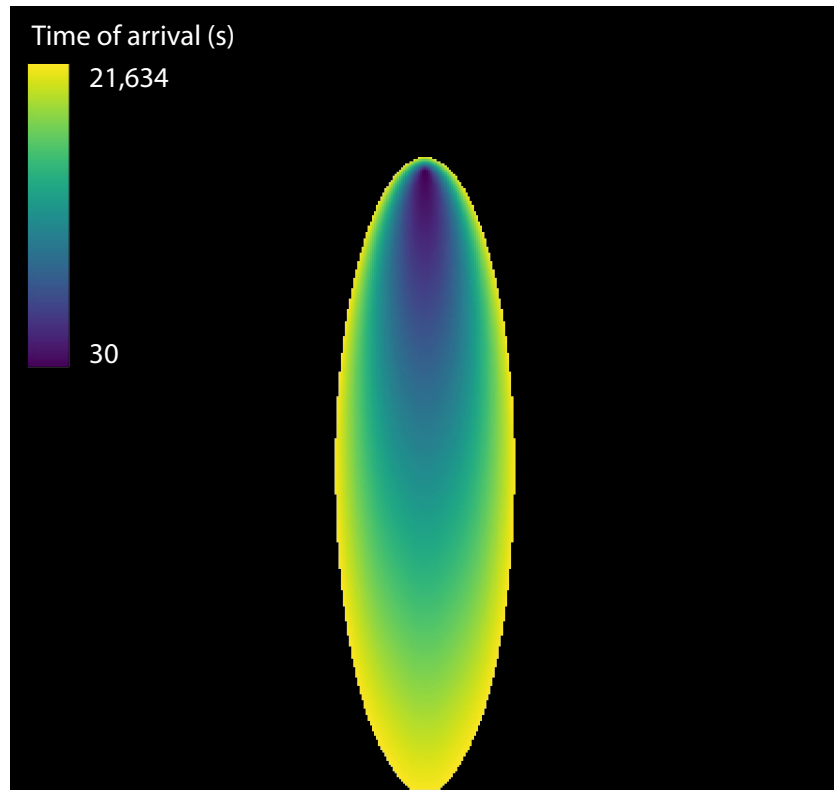


Figure A.1: Time of arrival (s) of a sample fire under constant wind used to verify Rothermel spread model implementation.

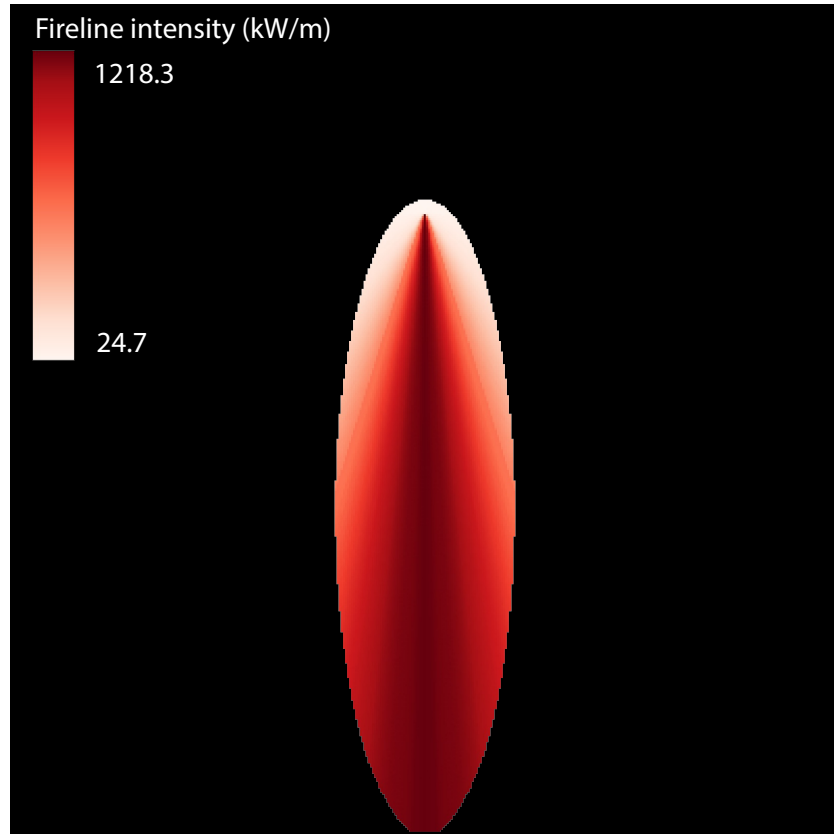


Figure A.2: Fire line intensity of the same sample fire under constant wind used to verify Rothermel spread model implementation

equation gives a linear relationship between ROS and fire line intensity. As a result of decreased ROS on the flanks of the fire and in the backing fire, the fire line intensity is expected to be greatest in the forward spread direction, lower on the flanks, and lowest in the backing fire, as shown in the figure.

Appendix B: Results of Risk Assessment

Additional damage plots and details of the database are shown in the following sections.

B.1 Quality Assessment of Database

The following tables show the number of structures exposed to each level of embers for each damage state, for both the raw ember output (Table [B.1](#)) and the bucketed ember levels (Table [B.2](#)). The former shows that, particularly for large numbers of embers ignited in a cell, there are too few structures in a given category to draw statistically significant conclusions. When embers are bucketed into levels, the Undamaged and Destroyed damage states have sufficient structures; however, the Damaged state still has few structures for structures exposed to no embers or severe embers. This lack is part of the reason that the Damaged state is generally not shown in the damage bar charts.

B.2 Damage Plots for Additional Structure Characteristics

Figures [B.1-B.9](#) show damage plots for a variety of additional structure and local characteristics. A number of these characteristics are from the CALFIRE DINS reports and have insufficient data for undamaged and partially damaged structures.

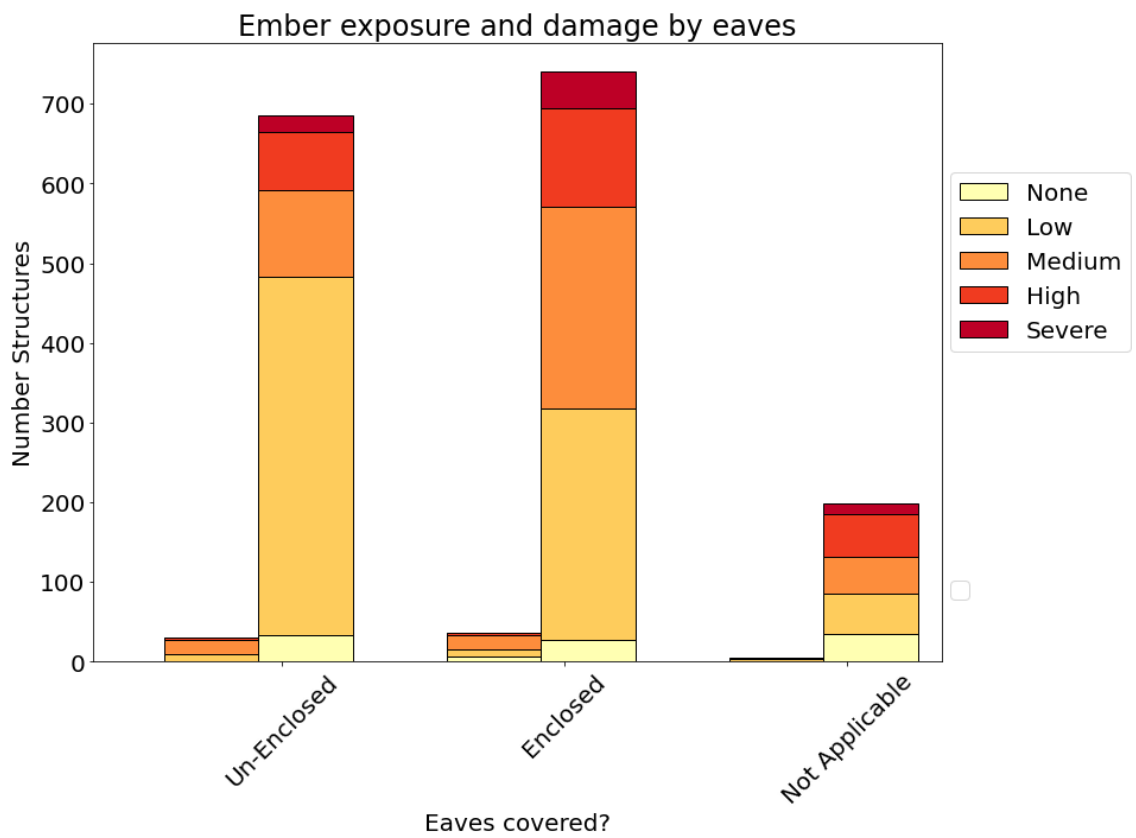


Figure B.1: A comparison of undamaged and destroyed structures exposed to embers as a function of whether eaves are closed.

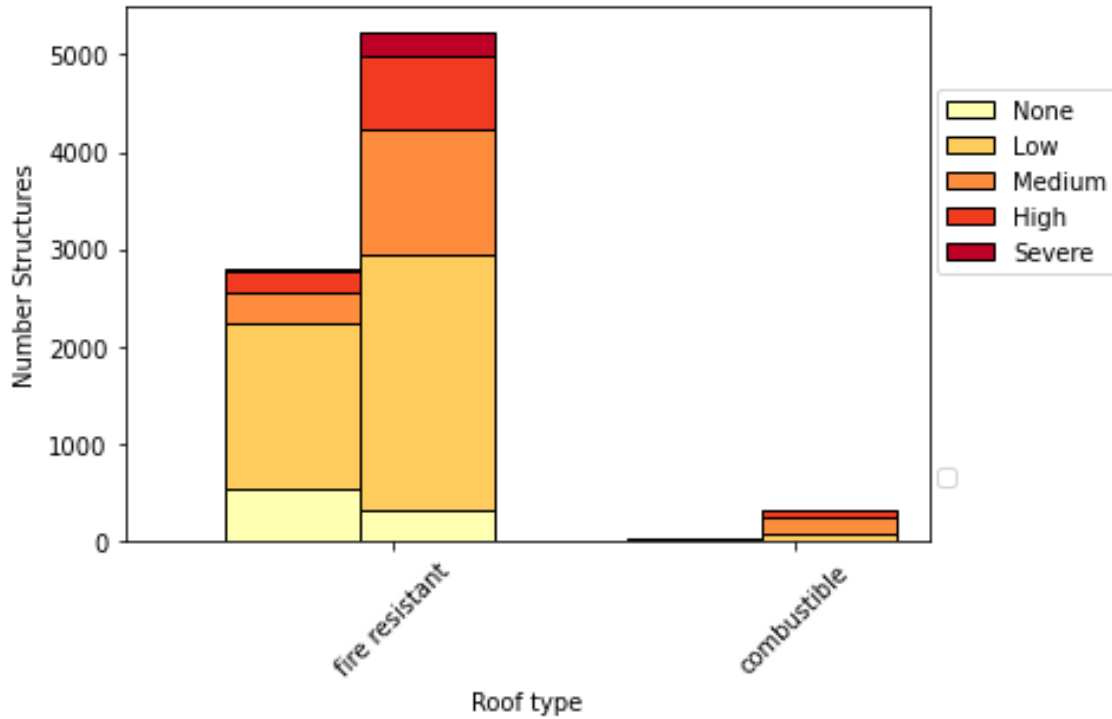


Figure B.2: A comparison of undamaged and destroyed structures exposed to embers for combustible vs fire resistant roof construction.

B.3 Normalized Damage Plots

Figure B.10 shows the same data as Figure 6.10 but normalized by the total number of structures in a given damage state for a given value of defensible space. Trends are clarified here: including the impact of severe ember levels at higher distance of vegetation clearance and for dense vegetation near a structure. Additionally, low ember levels exhibit less clear trends.

Figure B.11 shows the same data as Figure 6.9 but normalized by the total number of structures in a given damage state for a given range of year built. Again, medium to severe ember levels are seen to have an influence on likelihood of destruction, particularly for structures built after 2008. A previous study [63] highlighted that, above certain fire

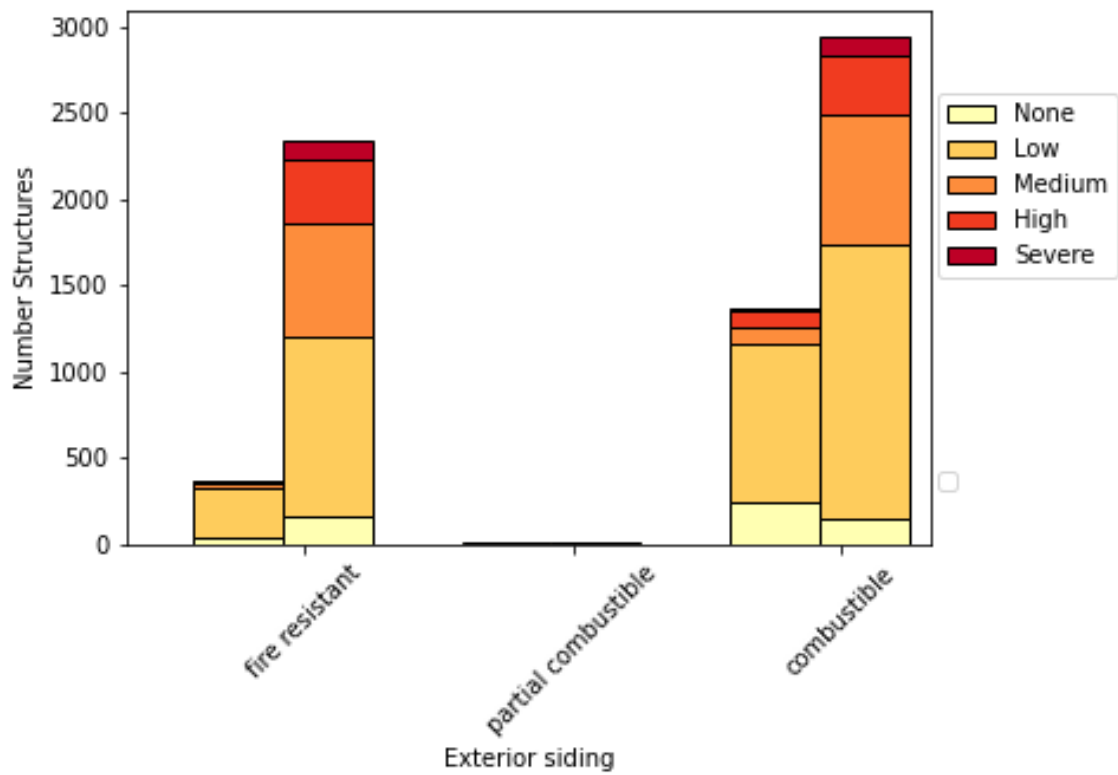


Figure B.3: A comparison of undamaged and destroyed structures exposed to embers for combustible vs fire resistant exterior siding material.

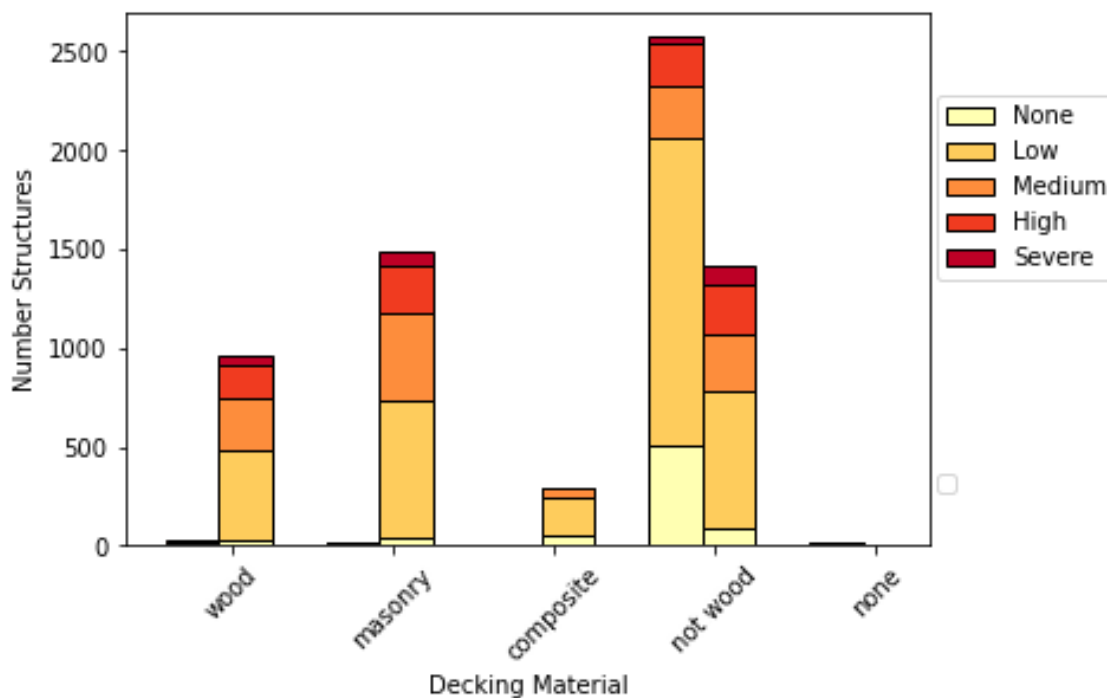


Figure B.4: A comparison of undamaged and destroyed structures exposed to embers based on decking material.

intensities, structure characteristics were less predictive, which we may be seeing here.

Figure B.12 shows the same data as Figure 6.11 but normalized by the total number of structures in a given damage state for a given range of structure-to-structure distance. Particularly for large distances between structures (expected to be rural areas), the impact of high and severe ember levels is clearly linked to destruction.

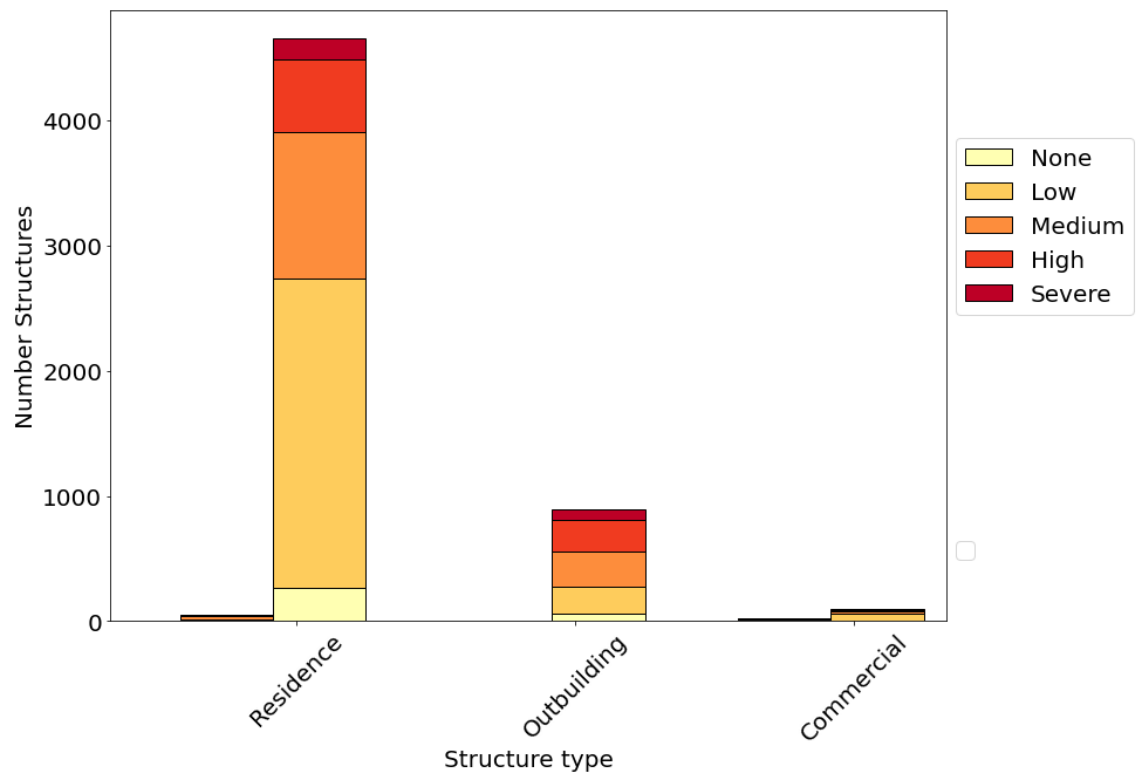


Figure B.5: A comparison of undamaged and destroyed structures exposed to embers for different structure types.

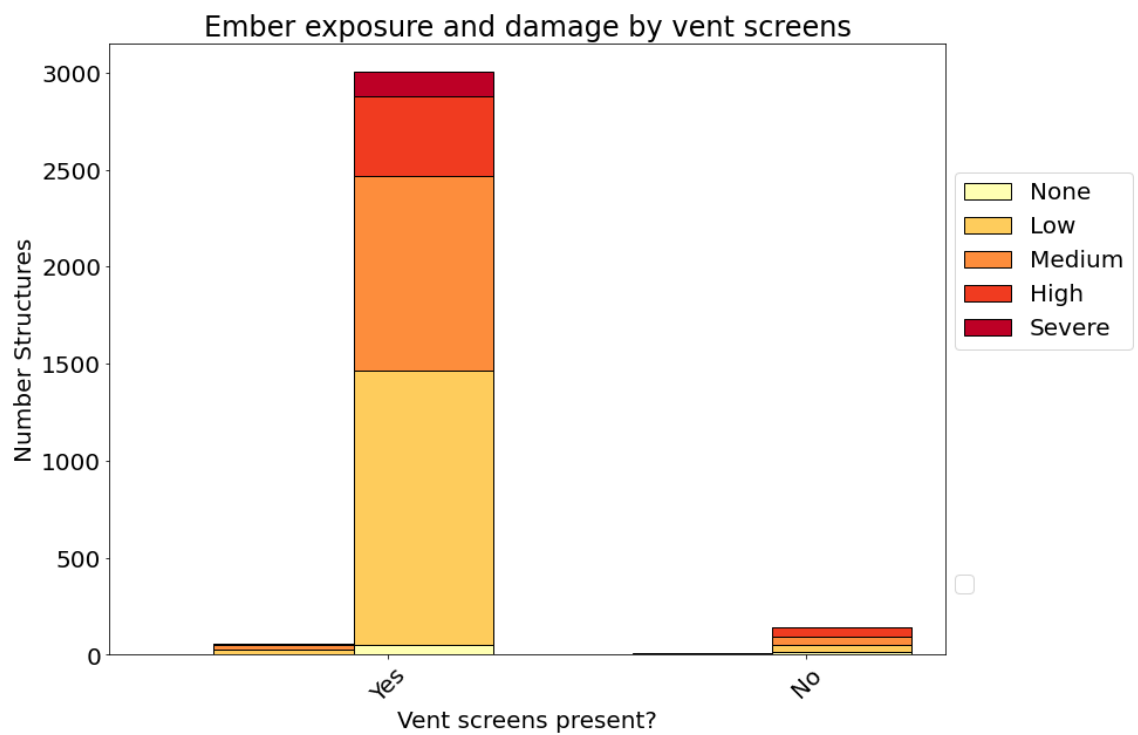


Figure B.6: A comparison of undamaged and destroyed structures exposed to embers for vents with and without screens.

Table B.1: Number of structures per damage state in each ember level.

Embers	Undamaged	Damaged	Destroyed	Total
0	553	26	326	905
1	868	64	1130	2062
2	519	30	634	1183
3	189	31	254	474
4	117	21	316	454
5	70	18	407	495
6	73	13	366	452
7	58	7	363	428
8	71	10	296	377
9	65	10	265	340
10	91	8	193	292
11	64	12	215	291
12	56	9	161	226
13	51	9	188	248
14	46	6	162	214
15	25	5	115	145
16	14	4	83	101
17	8	3	72	83
18	3	1	41	45
19	3	1	24	28
20	0	0	18	18
21	1	2	5	8
22	0	1	7	8
23	0	0	5	5
24	1	0	2	3
25	0	0	0	0
26	0	1	0	1
27	0	0	3	3

Table B.2: Number of structures per damage state in each ember level.

Ember level	Undamaged	Damaged	Destroyed	Total
None	553	26	326	905
Low	1763	164	2741	4668
Medium	358	48	1483	1889
High	242	41	841	1124
Severe	30	13	260	303

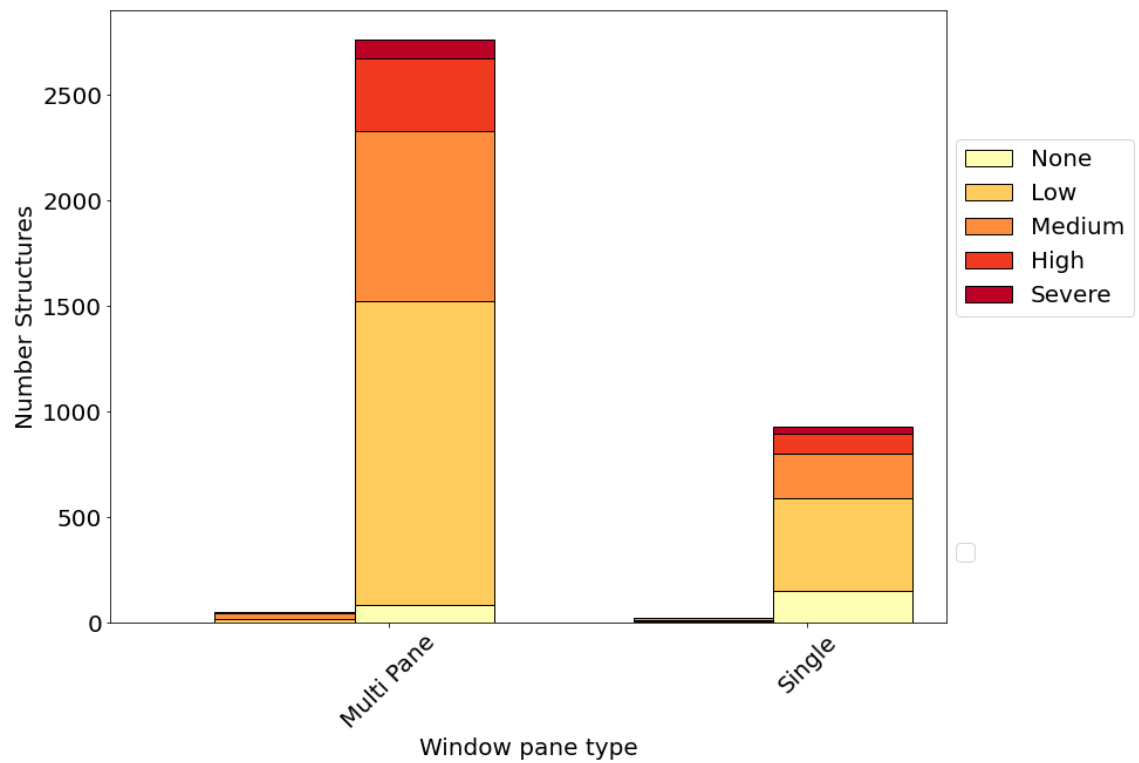


Figure B.7: A comparison of undamaged and destroyed structures exposed to embers for single and multi-paned windows.

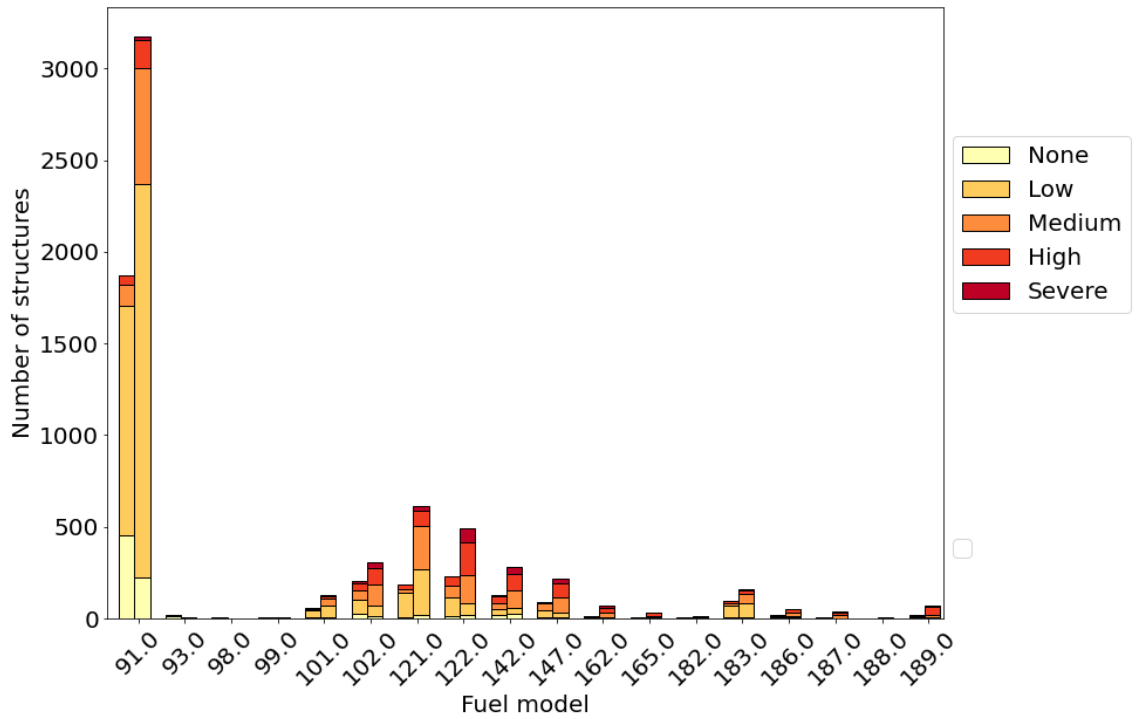


Figure B.8: A comparison of undamaged and destroyed structures exposed to embers based on the local fuel model of the structure.

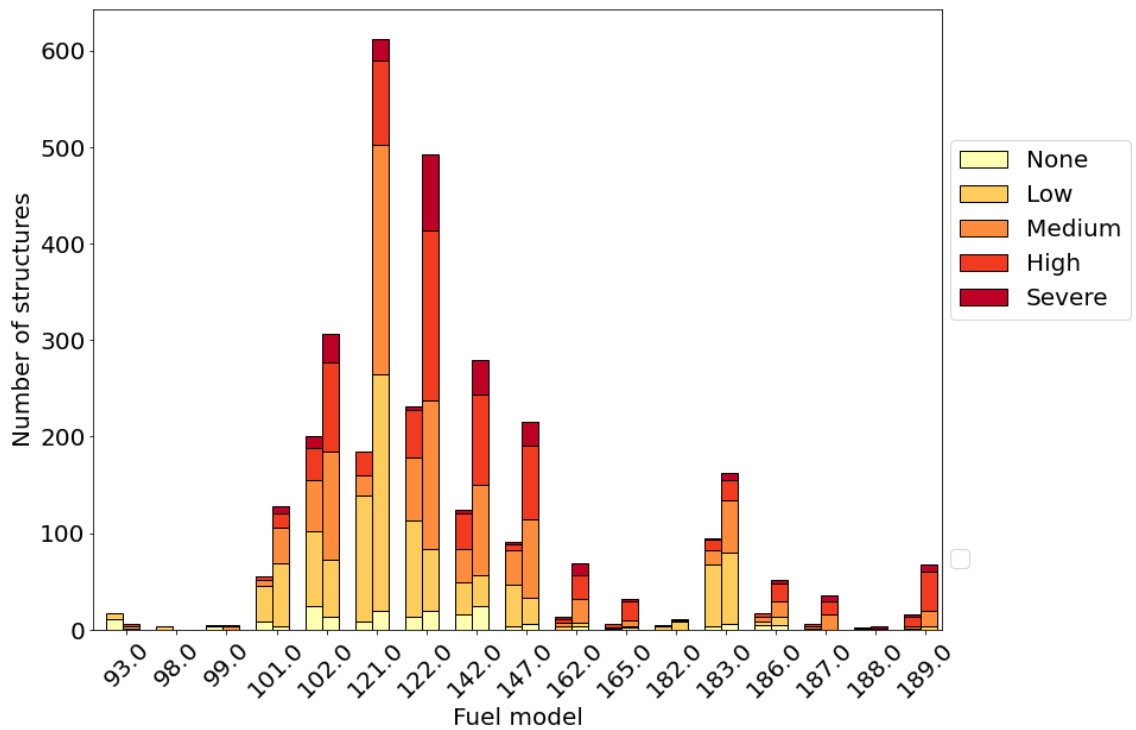


Figure B.9: A comparison of undamaged and destroyed structures exposed to embers based on the local fuel model of the structure, for non-urban fuels.

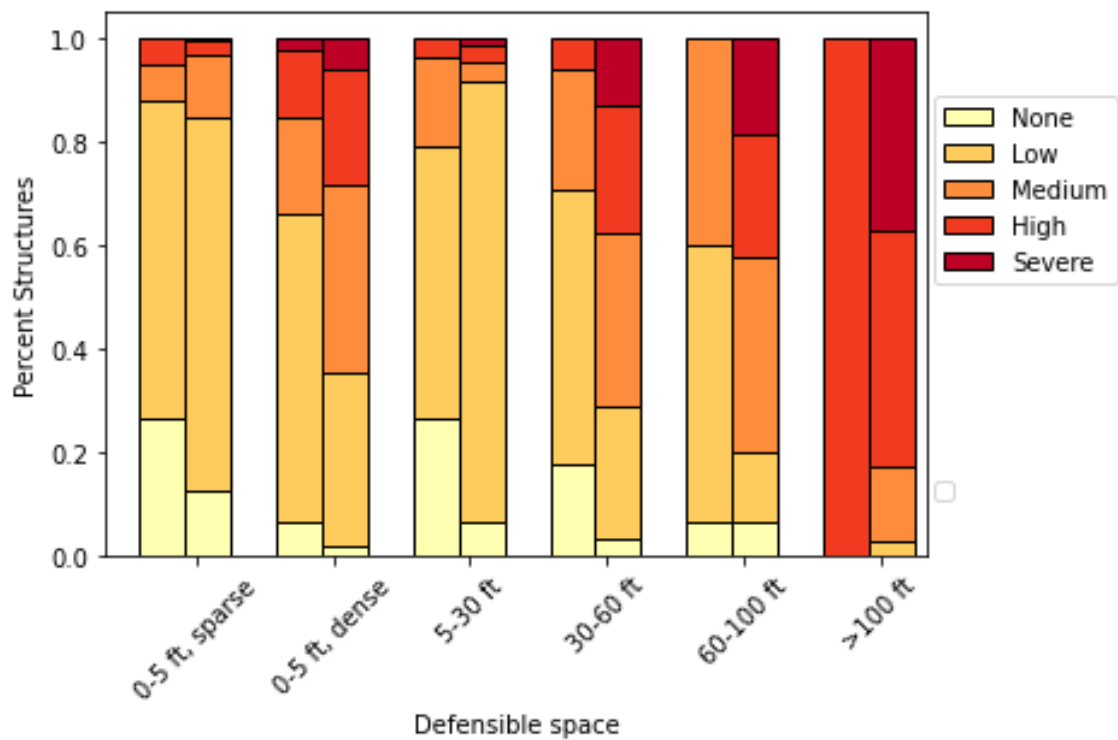


Figure B.10: A comparison of the percent of undamaged and destroyed structures exposed to embers at different vegetation clearances distances.

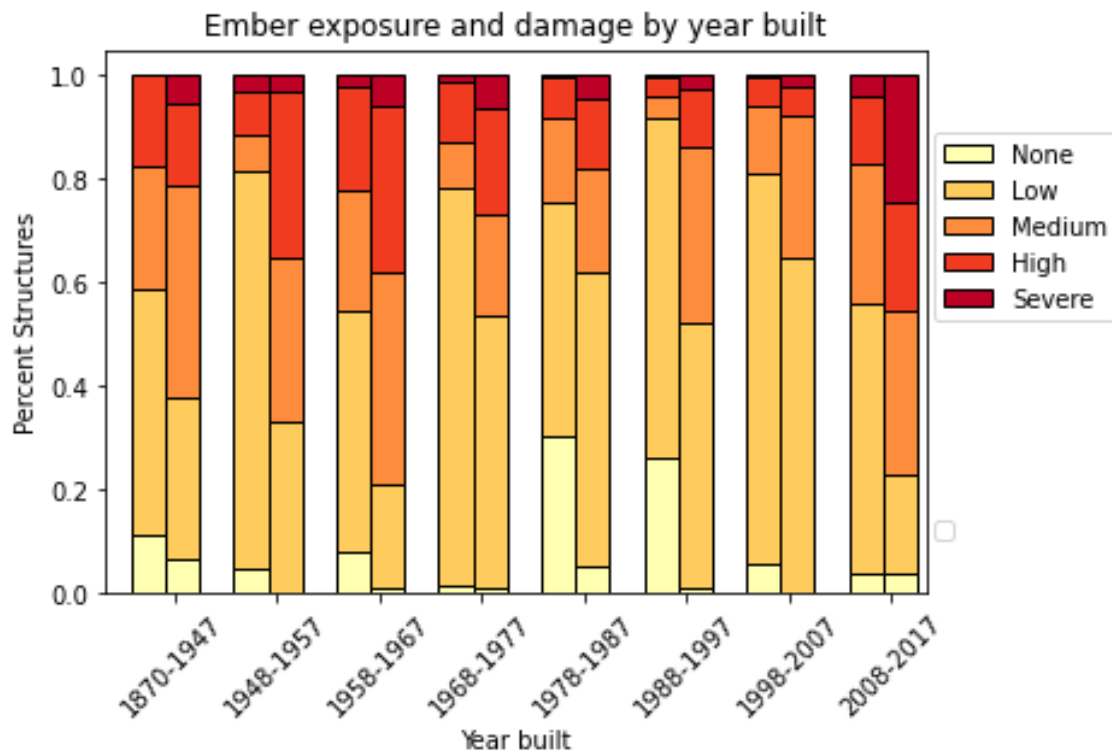


Figure B.11: A comparison of the percent of undamaged and destroyed structures exposed to embers for different ranges of year built of the structure.

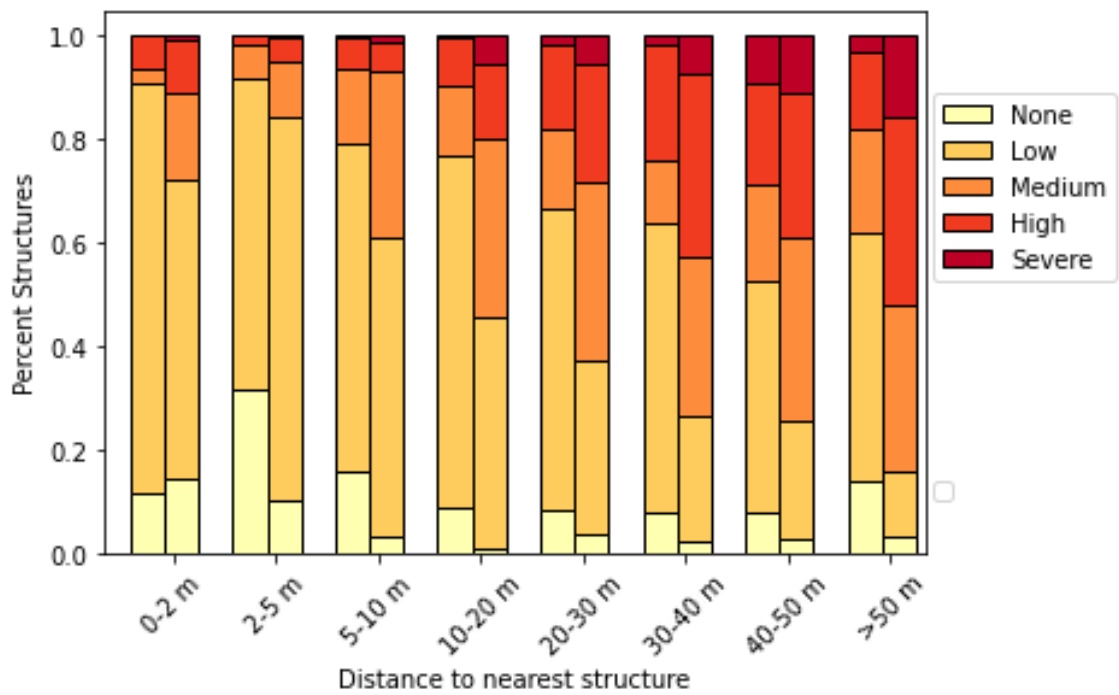


Figure B.12: A comparison of the percent of undamaged and destroyed structures exposed to embers at different structure-to-structure distances.

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