THE RETURN OF CONFLAGRATION IN OUR BUILT ENVIRONMENT

IBHS WILDFIRE RESEARCH REPORT
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Introduction

Many of the most catastrophic wildfires in United States history share a common thread: fire spread from the wildlands into the WUI and suburban environment. Structural conflagration is defined as fire encompassing all of a given structure. Here, we will focus on the concept of a built environment conflagration resulting from wildfires, where fire spreads uncontrollably from structure-to-structure. Most recently, the Lahaina Fire on the island of Maui, Hawaii and the Marshall Fire in Colorado demonstrated the chilling impact of a wildfire-induced conflagration in the built environment. Both fires spread from arid grasslands into a community environment and in both cases over 1,000 structures were lost in just twelve hours.

Across history the five overlapping factors that have always accompanied urban and suburban conflagrations are:

- Drought
- Wind
- Ignition mechanism, often human-based
- Dense construction using materials with little to no resistance to the hazard
- Dense combustible elements surrounding and between structures

History of Urban Conflagration

Urban firestorms have been a part of cities and their evolution across the globe for centuries. They have been applied as weapons of war as well. The 1666 London Fire was one of the first well documented urban conflagrations. It had similar characteristics to what we see in today's wildfire-driven built environment conflagrations: drought conditions, human causation for ignition, and a high structure density with fuels between buildings. From the 1600s through the early 1900s urban fire plagued cities globally.

In North America, vast timber resources drove the widespread use of wood-frame construction. This created urban centers nearly perfect for conflagration and which mirror today's suburban construction practices[1]. Multiple ignition sources (such as hearths, candles, fuel oil, and lamps) were in constant proximity to volatile fuels. Between 1820 and 1835, Boston had three major urban fires. The Great Chicago Fire of 1871 underscored the need for mitigation, with 300 fatalities and over 17,000 structures destroyed. It was during this time that the first building codes and city ordinances began to emerge along with the founding of the National Fire Protection Association (NFPA). New codes and ordinances focused on protecting life safety within structures, mitigating the impact, and spread of interior fires, and reducing the probability of urban conflagration through building-to-building spread. Post-fire analysis of the Great Chicago Fire and the Boston fire of 1872 revealed that combustible construction, water supply problems, and the lack of quick response capabilities played key roles in fire spread.

Up until this point in history, the factors that were able to stop a conflagration were quick suppression if rudimentary response capabilities were able to get ahead of the fire, favorable weather, a natural fire break (such as a river), or random chance. Through the analysis of these conflagrations, it was determined the following intrinsic factors[2] could be addressed:

- Flammability of construction materials
- Structural and architectural design
- Height
- Volume and flammability of building contents
- Average distance between buildings

By the late 19th century, codes and ordinances emerged to address these factors. Efforts were also made to improve fire response through widening urban streets and removing shanties that served as ladder or connective fuels between structures. Through building codes, commercial construction required more noncombustible exterior wall materials such as stone and brick. The emergence of concrete as a primary building material hastened progress. The technological advances of this era also brought steam-driven pumps for fire engines, expansion of professional fire departments, and widespread telegraph capabilities for alarms and response.

Rapid suppression of fires, along with improvements in codes and ordinances became the dominant strategy for reducing the probabilities of urban fire. The 1904 Baltimore Fire also helped usher in standardization of hydrant connections and firefighting equipment for joint response. It was during this time that the property insurance industry emerged along with the precursors to today's commercial testing laboratories like Factory Mutual and Underwriters Laboratories (UL). By the early twentieth century, fire trucks using internal combustion engines had replaced steam pumps and professional fire departments became standard. Unfortunately, vulnerabilities were still present, especially when considering the concept of compounding hazards.

The firestorm that followed the 1906 San Francisco Earthquake revealed how compounding disasters can lead to catastrophe and highlighted the major gaps in understanding urban fire spread. This event hastened the pace of codification of improved materials, applying rapid advances in building material science. By the 1920s there was a sentiment that the urban conflagration problem had been solved through codes, active mitigation measures such as sprinkler systems, and vastly improved fire service response capabilities[1]. However, urban conflagration following a major earthquake remains a sincere concern today given the compounding demand that would be placed on response resources.

History would demonstrate that while mitigation actions reduced elements of the urban conflagration risk, another would rear its head.

A Collision Course: Wildfire and Built Environment Conflagrations

Wildfire has long been a part of our landscape and plays a critical role in the health of ecosystems across the globe. The juxtaposition of the great urban firestorms of the 18th, 19th, and early 20th centuries combined with expansion across the western United States brought people and the built environment into landscapes prone to wildfire. The Great Fire of 1910, also known as *The Big Blowup*, burned across Idaho and Montana and would shape our view of wildfire and the threat of built environment conflagrations for nearly a century. The combination of extreme drought, human-driven ignitions, and dry lightning resulted in over 3 million acres burned and several towns destroyed in Idaho and Montana in just two days. The resulting wildfire policy from the newly created United States Forest Service (the *10 am policy)* centered around rapid suppression of all wildland fires on federal lands with the goal of suppressing any wildfire by 10 am on the day after the fire began.

Perhaps an early view into the future occurred in 1918. The Cloquet Fire in Minnesota, started by sparks from a passing train, ignited areas which had been previously logged heavily. The combination of dry surface fuels from logging debris, significant drought, and high winds behind a passing cold front resulted in a rapidly moving fire which quickly destroyed the towns of Moose Lake, Brookston, and Arnold resulting in 453 fatalities. The accounts of this fire have been compared to those from the 2018 Camp Fire[3].

The Cloquet Fire remains Minnesota's worst natural disaster.

- **Post-disaster investigations show that 90 to 95 percent of all structures that catch fire will be destroyed.**
- **Seventy percent of all structures destroyed in a wildfire are homes.**
- **For fires where 100 or more structures are damaged or destroyed, the top 20% of those events account for nearly 95% of the total wildfire-related losses.**

Through the mid-twentieth century, wildfires generally did not lead to substantial incursions into the built environment as the aggressive *10 am policy* accomplished its goal of keeping wildfires from entering communities. During this period, there was little upward trend in the number of fires or in acres burned. Research into fire spread also centered around fire as a weapon of war, and fire spread following incendiary bombing campaigns and detonations of nuclear weapons. However, through this work the concepts of defensible space and the hardening of residential structures through noncombustible wall cladding and roof covers began to emerge[4].

Beginning in the late 1940's post-World War II era, the bulk population and density across the western United States grew rapidly (Figure 1). Suburban sprawl emerged and communities expanded into what were previously wildlands that rely on wildfire as vital parts of their ecosystems. Building codes and ordinances have long been established to mandate the use of materials and building design elements that reduce fire spread in commercial urban areas. However, the implications for residential single-family construction and its relation to exterior ignitions from wildfires had not been considered. Wood frame construction dominated this construction type, as it still does today. Cladding elements, such as siding and roof cover materials, had little fire resistance. Residential building codes centered around internal fire risks and improving life safety provisions. However, those residential building codes did not explicitly address external ignition sources such as wildfire and its associated ignition mechanisms on the exterior of a structure (ember attack, radiant heat, and direct flame contact).

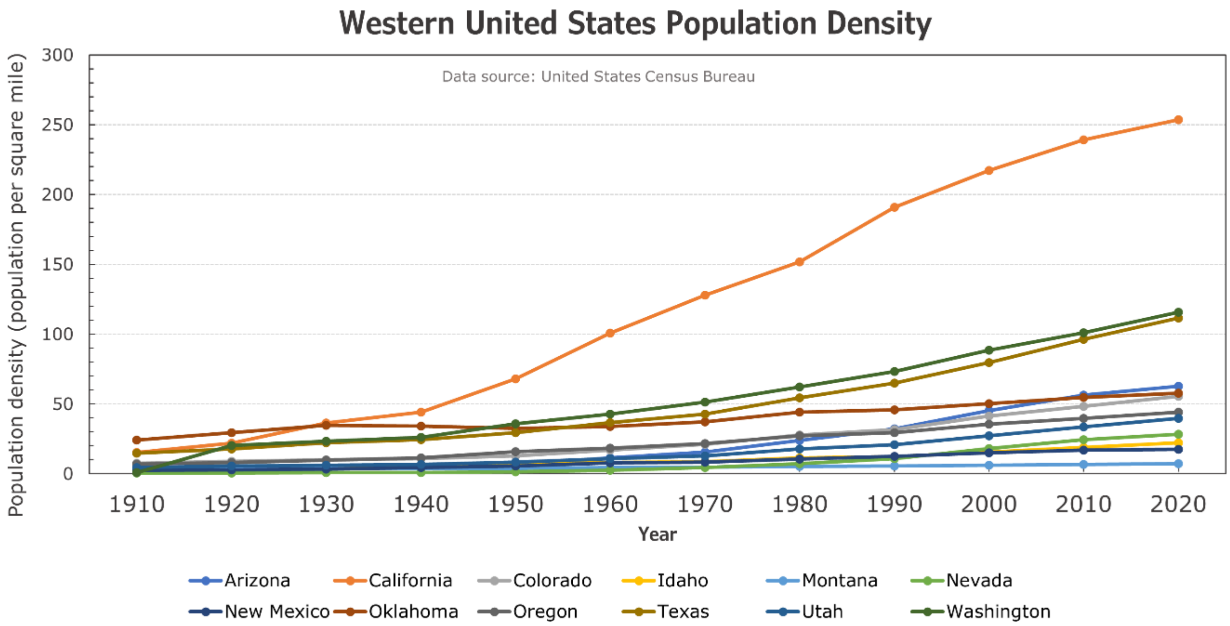

Figure 1: Time history of population density across thirteen western US states. Data source: US Census Bureau

Over the span of 13 days in 1970, an outbreak of fires occurred across Southern California during a strong Santa Anna wind event. These fires burned over 500,000 acres and destroyed 722 homes. From a structural damage perspective, the Laguna Fire was the most damaging, with 384 homes destroyed. Fire moved into the outermost residential areas of El Cajon. At the time, fire resources were stretched thin because of the sizable number of active fires at the time across Southern California. Like the Marshall Fire in 2021, airborne resources were also unavailable early in the lifespan of the Laguna Fire due to the high winds.

In the aftermath of these fires, changes were made in emergency management practices, and the post-fire investigations revealed both positive and negative outcomes related to defensible space and vulnerable roof cover materials. The widespread use of wood-shake shingle roofs in this region at the time proved to be a critical and overlooked vulnerability. Roofs were ignited by embers far away from the fire front, beginning the chain of built environment conflagration.

Unfortunately, the Laguna Fire would foreshadow what was to come in the first two decades of the twenty-first century. In the years that followed that event, the concept of the Wildland-Urban Interface (WUI) took shape, the definition of which focused on the area where wildland vegetation meets human settlement[5]. In 1987, the WUI concept was first included in policy-level discussions and became a focus of US Forest Service research. However, the threat posed by construction in WUI areas was not recognized in the National Fire Plan until 2000. Coincidentally, it was at this time that the potential impact of climate change on wildfire activity was introduced to the public policy realm[5].

Despite an increasing trend in acres burned by wildfire and an increase in human-caused ignitions during the 1970s and 1980s, the average number of structures destroyed in the most extreme fires stayed below 1,000. Wildfire as a catalyst for built environment conflagrations had not materialized, despite the scientific awareness of the risk through an improved understanding of WUI fires. Residential development continued its reach into the wildlands by putting large numbers of structures with little to no fire-resistant exterior materials close together. Building codes and the testing standards that underlie them were lagging the growing risk. The elements of urban conflagration of past centuries were now aligned in suburbia.

The wildfire hazard combined with the vulnerability of the suburban environment to fire manifested itself on October 20, 1991, in the hills above Oakland, California. The Tunnel Fire (also known as the Oakland Hills Fire) was perhaps the first modern era example of wildfire acting as the mechanism to start a catastrophic built environment conflagration. Five years of persistent drought created volatile vegetative fuels. A significant diablo downsloping wind event developed accompanied by extreme heat. The fire started initially on October 19th near the Caldecott Tunnel. The fire was near a moderately dense built environment connected by dense vegetative fuels, spread across complex terrain. Despite nearby fire resources, high winds and ember transport led to rapid spot-fire ignitions, including on wood-shake roofs of nearby homes. The event quickly grew out of control[6].

The speed at which suburban conflagration can unfold was observed as fire entered the Hiller Highlands Development. **All homes in this neighborhood were ignited within 16 minutes** and all were destroyed[7]. Despite the fire's relatively small size (1,600 acres burned), it destroyed 3,354 single family homes and 456 apartment units and became the first billion-dollar wildfire disaster in the United States[8].

Over the next three decades, wildfires entering the urban interface and wildfire acting as a catalyst for built environment conflagration would repeatedly play out (see Table 1). In 1991, the very first WUI specific building code was adopted in Australia to combat a similar problem of vulnerable suburban construction. As previously mentioned, the Tunnel Fire spurred updates to building codes specifically on the use of noncombustible roofing materials but a true WUI code would not emerge in the United States until the first edition of the International Code Council's IWUI code in 2001. Although modern WUI codes have been proven to reduce the potential for a structure to ignite in traditional WUI areas, there remain some questions about their ability to substantially reduce the probability of a conflagration when fire enters a community (see "Code Gaps" on page 8).

Table 1. List of fires (not exhaustive) in which notable WUI fire and suburban built environment conflagrations occurred 1990–2022.

Year	Fire Incident	Location	Cause - Source	Residential structures destroyed (approx.)
1990	Painted Cave	Santa Barbara, CA	Human - equipment use	479
1991	Tunnel Fire / Oakland Hills	Oakland, CA	Human – debris fire	3,354
1993	Laguna Hills / Old Topanga Fires	Laguna and Malibu, CA	Human - unknown	634
1998	Florida Fires	Flagler and Volusia Counties, FL	Natural - lightning	300
2000	Cerro Grande Fire	Los Alamos, NM	Human - escaped controlled burn	235
2002	Hayman Fire	Colorado Springs, CO	Human - campfire	600
2002	Rodeo-Chediski Fire	Coconino and Navajo Counties, AZ	Human - campfire	426
2003	Cedar Fire, Old Fire	Southern California	Human - campfire	3,640
2003	Aspen Fire	Summerhaven, AZ	Human - cigarette	340
2007	Angora Fire	Lake Tahoe, CA	Human - campfire	245
2007	Witch Creek Fire	San Diego County, CA	Human - powerlines	1,265
2007	Harris Fire	San Diego County, CA	*Unknown*	257
2011	Bastrop County Complex	Bastrop, TX	Human - powerlines	476
2012	Waldo Canyon Fire	Colorado Springs, CO	Human - unknown	346
2013	Black Forest Fire	Black Forest, CO	Human - unknown	511
2014	Carlton Complex	Okanogan County, WA	Natural - lightning	300
2016	Chimney Tops 2 Fire	Gatlinburg, TN	Human - juveniles	2,460
2017	Tubbs Fire	Napa and Sonoma Counties, CA	Human - electrical	4,661
2017	Nuns Fire	Sonoma County, CA	Human - powerlines	642
2017	Redwood Fire	Mendocino County, CA	Human - powerlines	313
2017	Thomas Fire	Ventura and Santa Barbara, CA	Human - powerlines	792
2018	Camp Fire	Paradise, CA	Human - powerlines	13,696

Year	Fire Incident	Location	Cause - Source	Residential structures destroyed (approx.)
2018	Carr Fire	Shasta and Trinity Counties, CA	Human - vehicle	1,084
2018	Woolsey Fire	Los Angeles/Ventura Counties, CA	Human - powerlines	1,187
2020	Glass Fire	Napa and Sonoma Counties, CA	*Unknown*	642
2020	Almeda Drive Fire	Jackson County, OR	Human - arson	2,500
2020	Santiam Fire	Clackamas, Marion, Linn and Jefferson Counties, OR	Human - powerlines	1,500+
2020	Cameron Peak Fire	Larimer and Jackson Counties, CO	Human - unknown	469
2020	East Troublesome Fire	Grand County, CO	Human - unknown	580
2021	Marshall Fire	Louisville and Superior, CO	Human - unknown	1,036
2022	Calf Canyon / Hermits Peak Fire	San Miguel, Mora and Taos Counties, NM	Human - escaped controlled burn	1,000+
2023	Lahaina Fire	Lahaina, Maui, HI	*Under Investigation*	2,200+

Code Gaps

A well-defined ignition-resistant construction method can offer adequate protection against exposure to embers and flames. Some WUI codes focus on structures purely located in traditional WUI areas. Their design criteria are based on access to water supply, defensible space conditions, vegetation, topography, and critical fire weather frequency. These are the main parameters that influence the broad level of wildfire risk but do not account for factors such as structure density that may play a greater role in the fire exposure for a given structure and the broader probability of conflagration scenarios. Construction material requirements (ignition-resistant and noncombustible) are defined and based on the anticipated fire hazard severity of the area the building is being constructed in.

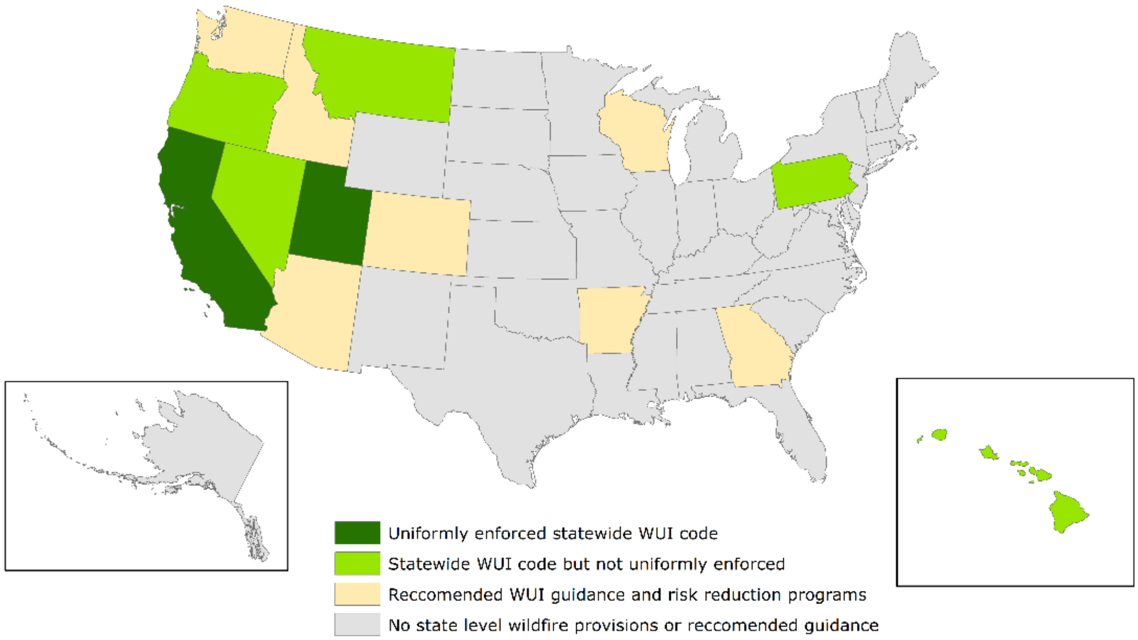

Figure 2. WUI code adoption in the US

Unfortunately, there are some obstacles and gaps with some of the provisions of the current codes that could reduce the applicability and their performance. The first is the reliance on active mitigation systems such as interior or exterior sprinkler systems. Interior sprinkler system requirements fall under the IRC and IBC, whereas the usefulness of exterior sprinkler systems is still in question. The probability of having a consistent water and electrical power supply at the time of an event is questionable. There are also concerns about the effectiveness of the systems as water droplets can be easily dispersed in high winds, effectively reducing their ability to cover the area's most susceptible to ember attack.

Considering the dynamic nature of these events and the potential scope, it does not seem wise to lean on active fire protection systems the way that the current codes, specifically the IBC do today. Also, there is an inconsistency in the level of fire protection provided by different solutions even within one risk level. The different prescriptive solutions provided for each building element do not provide the same level of resistance. One of the biggest gaps that exists in current WUI codes relates to fire impingement and spread on, or within, a building component or assembly, such as a wall or roof system. Fire performance of a wall assembly addresses fire impinging on the surface of the wall, stability of the assembly and its insulation. This is dealt with in the current IBC/IRC but typically not in WUI codes. While flame spread addresses the fire spread behavior on the surface of the exposed assembly. The model residential and commercial codes (IRC and IBC) provide requirements addressing these two parameters (flame impingement and flame spread) based on fire separation distance in dense settings to overcome interior fire hazards and conflagration.

The WUI codes do not consider such requirements, leaving a major gap if a built environment conflagration scenario begins to unfold. There is also a need for new test standards to address both external ignition potential of wall materials and fire spread through wall systems, as well as other materials and assemblies used in residential and commercial construction.

Built Environment Conflagration: The Common Threads

There are striking similarities between urban conflagrations of the past and the modern era of wildfire-driven suburban conflagration. There are four elements that all conflagrations share:

- They are typically preceded by or occur during drought conditions.
- They include densely packed structures with combustible exterior and framing materials.
- Weather conditions with winds of at least 20–30 mph.
- Fuels that connect the dense structures together, providing a pathway of fire.

Connective fuels increase the probability that fire spreads from structure-to-structure and the rate at which it happens. In the 18th and 19th centuries these connective fuels were often temporary dwellings, shelters, or shanties that sprung up between larger buildings within small alleyways. In the modern era, connective fuels are represented by typical elements of suburban landscaping, ornamental vegetation, wooden privacy fences, sheds, playhouses, etc. These are sometimes also referred to as part of the ladder fuel category. Lastly, built environment conflagrations take place when these factors meet humans with ignition sources. Today, over 90% of wildfires are started by humans, and as the built environment and its infrastructure grows outward into the wildlands the probability of ignitions near or within our neighborhoods also increases[9].

One of the critical differences between the built environment conflagrations of the 18th, 19th and early 20th centuries and wildfire-driven conflagrations is the source. For urban conflagrations, events typically began as a point source fire. A single or a small number of structures were ignited, and fire then spread from structure-to-structure. By improving building design for fire, the interior spread rates were slowed, not only allowing for evacuations from the burning structure, but also containing the fire and allowing time for fire response. Improved construction practices, many of which were codified, coupled with improved fire response capabilities helped contain fires in urban centers. While fires certainly still occur in urban areas, conflagrations have nearly been eliminated in this environment. It is one of the earliest success stories of how building codes can leverage technological advances and be effectively employed as a mitigation tool.

Wildfire, spreading under high wind conditions through volatile fuels, presents a different challenge relative to urban fires. The wildfire environment can stretch emergency response capabilities in a situation that is already challenging in its dynamic nature and scale. The combination of an active wildfire and a built environment conflagration can be too dangerous for direct fire suppression tactics, especially in such situations where weather conditions are so extreme that aerial fire suppression resources cannot be used in coordination with ground resources. Fire can spread uncontrolled both through the suburban and wildland environments. To slow fire spread neighborhoods must function as fuel breaks rather than fuel sources. Primarily, they must resist ember attacks as wildfire approaches. Then the structures and the space between must also serve to break the chain of fire spread through flame contact and radiant heat. Unfortunately, the lessons of past conflagrations in urban settings have not been applied to our residential neighborhoods in materials and design. In addition, the population moving into WUI areas has grown 41% between 1990 and 2010[10]. **Today nearly one-third of all Americans live in areas that could be considered part of the Wildland Urban Interface**[11].

Marshall Fire Case Study

A recent example of a wildland fire acting as the initiating mechanism for a suburban conflagration occurred on December 30, 2021, in Boulder County, Colorado: the Marshall Fire. Its cause remains under investigation at the time of this report but the spread of fire through the extremely dry grasslands between Superior and Louisville was the initiating mechanism for a suburban conflagration. Extreme drought conditions were in place across much of Colorado, with the six-month period before the fire being one of the warmest and driest on record in Denver. However, preceding the drought was a three-month wet period that supported rapid and high growth of prairie grasses. A very severe down sloping high wind event that created significant turbulence across the foothills of the Rockies prevented the use of aerial fire suppression resources to control the fire. Wind gusts over 90 mph were common across the foothills.

The Marshall Fire started near the Marshall Mesa Trailhead between Boulder and Superior, approximately 2.5 miles from where the first structures were ignited. The area where the fire began allowed it to spread and impact two communities at nearly the same time (Superior and Louisville). The proximity where the fire began to vulnerable high-density construction aided in starting the chain of events that led to a built environment conflagration. Within an hour, the first structure ignitions were ongoing in both towns. By the time the event ended, 1,036 residential structures, 9 apartment buildings, and 11 commercial structures were destroyed.

The event contained different examples of how the factors that influence built environment conflagration can align in different combinations but yield the same catastrophic outcome. Consider the suburban neighborhoods of Louisville, Colorado near McCaslin Boulevard shown in Figure 3.

Figure 3. Damage from the Marshall Fire near McCaslin Boulevard in Louisville, Colorado.

This area experienced a built environment conflagration with more than 200 single family homes destroyed. The mean home-to-home spacing distance was approximately 30 feet. Most homes likely featured a Class A asphalt shingle roof (sporadic wood shake and concrete tile roofs were also present but not dominant). However, nearly all had some degree of combustible wall cover. The connective link between structures, at a relatively large suburban spacing (30 ft), was vegetative coverage. The total vegetative areal coverage (canopy and identified ornamental vegetation) between homes averaged approximately 60%. This vegetation coverage was combined with wood privacy fences that physically connected nearly 70% of the homes in this neighborhood.

To the south of this area, the Sagamore neighborhood along the western side of Superior, was also destroyed. These homes were tightly clustered, with an average separation of less than 9 feet. Experimental testing at IBHS has shown that at this spacing, without fire service intervention, ignition is nearly guaranteed if a neighboring structure ignites. All homes had asphalt shingle roofs, but other exterior combustible elements were identified from pre-fire street level imagery. The vegetation coverage on each parcel was approximately 55% but over 90% were physically connected to their neighbors by wooden privacy fences.

West of the Sagamore neighborhood, there was a smaller section of houses that were bisected by Spring Drive. This area was characterized by larger homes with larger parcel sizes. Variable home-to-home spacing was observed, ranging from 25 feet at the closest distance, to nearly 80 feet at the maximum distance. Homes typically had asphalt shingle or concrete tile noncombustible roofs. Wall covers were typically stucco or stone veneer. Most homes had elements that could be considered as "home hardening" measures. The mean parcel level vegetation coverage was below 50%. Yet, despite these factors only 13 of the 57 homes survived.

One major vulnerability at the parcel level was present. Dense vegetation within the 0- to 5-foot home ignition zone was observed on nearly all homes. In addition, the native grassland was interconnected within the neighborhood with no fuel breaks. This likely brought significant radiant heat and direct flame into the 0- to 5-foot home ignition zone of the first structure that ignited. At that point, extreme flame and radiant heat exposure overwhelmed the hardening elements that were present and/or exploited other vulnerabilities, such as vents, combustible soffit material etc. After the initial structure ignited, embers likely cascaded downwind, igniting subsequent homes. Of note was a significant percentage of the vegetation in the area 10 to 50 ft from destroyed homes was still present, indicating a lack of surface fire progression and the presence of ember-driven ignitions. Once the first home ignited in this area, embers produced by structural fuels became the dominant mechanism for fire spread.

The Marshall Fire is a reminder of the multiple ways in which a suburban conflagration can unfold. It clearly illuminates how community scale protections must work as a system to defend against wildfire as a single weak link can begin the cascade to catastrophe.

The Chain of Suburban Conflagration

The variables that lead to a suburban conflagration can be conceptually viewed as a matrix of interconnected and aligned factors; many of which are inherent to the environment both surrounding and within a community. In simplistic form, wildfire-driven built environment conflagration potential is tied to the characteristics of the natural environment, such as the topography, regional climate, local weather conditions, and natural vegetative fuels. It also is coupled with the proximity to the built environment and its characteristics. Built environment wildfire-driven conflagration follows the conceptual WUI fire chain of events described in detail by Cohen (2008)[12] and illustrated in Figure 4.

Figure 4: Wildland Urban Interface disaster conceptual chain of events. Adapted from Cohen (2008).

Within this sequence of events, there are three main categories of variables with many sub-categories that ultimately dictate the probability distribution in which a conflagration scenario is unlikely, possible, or highly likely if a wildfire invades a given community. They are listed in Table 2 while Table 3 provides the sub-sets of variables which could be mitigated for or controlled at a community level.

The natural environment consists of topography, climate, local weather, and fuel. All of which make up the wildfire behavior triangle. In the context of built environment conflagration, the structures are intertwined with the natural environmental variables, especially fuels and topography. The critical linkages in the progression from an intense wildfire and a built environment conflagration disaster lie here.

Table 2. Contributing Factors

Natural Environment	The Built Environment	Humans
Topography	Structure density	Preparedness and mitigation
Climatology	Building materials	Ignition sources
Local Weather	Connective fuels	Fire service intervention
Wildland Fuels	Infrastructure	

Table 3. Controllable Factors within a Community

Parcel level mitigation actions
Distribution and density of ladder and connective fuels
Building codes, ordinances, HOA covenants
Vegetative fuel types
Fuel or Fire breaks
Existing or in-place preparedness programs

The Natural Environment

Long term climate cycles, localized weather conditions and geography are factors that can increase the risk of wildfires.

Climate

The global circulation that gives rise to Earth's climate is the reason some parts of the world are more prone to fire than others. It is what governs plant species, their density, how they reproduce, and how they have adapted to fire. It is also important to note that fire is a critical part of many ecosystems. Global climates that are prone to wildfire can be identified using both the standard climate classification systems (Köppen-Geiger) and by including additional elements that make regions more prone to fire (such as, thunderstorm frequency, temperature fluctuations, wind climate etc.)[13] The expansion of the built environment into these ecosystems has raised the probability of a conflagration by aligning the factors necessary for a catastrophe but also increasing the probability of human-driven ignitions within areas already prone to fire.[14]

Historically, the urban conflagrations of the past occurred in regions that were not necessarily climatologically prone to wildfires. In the modern era, climate change has altered the fuel landscape through changing the patterns of precipitation and extreme heat, leading to prolonged droughts, and increasing the volatility of fuels. This is also changing the global spatiotemporal distribution of fire, increasing the hazard frequency, geographically expanding it into areas not accustomed to it, and lengthening the seasonality of fire. The two primary climatic means that effect wildfire is increased fuel flammability due to warmer and drier conditions and increases in fuel availability due to more rapid swings between wet and dry periods[15]. The impact of these factors on vegetative fuels is becoming well understood, their influence on the fuels of the built environment is less quantified; however, in nearly all the conflagrations in the past four centuries, fires were preceded by some period of drought. Climatic factors are certainly not the cause of built environment conflagrations but through their linkage to the frequency and severity of wildfires they do aid in increasing their probability.

There is no better example of the climate mechanisms that influence wildfire than the persistent drought conditions experienced across the Western United States from 2011–2022. Interspersed with a small number of wet years, the semi-permanent drought created the necessary large scale fuel conditions to support frequent and very intense wildfires. When these fires intersected with the built environment it produced losses that had not been experienced before. During this period, six notable conflagrations occurred in four western states, with wildfire acting as a catalyst. The two most destructive being the Camp Fire (2018) and the Tubbs Fire (2017).

However, when exploring all fires over this time frame, persistent drought was found to account for only approximately one-third of the variance associated with wildfire acreage burned. The result illustrates the cumulative effect and differences in temporal scales between climate and weather[16]. Drought certainly serves as a necessary ingredient for fire, both urban and wildland; however, the temporal scale on which it evolves may be of less importance when considering built environment conflagrations. The patterns of wet years quickly transitioning to dry years and how these cycles evolve with our changing climate will be critical to understanding how climate mechanisms will set the stage for future conflagrations to play out.

Weather

The local weather is one of the three primary natural factors: weather, topography and fuel, (Figure 5) that affect fire behavior and consequently the potential for a built environment conflagration to ensue. In the context of historical urban conflagrations, it was typically the favorable weather conditions for rapid fire spread combined with dense fuels that turned a single structure fire into a large-scale catastrophe. When exploring the impact of weather on conflagration potential several factors emerge:

- Seasonal trends in precipitation (i.e., weeks to months changes leading to short-term drought)
- Wind conditions
- Relative humidity
- Atmospheric instability and often the initial ignition such as lightning

All of which need to be aligned to produce conditions favorable for rapid fire development, extreme fire behavior, and rapid spread.

Potter and McEvoy (2021) were able to explore all these factors, except atmospheric instability, and their effect on rapid fire spread of large wildfires. It was found that indices, including the widely used Fosberg Fire Weather Index (FFWI), that coupled both a measure of atmospheric moisture in the lowest 500 m with wind, were useful in determining the thresholds in which rapid fire growth is more likely[16]. However, the variance in growth rate is far more dependent on local elements of fuel, topography, complex wind flow characteristics, and diurnal cycles. In the United States, those conditions come together most frequently from the Rocky Mountains westward and are often associated with wind conditions flowing down large terrain features (for example, Santa Anna, Chinook or Foehn, and Diablo winds). As the air flows downward over the sloping terrain it compresses, warms, and dries creating the conditions previously discussed.

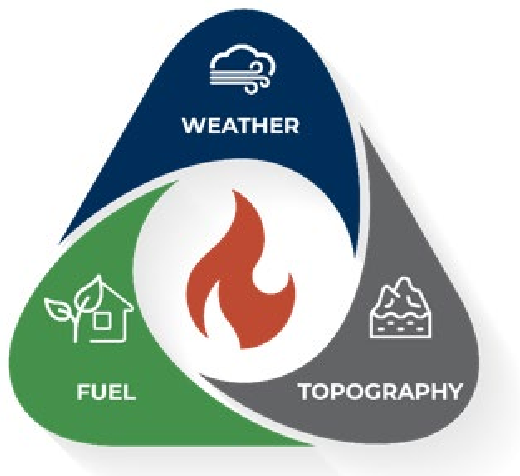

Figure 5: Fire behavior triangle.

The influence of atmospheric stability and its scales (both evolving in time and depth) is less understood. In general, the stability of the lowest few kilometers of the atmosphere plays a role in fire behavior, especially plume-driven wildfires. Broadly, it is understood that strong static stability helps temper fire behavior and is typically why extreme fire behavior is not common overnight as stability and relative humidity increases. For the most extreme plume-driven fires, the presence of strong atmospheric buoyancy (unstable conditions) can exacerbate plume growth leading to extreme updraft speeds within the plume, often accompanied by pyrocumulus clouds[17]. With improvements to observational and computational modeling capabilities, it has been found that in these extreme plume-driven fire events, plumes act like rotating supercell thunderstorms[18,19]. This leads to strong ground-level circulations, strong vertical motions, fire whirl activity, and extreme fire behavior as air rapidly spirals in towards the rotating plume helping feed more oxygen to the ongoing fire. The Carr Fire (2018) was perhaps the most extreme example, producing a large tornado-like vortex accompanied by EF-3 wind damage amidst burning structures.[20]. These fire-generated vortices have also been observed in urban fires as well[21].

Wind

The wind flow conditions both during pre-fire conditions and as a wildfire unfolds are a critical variable in nearly every aspect of the fire and its evolution. The general relationship between surface winds and wildfire behavior has been understood for over a century[22]. High winds and their interaction with complex terrain can drastically change fire behavior. This plays a substantial role at the time of ignition and as fire spreads into the WUI and suburban – exurban environments. In real-world scenarios, the strong updrafts associated with strong buoyant plumes can alter the local wind flow conditions. In situations with intense heating from the fire as it consumes a large volume of volatile fuels and a buoyant ambient airmass, updraft speeds can exceed 100 mph (45 ms^{-1})[20]. At the surface, strong convergence develops in response to the rapidly rising air, and wind speeds increase quickly as air rushes inward toward the fire. For the purposes of exploring suburban or built environment conflagrations, we will focus on how wind flow affects building material ignition potential.

Since the 1960s, researchers have been contemplating the impact of wind on the ignition of building materials. From the fundamental perspective, ignition of a building from another nearby structure occurs when the local heating rate of a building component exceeds its cooling rate due to local air flow. When there is a slow or moderate air flow, localized flames around structures can intensify due to the increased oxygen supply. As flames grow, the wind stretches and tilts flames towards adjacent structures and increases the heating rate on exterior building materials on downwind structures. This, in turn, causes the materials nearby to start decomposing from radiative, convective, and conductive heat transfer mechanisms. Wind can also aid in mixing the flammable gases that are forced out of building materials or it can dilute pyrolysis gases enough to make them less-flammable. Even after ignition as the wind speed increases, the flow of air can help diffuse heated gases and cool the surface of the materials to stall fire growth or even extinguish it. The relationship between fire and the small-scale flow of air around structures can be complex, with some factors exacerbating fire spread and others helping to limit combustion.

Simms[23] and his personal correspondence with Law[24] noted that when wind was introduced to small-scale specimen, common building materials exposed to radiant heat demonstrated a complex reaction. Low wind flow on sample building materials decreased the minimum heat intensity required to produce spontaneous ignition. Flow velocities exceeding 2 mph (1 ms^{-1}) dispersed flammable gases and delayed ignition significantly. It was also shown that the time required to produce spontaneous ignition decreased as the material sample size increased. This highlights the gap between small-scale experiments and the reality of ignition process in the field. Hurley et al. (2015) stated that, "…*extrapolation to realistic scenarios and fire models has to be done with significant care*." [24]

For historical urban conflagrations since 1900, almost all were associated with wind gusts estimated at 20 to 30 mph, and higher[25]. There is minimal knowledge of the correlation of local wind speeds at the community level and the reported measurements. The response of the flame to wind is a function of the flame intensity itself. A well-developed flame is less likely to extinguish when it is exposed to wind. The response of building materials to wind, cooling effects and diluting the pyrolysis gases, has only been studied in small experiments[23,24,26]. This is an area where IBHS is committed to bridging the knowledge gap over the next 5 years.

Moisture and Relative Humidity

The moisture content of fuel has a significant impact on fire behavior in large outdoor fires. Fuel moisture content is strongly correlated with relative humidity, which is itself a function of atmospheric vapor pressure deficit. As the vapor pressure deficit is high, the atmosphere can hold a large amount of water, which results in a large moisture gradient between plants and the air, allowing for higher evaporation rates. Vapor pressure deficit controls several stages of fire, including ignition probabilities, initial spread rates, burn area, and extinction likelihood[27].

Both live and dead vegetation are consumed as fuels in a wildland fire, where the flammability of dead fuels is typically higher, due to lower moisture content, compared with live fuel. The moisture content of the dead fuel is constantly changing due to the fact the only mechanism of exchanging moisture is through diffusion with the surrounding air. In other words, depending on the relative humidity, solar radiation and thermophysical properties of the dead fuel, the fuel can absorb or desorb moisture in different time scales[28]. These two processes happen at different rates; for woody particles, losing moisture happens faster than gaining it[29].

The same concepts apply to structural fuels, but the details and relationship between moisture content and ignitability are less understood due to their complex behavior. Structural fuels are often a combination of cellulosic and synthetic materials which respond differently when exposed to heat. Given that nearly all the urban conflagrations of the past were preceded by some degree of drought, the response of structural fuels to ambient moisture is clearly a factor. However, there have been only a few small-scale studies focused on understanding the effects of moisture content on ignitability of common building materials. While Moysey and Muir report that moisture content did not greatly affect time to ignition if the moisture content of samples were below 20%, Hedayati et al (2018) demonstrated that varying the moisture content between 5% and 15% affects time to ignition when the sample of structural fuel materials (both engineered and natural wood framing materials) were exposed to 20 kW m^{-2} radiative heat flux. At higher heat flux levels, moisture content played little or no role in the time to ignition.

Topography

The topography of a region interacts with weather conditions, fuel properties, and fire behavior feedback loops to influence fire spread. In combination, these factors influence fire spread rates, making it difficult to isolate the effects of topography[30]. The influence of terrain on a built environment conflagration is tied to the ignition potential of homes during the initial stages of an event, and its potential to slow or accelerate fire spread through a community. When applied, a slope that increases by 10 degrees generally leads to a twofold acceleration in the speed of a fire. If the slope measures 20 degrees, the fire could propagate four times faster compared to its spread on level terrain[31].

Both radiation and convection mechanisms are responsible for heating the fuel ahead. However, several studies have demonstrated that convective heat transfer becomes the dominant effect as the slope increases, particularly for slopes greater than 30 degrees. In the flame scale, flame attachment area increases with slope, causing increased heating of the fuel downstream. Flame attachment is due to the interaction of the buoyant plume of the flame, air drawn into the fire supplying the reaction with oxygen, and an incline. These factors push the flame toward the surface and result in both increased radiative and convective heat transfer to the surface and downstream fuels. It is known that convective heat transfer can extend further up the slope and dominate downstream heating effects, particularly in fine fuels[32].

Wind-induced flames exhibit similar fire behavior. In wind-induced fires, the attachment length increases due to external forces, unlike slope, which results from internal coupling of air coming into the fire and buoyant forces of the plume. In a non-aligned wind and slope environment, the combined influence of wind (speed and direction) and sloping terrain is more complex, as their combined effects are not as simple as just vector sums[24].

Observation during wildfire suggest that topography affects the fires by:

- Changing the burning behavior itself because of the complex wind flow
- Altering the behavior of the plume above the fire[33]

Often in typical wildfires, terrain conditions are characterized as complex. By restricting intake from the sides, sloping canyons alter air entrainment by forcing most of the air intake to occur down-canyon which increases the fire spread rate and its intensity[24]. In general fire can behave explosively as it accelerates moving up a slope. The interaction between air flow and flame intensity was observed in IBHS's Camp Fire post-event investigation.

Despite similar uphill slopes for the buildings on the ridge top (Figure 6), the lateral changes in slope impacted the local flame intensity and resulting exposure to each structure on the ridge top. The house that survived probably had less flame exposure. In an idealized scenario, a home in a more vulnerable location due to local topography requires a higher level of mitigation elements to achieve the same level of protection as a home in a less vulnerable location, like the example shown in Figure 6.

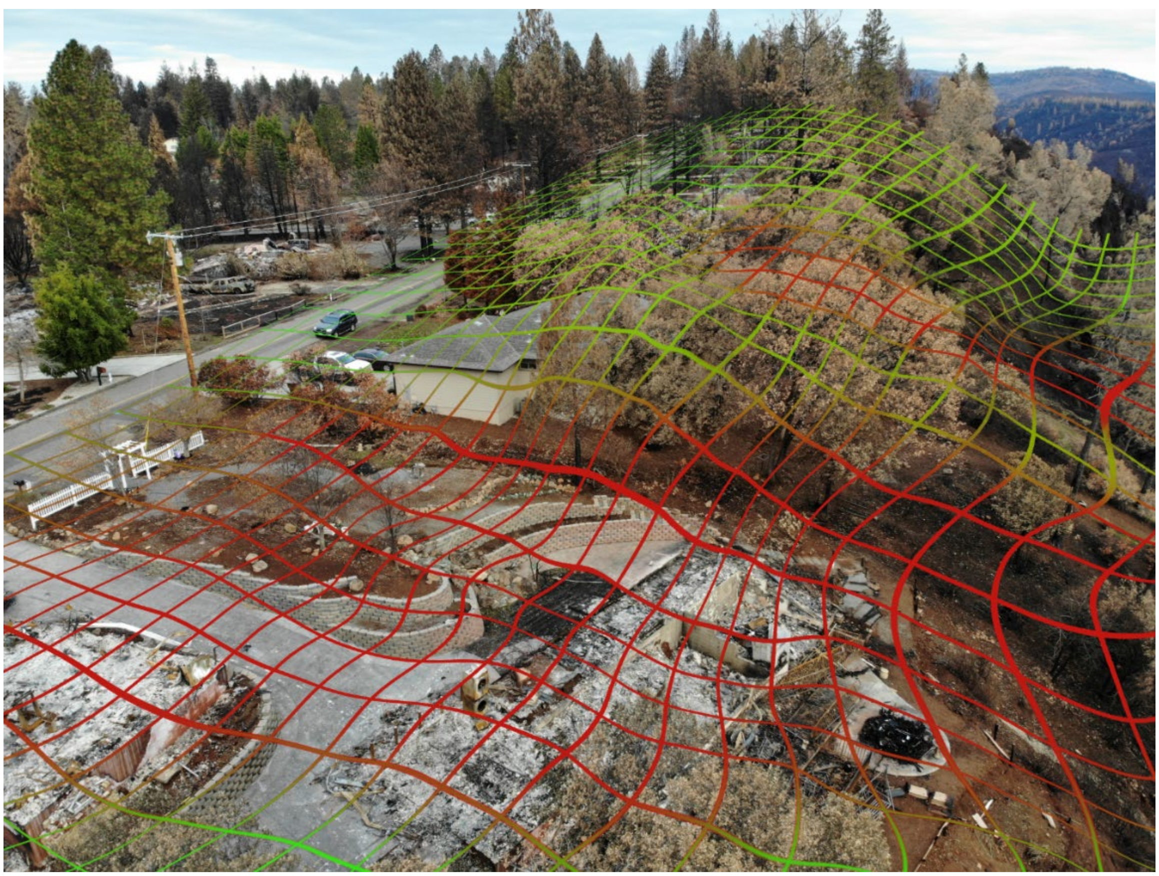

Figure 6: Drone photograph of structures that survived or were destroyed following the Camp Fire. The terrain slope is gridded and overlayed over the aerial photograph to illustrate the influence of the convex and concave nature of sloping terrain and its influence on fire spread.

Vegetative Wildland Fuels

The behavior of fire in wildland areas differs significantly from that in Wildland-Urban Interface (WUI) environments due to the complexities of the terrain and the variability in fuel types, such as their composition, height, density, and connectivity. Traditionally, wildland fuels were classified based on their ability to sustain the spread of flames. Ground fuels, comprising dead organic matter on the forest floor, can ignite and sustain slow-moving fires, typically smaller than 1 meter per minute. Surface fuels, consisting of live and dead vegetation above the ground, can sustain fire spread rates of up to 20 meters per minute. Canopy fuels, including large shrubs and trees, can sustain fire spread rates of up to 100 m per minute when ignited[28].

Each of these fuel types possesses various levels of flammability, encompassing four characteristics of wildland fuels:

- Ignitability
- Sustained ignition
- Consumable material
- Combustibility

Low-flammability vegetation is difficult to ignite, has a slow combustion process, and releases less energy, compared to other plants[34].

The accuracy of fire spread predictions relies heavily on the fuel characterization input in the model. Despite decades of research, there is no widely accepted fuel characterization that can be universally applied in models for predicting the spread of wildfires in wildland areas[35]. Different fire spread models have been developed to address specific needs and goals, often sacrificing accuracy to achieve their practical objectives in different as risk assessment programs[28,36].

Regardless of how the wildland fuels are characterized, the presence of abundant flammable wildland fuels, such as dry grass, shrubs, and trees, can provide continuous sources of fuel for wildfires resulting in rapid fire spread towards adjacent communities.

Extent and Size of the Fire Front Reaching a Community

The extent and size of the fire front, including ember cast, when it reaches an urban area has a substantial impact on the community's ability to respond to the fire. A fire that starts closer to a community will have a narrower fire front and ember-cast exposure toward the exposed community. Likewise, a fire that starts further away will have a larger fire front and ember cast exposure as it consumes more total fuel. In this scenario, a larger cross section or perhaps even the entire community is exposed to conditions more conducive for structure ignitions.

The second scenario presents a much bigger challenge for evacuations, life safety, structure defense actions, and fire suppression than the first scenario. As an example, the Camp Fire (2018) would have had a much different scenario if the fire had started closer to the Town of Paradise than where it did begin, approximately seven miles distant. The resulting fire front and ember transport downwind exposed the entire Town of Paradise to all three ignition mechanisms (ember attack, direct flame contact, and radiant heat) complicating an effective response to the rapidly developing extreme fire conditions.

The Built Environment

There a several components of the built environment that can contribute to the risk of conflagration or, if effectively managed, reduce that risk.

Structure Density

The built environment, specifically where high-density construction built with little to no fire-resistant materials meet ignitions under volatile weather conditions, is where the catastrophes unfold. The link that must be broken to avoid catastrophe is fire spread between structures. The fuel load of a typical home is easily sufficient to produce a flame and radiant heat exposure on a nearby structure to ignite it, even with some degree of hardened or fire-resistant materials, especially in the presence of wind which helps stretch flame lengths.

Once a structure ignites directly or indirectly, the probability of complete destruction is high. As shown in Figure 7, data from California wildfires indicates the probability of a structure within a wildfire boundary being destroyed is above 75% for residential, multifamily, and commercial construction. As structures are consumed, they also become prolific ember producers allowing for all three ignition mechanisms (ember attack, radiant heat, and direct flame contact) to act simultaneously on neighboring structures.

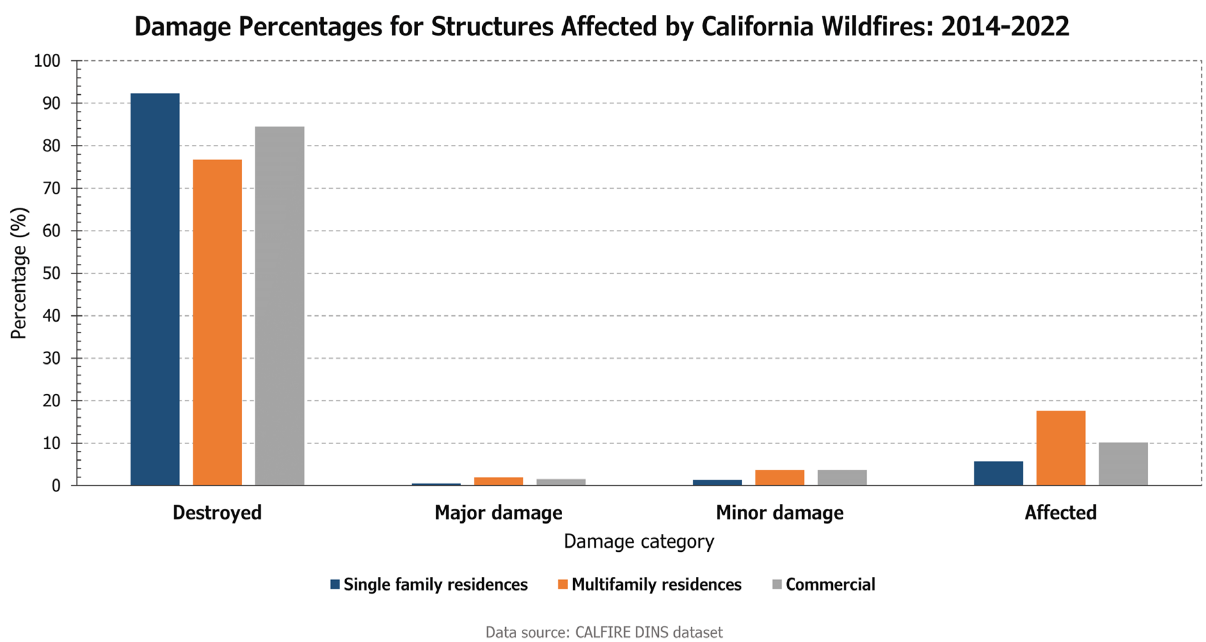

Figure 7: CAL FIRE damage inspection specialist (DINS) data for structures destroyed, those with major damage, minor damage, and marginally affected by California wildfires from 2014–2022.

Structure-to-Structure Fire Spread

Once structures are ignited in a community, the risk to the rest of the community increases as burning structures produce significant heat and embers. Field observations show that under normal to above average fire intensity, areas with lower density housing experience more loss. However, under the most extreme burning conditions, which are associated with costly wildfires in the WUI, more buildings burn in high density neighborhoods. This is associated with the limitations and risks for first responders to suppress the high intensity fires. It is much easier to defend homes under non-extreme fire conditions when the homes are close together, taking fewer firefighting resources to do so. Under extreme fire behavior conditions, structure defense becomes much more difficult due to the concern for life safety of firefighters and the public.

Most buildings are not designed to resist intense flame impingement, and once ignited, they contribute as additional fuel to the fire. Therefore, to stall this “domino effect,” maintaining a proper separation between buildings is crucial in a resilient community. There have been a few experimental studies regarding fire spread between buildings, most of which have been based on radiation from flames jetting out through openings following an internal fire. McGuire[37] developed a theoretical model that calculates building separation based on the size of the buildings and the opening percentages. McGuire’s calculations are based on the ratio of the radiant intensity at the receiving surface to that at the (one or more) radiating surfaces. The calculations provide an estimate of the threshold for flame spread between buildings.

However, during wildfires, the entire structure could be engulfed in flames. A structure engulfed in flames ignited from the exterior behaves differently than an internal fire with flames jetting from an opening. These differences resulted in different exposures to surrounding structures. There is little research on building-to-building fire spread, especially under windy conditions.

Extreme wildfires almost always occur during periods of high winds and dry weather. High wind speeds cause the flames to stretch and tilt towards neighboring structures. Convective heat transfer will cause ignition only if the temperature of the gas stream is several hundred degrees Celsius, which only happens very close to the flames. The geometry of the flames depends on the wind speed and relative location and orientation of the two buildings[38,39].

Connective Fuels

Several factors affect the intensity of a fire, including the type, arrangement, amount, and moisture content of the fuel. Fine fuels like grass and pine needles tend to ignite and burn quickly, producing high-intensity fires and contributing significantly to the initial stage of the fire spread. On the other hand, larger fuels such as logs or standing trees may burn more slowly but can contribute to higher heat release and longer-lasting fires. Additionally, the arrangement and continuity of fuel can affect the fire's ability to spread, influencing the intensity of the flames. The arrangement and distribution of fuel, both vertically and horizontally, is referred to as fuel continuity[40].

This continuity or connectivity describes the degree to which fuels are interconnected to provide a continuous path for fire to spread. In terms of fire behavior, fuel continuity plays a significant role in determining the rate and intensity of fire spread. High fuel continuity, where fuels are densely distributed and interconnected, can promote the rapid spread of fire, as flames can easily propagate from one fuel source to another. In general, live vegetation exhibits gaps between needles, shrubs, or trees, and clumps of them, arguing that understanding continuity of fuels is critical for fire suppression and fuel management. Even at small scales, the separation between fuel particles has been shown to create critical conditions for fire spread on both natural and artificial fuel beds.[41,42,43,44,45] This concept of critical conditions or thresholds also applies to larger scales, where discontinuity occurs between plants rather than individual particles.[46,47,48] In either case, the fire spread threshold is determined by fuel characteristics and environmental factors such as wind, slope, and fuel moisture content.

Over the past few years, IBHS has collaborated with the United States Forest Service (USFS) to investigate and identify the critical physical processes that drive ignition, considering the spatial distribution of fuel and a range of environmental conditions. As a result of this collaborative effort, valuable insights have been gained, particularly regarding the threshold separation distance between pine needle fuel beds for continuous flame spread under various wind conditions. As can be seen in Figure 8, the findings have demonstrated that the separation distance required for sustained flame spread varies depending on wind speed and moisture content conditions. Understanding this threshold separation distance is crucial for effectively predicting fire behavior and implementing appropriate fire management strategies.

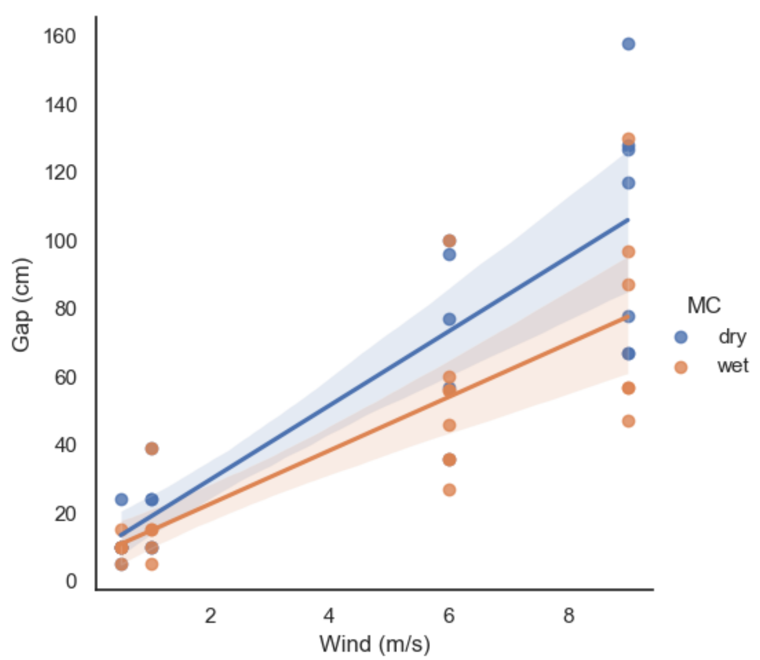

Figure 8: Maximum separation distance required for sustaining flame spread. Fuel break gap distances shown as a function of wind speed for fine fuels at two different moisture content levels at the IBHS Research Center.

The concept of fuel connectivity observed in vegetation fuels can also be extended to structural fuels such as fences, sheds, accessory dwelling units (commonly referred to as ADUs), and other similar objects. The underlying mechanism driving fire spread remains the same: when these structural fuels are closely spaced or connected, heat transfer between burned and unburned particles occurs at a high rate, leading to rapid fire spread.

Understanding the role of fuel connectivity in structural fuels is essential for assessing fire risk and implementing appropriate fire mitigation strategies. It emphasizes the importance of maintaining adequate spacing and reducing fuel continuity to minimize the potential for fire spread and mitigate the risks associated with structural fires.

Figure 9: Examples of structural fuel connectivity and the role in damaging the main building in a parcel during the Glass Fire. A combustible fence (A and B) supported flaming ignition, moving from downhill all the way to the main building, and caused severe damage (C and D). A and B are annotated with arrows representing the estimated direction of fire spread.

In the case of nonhomogeneous fuel, such as a mixture of different structural and vegetative fuels, details of the fire spread mechanisms are not yet well understood due to the interactions and complexities arising from the combination of different type of fuels. When low density fuels such as leaves meet larger fuels, such as building components, in general qualitative observations suggest a more rapid rate of fire growth. This fuel configuration can create a vertical fuel ladder that allows the fire to jump from the ground and engulf different building components in flames[49].

According to post-fire investigations, discontinuities between trees, bushes and structures can reduce the threat of tall, thick, high-intensity flames, which are strongly correlated with building damage. An analysis of Ramsay's[50] post-Ash Wednesday bushfire damage in Australia found that damage to homes was affected by the amount and type of vegetation around them. Dense vegetation around houses aided in connecting the fire to other nearby homes, making it less likely they would survive. During the Witch Creek Fire (2007), when evaluating the vegetation within the first 30 feet of houses in San Diego County, California, Maranghides et al[51] found that 67% of homes with unmaintained vegetation were destroyed, whereas only 32% of homes with maintained defensible spaces were destroyed. The importance of fuel discontinuity was found to be more important near buildings. Syphard et al.[52], after analyzing more than 2,000 structures in San Diego County, concluded that those structures with defensible space that contained spaced vegetative fuels "immediately adjacent" survived more fires. Additionally, Syphard et. al. also found that reducing woody vegetation by up to 40% immediately adjacent to structures and preventing vegetation from overhanging or touching structures were the most effective measures.

A fence or deck attached to the house can also facilitate the spread of fire or radiate enough heat to ignite the building cladding. Post event investigations and laboratory experiments show that these components, especially if they are in the vicinity or in contact with vegetation, can ignite the main building.

Figure 10. Testing deck vulnerability to embers at the IBHS Research Center. IBHS and others have conducted extensive testing regarding the vulnerability of decks[53] and fences.[54]

Response and Infrastructure

The United States has a long history of wildfire suppression for the protection of natural resources and defending against suburban conflagration. The combination of improved fire response capabilities and building codes requiring more fire-resistant materials in urban commercial construction solved the problem of urban conflagration.

Fire Service Response

Wildfire acting as the catalyst for suburban conflagration has significant differences from a fire in an urban setting. Figure 11 illustrates the complex fuel environment that fire services face in the suburban environment. The modern wildland fire service has evolved over time to become a complex coordination of emergency response agencies and fire suppression resources. Increases in technology, firefighting equipment capabilities, firefighter staffing levels, and training among other things have increased the overall effectiveness of emergency response, structure defense, and wildfire suppression.

Figure 11: Firefighters defend a structure from wildfire and the urban fuels (fences, couches, etc.) that create pathways for the fire to reach the home, leading to structural loss. Source: CAL FIRE

The California Department of Forestry and Fire Protection (CAL FIRE) strives to and is successful at containing 95% of all wildfires within its authority at 10 acres or less. Data suggests that 90 to 95 percent of all structures damaged during wildfires are defended, primarily by fire suppression resources.[55] [56]

The priority order for emergency response resource actions during a wildfire is the preservation of life, property, and natural resources. With the increase in fire severity in today's fire environment, many fire suppression resources will be used to preserve the public's safety rather than providing structure defense and direct fire suppression. Additionally, the number of structures threatened by a wildfire will generally outnumber the available fire suppression resources. Because of this, fire suppression resources can not be expected to defend every structure threatened by wildfire, especially in a built environment conflagration scenario.

Infrastructure as an Aid to Fire Response

Having adequate road infrastructure in place prior to a fire is key to the efficient and timely evacuation of the public from the fire's path and for access by emergency responders. Surface, width, grade, turnouts, turnarounds, signage, bridges, and gates are key components of the road infrastructure. Conversely, limited, and narrow evacuation routes do not allow for simultaneous use by evacuating citizens and emergency responders, leading to traffic gridlock and potential life-threatening burn over situations. These situations require a large focus from emergency responders in assisting with the evacuation process for life safety, which slows access by emergency response resources to suppress spot fires and slow the overall fire spread.

One of the primary methods used by firefighters for fire suppression and structure defense is the use of water to cool the fire. The ability of a water supply system to deliver water to firefighters when needed can be degraded by an aging infrastructure, the infrastructure being directly impacted by the fire, loss of electrical power, and being overtaxed by firefighting operations. The loss of the water supply system will hinder fire suppression operations and has occurred on several notable wildfires including the Camp Fire[57].

Several communication systems, tools, and methods are used to deliver timely and accurate fire information and evacuation notices (warnings and orders) to the public. Combinations of different evacuation tools and methods are needed to deliver this information because no single notification method will reach everyone within the affected area. The increased reliance on cell phones as the primary source for information makes them a crucial tool for notifications via news outlets, social media, and the Wireless Emergency Alert system.

However, cell phones rely on cell towers and electrical power to work. We have seen several wildfires (such as the Tubbs [2017] and Camp [2018] Fires), where fire damage rendered the cellular network inoperable in the area where the information was needed the most. This significantly hindered the timely delivery of critical life safety information to the public and altered the dynamics of the evacuation and response efforts.

Infrastructure as an Ignition Source

Wildfires can be caused naturally by lightning or by human activity like campfires, debris burning, arson, equipment use, fireworks, and powerlines. Nationally, approximately 90% of all wildfires are caused by human activity. The presence of infrastructure whether it is roads, powerlines, structures, etc. increases ignition potential under the critical conditions previously discussed. Of the fires listed in Table 1, ten were caused by things connected to human infrastructure.

Figure 12: Electrical utility infrastructure that fell in the roadways in Paradise, CA during the Camp Fire in 2018, hindering the evacuation of residents from the Town of Paradise. Photographs courtesy of CAL FIRE.

The electric utility infrastructure is of particular importance as it can cause the ignition of a wildfire and significantly impact the evacuation of a community from a fire. The percentage of powerline caused wildfires in California averages 10% per year, with 63% of those fires being caused by contact with an object like vegetation, animals, or vehicles[58]. However, the percentage of power-line-caused fires significantly increases during high wind events due to contact with vegetation and *line slap* or *galloping*. The wind engineering community has studied the galloping failures of power lines in various high wind conditions, including extreme hurricane winds and winter weather. This led to solutions that have been slowly integrated across the hurricane-prone coasts of the United States but rarely elsewhere.

The second problem is the maintenance of vegetation along electric power distribution infrastructure. Tree limbs can easily fall on power lines in winds that would not typically cause damage to the lines themselves. Unfortunately, the vulnerability of this infrastructure has created a recipe for larger fires and built environment conflagrations as these ignition sources are typically closer to WUI communities. Eight of the top twenty most destructive wildfires in California were caused by power lines, resulting in 32,427 structures being destroyed[46].

Human Factors

In addition to the natural factors, human presence plays a significant role in igniting and suppressing WUI fires. Most wildfires are directly or indirectly caused by humans and historically many of the conflagrations of the past few centuries were also a result of human actions. Firefighting activities at various stages of the fire, creating fuel breaks and defending structures, is one of the most important parameters in reducing the risk. Hence, human activities could be added as the fourth factor that affects wildfire behavior.

Population and associated infrastructure growth have introduced more sources of ignition. The result has been a change in the frequency of large fires, especially in the coastal zones of the western United States and east of the Appalachian Mountains[59,60]. Coinciding with the policy of rapid wildland fire suppression, outreach campaigns focused on stopping human-driven ignitions. In fact, the *Smokey Bear Wildfire Prevention* campaign, which began in 1944 is the longest running public service advertising campaign in United States history. During the program's first two decades human-caused wildfire ignitions were shown to have been statistically reduced by the campaign.

However, research also showed that the campaign fostered a highly negative view of wildfires, despite the knowledge that wildfires are beneficial for many ecosystems. This negative view of wildfire generated support for the federal policy of wildfire suppression[61]. By the 1980s, despite the outreach campaigns and consistent messaging, human-caused ignitions overtook natural mechanisms. Today, the gap continues to widen due to a combination of human activities and infrastructure.

It wasn't until the 1990s that outreach, and messaging campaigns began to center more around mitigation actions and communicating the concept of living with wildfire. At the community level, the first Fire Safe Councils in California emerged in the early 1990s. In 2002, NFPA launched their Firewise USA® community recognition program. These programs were the first steps toward addressing community-scale vulnerability. Progress however has been slow both at the parcel level and community scale in integrating mitigation elements. Wildland-Urban Interface building codes are a useful tool for mitigation at scale but have been underutilized across the United States. There are only four states (California, Nevada, Utah, and Pennsylvania) that have adopted a state-wide WUI code, and only two (California and Utah) uniformly enforce it at the state-wide level. Elsewhere, only a patchwork of local code jurisdictions exist that use these provisions[62].

Social science research efforts have begun to try to understand why people struggle with implementing wildfire mitigation actions. Studies have centered on understanding people's perception of risk and understanding the sociological and psychological barriers that lead to action or inaction. A common belief is that people do not take mitigation actions because they do not understand the risk to their life and property. Research has shown that this is not the case and that the problem is more complex[63]. The work of Meldrum et al. (2015) explored in detail how beliefs related to the attributes of a person's home compared to those of wildfire experts.

At the parcel level, homeowners significantly underestimated the importance of the local property-level topography, as well as roofing and siding materials. While their beliefs about the importance of vegetation and attached decks, were closer to those of wildfire experts[49]. Homeowners grasped the influence of surrounding elements outside their neighborhood on their own wildfire risk, but when moving to a more granular view of how interconnected a neighborhood is, homeowners underestimated the local view of their risk. This barrier in risk assessment presents challenges as a neighbor's home and their mitigation elements (or lack thereof) directly affects a home's ability to resist fire.

A path to improving a neighborhood's ability to defend against wildfire could lie with homeowner's associations (HOA) and their ability to enforce mitigation standards across the community. However, when IBHS and the Southeast Institute for Research (SIR) conducted focus groups with suburban homeowners in Colorado and California, HOAs received mixed opinions regarding their effectiveness to set wildfire mitigations standards, but participants did suggest this would be a useful means to communicate across communities.

The barriers to parcel level mitigation will likely be amplified when moving toward community-scale mitigation. Current research suggests that some psychological factors are more influential than others[64,65]. An awareness of the risk is certainly necessary, but that alone is not enough to promote widespread action. Factors that influence mitigation are the perceived effectiveness of risk reduction activities and the attitudes of others (i.e., family members, friends, neighbors, or social groups) toward those mitigation activities. Fortunately, at the community scale, both formal and informal outreach between government agencies and groups such as homeowners' associations have shown positive outcomes in building trust between stakeholders[66,67]. However, the beliefs of others are balanced with a homeowner's personal beliefs about their property. The tradeoffs between preparedness and amenities, personal privacy, neighbors' properties, and other factors, along with their perception of their ability to complete mitigation tasks, all influence the decision. Many of the maintenance activities described in most wildfire mitigation best-practices are near-continual processes. This has been shown to be a barrier to entry for many people because they feel they cannot complete the work.[65,66,67]

When considering urban conflagrations of the past, the primary focus and impact of conflagrations was on commercial construction. The problem was substantially mitigated, generally through improved fire response and building codes that required more fire-resistant materials in commercial construction. This dealt with both life-safety and structure loss reduction. Over time some of the interior fire spread provisions and material standards for fire resistance spread into residential construction codes. There is little literature available that considers human responses to proposed changes and then what were the barriers then that may have slowed implementation. However, it is important to note that these large- scale actions were mandated through policy changes and building code adoption. They were not reliant on voluntary actions. The use of social science to explore human behavior regarding how people respond and take mitigation actions to wildfires is relatively new but as described previously, there are significant complexities to voluntary decision making by homeowners regarding mitigation steps.

The following questions must be asked:

- Are today's human barriers to mitigation different from those encountered in the early 1900s when the mitigation of urban conflagrations was ongoing?
- How do perceptions of residential versus commercial construction differ when considering voluntary actions or mandated mitigation policies?

Limitations and Knowledge Gaps

Before humans began excluding wildfire from the environment, wildfires were an integral part of ecosystems, and certain plants and animals evolved to depend on them to maintain ecological balance. Humans, centuries ago, demonstrated that they can coexist with fire and develop healthy fire practices. There has been an increase in high severity fires in recent years, which have impacted soil erosion, carbon storage, forest succession, wildlife habitat, and human safety. Studying fires from 1985 to 2017, Park and Abatzoglou (2020) found that the area burned by high severity fires increased eightfold in western US forests[68]. Despite all the efforts being made to address this issue, these statistics highlight the need to discuss limitations and knowledge gaps.

While flame contact and radiation cascade the damage in the WUI, the spread of fire within the WUI is dominated by the complex chain of fuels and its characteristics. Before the fire front arrives at the WUI, embers from wildland fuels produce irregular ignition patterns in connected fuels within a community and within the structures themselves. The intensity and spread rate of these fires depend on local fuel flammability and the hyper-local wind flow conditions. Flame spread rate and fire intensity can be accelerated, slowed, or even extinguished based on fire stage, fuel characteristics, and wind speed[69,70]. This makes performance-based design and mapping the potential risks extremely challenging, specifically for large scale fires such as a built environment conflagration under complex, mixed time dependent radiative and convective heat transfer mechanisms. Additionally, as mentioned before, the interconnected effects of terrain, weather and climate, vegetative and structural fuel connectivity, and characteristics on large scale fire behavior both in the wildlands and within the WUI are not well understood.

Several challenging tasks need to be addressed from a social and policy perspective. While home hardening and fuel management do reduce the likelihood of building ignition, identifying mitigation strategies based on their cost-effectiveness and their correlation with the overall reduction of risk to the structure is not established yet[71]. The balance between practicality, cost, and science-backed risk reduction is only recently becoming clearer. In

California alone, the vast majority (95%) of the homes were built prior to adoption of any WUI code (Chapter 7A of the California Building Code)[72]. Allocating funding resources to retrofit buildings is challenging yet has been successful for other hazards such as earthquakes and hurricanes. Furthermore, the construction workforce and homeowners may not be trained or aware of fire-resistant materials. This issue becomes apparent when considering easily overlooked elements, such as vent screens or vertical clearances at the base of the wall, each of which can alter the probability of a building being damaged or destroyed.

Weather, Climate, Topography, and Wildland Fuels

Weather and climate elements are what set the stage for built environment conflagrations. Nearly all built environment conflagrations were preceded by some scale of drought. When they do occur, it is often the local weather that dictates where and when a conflagration ends. Fire weather research has been ongoing for nearly a century. At large spatial and time scales, the impact of wind and relative humidity on conditions that support wildfires have been well characterized. However, the effect of atmospheric stability on fire behavior is not well captured. The extreme fire behavior observed during fires of the last decade has revealed that the influence of atmospheric stability on available buoyancy and how it interacts with wildfire plumes may be more important than previously thought. It is these extreme plume driven fires that often are the catalyst for today's wildfire-driven built environment conflagrations. Their behavior makes it difficult for fire response resources to effectively slow the rate of spread, they can transport embers long distances, and stretch flame lengths. While the concept of critical fire weather has been in existence for more than 50 years, it has not been extensively used yet in medium and long-range forecast applications to provide predictive value on when large fires or extreme fire behavior is likely to occur.

The influence of climate change on the patterns of extreme heat, rainfall, droughts, and floods is advancing quickly and our understanding has grown extensively over the last two decades. This work has led to the suggestion that the changing climate will create longer periods of time in which critical fire weather may be present. However, as we observe large variances in fire season severity, research is also needed to explore the possible relationship with oceanic circulations (i.e., ENSO cycles) and global climate teleconnections that are known already to influence other hazards such as tropical cyclones and severe thunderstorms.

The current state of scientific knowledge of fire behavior within complex terrain is primarily through laboratory experiments and numerical modeling. There is still a large gap in understanding the role small-scale wind flow conditions within complex terrain and how that influences fire spread in this environment. Results from numerical simulations have shown that terrain has a more pronounced effect on fire spread on slopes than ambient wind conditions. However, field data to validate these results are non-existent in real-world wildfire conditions. There is a substantial need for in situ observations in these environments that can confirm or refute what has been seen in model simulations and laboratory experimental testing.

Built Environment

The spread rate of fire in the built environment can be influenced by several factors, including building materials, structure layout, and vegetation connectivity. Increasing the resilience of buildings through WUI building codes has been proven effective to slow fire spread in the built environment. Unfortunately, the use of WUI building codes has been an underutilized tool. California and Utah have used codes effectively in WUI areas, but most buildings were constructed before the WUI codes were adopted[61]. When ignited, these buildings expose the surrounding buildings to extreme heat exposure beyond the tolerance of most building materials, even those built in accordance with WUI standards. Even hardened buildings that meet the latest WUI codes can lose their integrity when the weakest component fails during extreme heat exposure. Small openings and details of construction are among other key factors that are challenging to address in all construction and are somewhat related to the practitioners' skills.

One of the largest gaps that remains is understanding the rates of fire spread through different built environments under realistic wildfire conditions. Research on the spread of fire between buildings has primarily focused on interior or compartment fires where flames extend through broken windows. However, in the case of wildfires, the entire structure can become engulfed in flames due to elevated wind speeds and typically a very dry and preheated airmass, resulting in significantly different fire behavior. Combining the complex wind flow conditions in a dense suburban environment and the response of the surrounding building's cladding elements to fire is poorly understood. The complexity increases when additional fuel sources, such as vegetation, are present between the two buildings. The presence of an inhomogeneous fuel pattern, coupled with the variability in vegetation maintenance, makes it extremely challenging to draw definitive conclusions during post-event investigations and requires large numbers of laboratory full-scale experiments to begin addressing this question.

Human Factors

The understanding of what human barriers remain to mitigating wildfire's impact on the built environment is just as significant as understanding how connective fuels and fire-resistant materials can be intertwined in affecting the potential for a suburban conflagration. Science and engineering are beginning to coalesce on what actions are necessary at the parcel level of mitigation and advances in computational abilities, machine vision, and machine learning applications are bringing to bear these advances in exploring how community-scale fire spread can be slowed or stopped.

Most catastrophic wildfires are started by humans or our infrastructure. It is unclear if improved messaging campaigns can help reduce human-started fires or not. While historically some success has been had in this area, there were also unforeseen consequences.

Two large research gaps and questions that are forefront:

- What human behaviors cause fires?
  - Are these human behaviors occurring more frequently?

  - Are they a consequence of population growth in regions where fire is prevalent?
- How are human ignitions altering annual occurrence probabilities?
- How are suppression activities altering occurrence probabilities?

The growth in the frequency of suburban conflagrations from wildfires has outpaced mitigation efforts. Programs such as NFPA's Firewise USA® have helped in improving awareness and establishing necessary community-scale ecosystems to implement mitigation actions; but unfortunately executing home hardening and defensible space measures in a large scale have lagged.

We must ask the following questions:

- Why has wildfire awareness not translated into action at large scales?
- How can a sense of hope be restored to motivate homeowners, homeowners associations, and communities to act?
- How do people respond to wildfires? How do they approach mitigation?
- What kinds of programs, nudges, and incentives could provide motivation?
- Why are wildland-urban interface codes a vastly underutilized tool for large-scale mitigation efforts?

Research has identified the communication gaps that are still present, and to some degree where messaging and outreach can be successful. While communication efforts are often focused through mass media, more effective channels have been found. These have included more personalized and local efforts such as one-on-one consultation with fire experts, townhall events, small workshops, tours, and demonstrations (Figure 13). These activities were more effective at changing beliefs; however, they are time intensive and typically do not reach large numbers of people[73]. The ability to link what must be done at the parcel level and how it can, when executed at scale, reduce the probability of a suburban or built environment conflagration and why, is critical to shrinking the gap between awareness and action.

Figure 13: Community wildfire awareness event held by the Butte County, California Fire Safe Council. Photograph courtesy of Lauren de Terra and Rachel Ostrander from the Butte County Fire Safe Council.

Summary

The elements of built environment conflagrations have remained the same for nearly four centuries. What has changed is the catalyst. In today's world wildfire has acted as the catalyst, and our most catastrophic wildfires are those where fire spreads quickly through the wildland-urban interface and into suburban neighborhoods. The rapid spread into these areas begins the chain of catastrophic fire as described by Cohen (2008). Setting the stage for conflagrations are drought, at any time scale, and wind. Droughts affect the volatility of fuels, both vegetative and building materials. Winds above 20 to 30 mph help drive fire spread through both flames and embers. However, these conditions are common among nearly all large wildfires. The difference between a large or even an extreme wildfire and a catastrophe lies in the presence of structures with little to no resistance to fire and fuels that connect them together. Once fire enters these communities, all three ignition mechanisms act simultaneously to spread fire structure-to-structure at rates and intensities that overwhelm fire suppression resources.

The factors that govern the probability of a built environment conflagration can be broken into those that are a function of the natural environment and the present built environment, and those that can be altered or mitigated. The elements of weather, climate, and topography that play vital roles in fire behavior, have conditions that are intrinsic to environments with fire as a part of their ecosystem. Forest management can help manage fuels in the wildland, but it is not possible nor advantageous to remove wildland fuels that may surround our communities. It is imperative that we adapt to living with fire such that intense wildfires can still occur but without them becoming catastrophic.

The key is reducing the probability of the initial structure ignition but also developing a system of protections within a community such that the community itself acts to slow fire spread or even stop it.

The first challenge is to develop a system that considers structure separation distances, the degree to which connective ladder fuels must be managed between structures, and the parcel level mitigations that matter to set a true community design standard. The second challenge is to implement a system in existing communities and sustain it for the communities of the future. Fortunately, this is a problem that has been addressed in another part of our built environment and through the same steps, our suburban communities can adapt to wildfire.

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