Wildfire Risk Analysis:

Understanding the Challenges and Advancing Solutions

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1. Introduction

Wildfire risk analysis has grown increasingly complex in recent decades, driven by rising fire frequencies, expanding wildland-urban interfaces (WUI), and the compounding influence of climate change on fire regimes (Moritz et al. 2012; Abatzoglou and Williams 2016). According to the California Department of Forestry and Fire Protection (CDFFP 2023), six of California's most devastating wildfires have occurred since 2010, including the 2018 Camp Fire, which resulted in 85 fatalities and caused damages exceeding $16 billion. The annual area burned in the western United States has nearly doubled since the 1980s (Westerling 2006), a trend exacerbated by prolonged drought conditions, higher temperatures, and extreme wind events (Berg and Hall 2015; Guzman-Morales and Gershunov 2019). Meanwhile, the expansion of WUI continues to place millions of homes at risk, with over 4.5 million U.S. residences now located in high wildfire-risk areas (Radeloff et al. 2018). In California alone, the WUI has grown by more than 20% since 1990, significantly increasing the financial burden of fire suppression and mitigation.

The severity of these risks was starkly illustrated by the 2025 Los Angeles wildfires—comprising the Palisades Fire and the Eaton Fire—which collectively burned over 62 square miles, destroyed more than 12,000 structures, displaced over 100,000 residents, and caused economic losses estimated at $250 billion (The Guardian 2025). Beyond the burned landscapes, these fires disrupted critical infrastructure such as electric power, potable water, and transportation networks (The Guardian 2025). Prolonged power outages, compromised water supply systems, and road closures highlighted the cascading failures that can occur when infrastructure vulnerabilities intersect with extreme wildfire events. These challenges underscore the urgent need for a comprehensive wildfire risk analysis framework that models wildfire spread, assesses infrastructure functionality, predicts socio-economic consequences, and informs intervention strategies.

In contrast to natural hazards like earthquakes and hurricanes, where risk analysis has advanced significantly (e.g., Gardoni et al. 2016; Gardoni 2019; Nocera et al. 2019; Sharma et al. 2020; Iannacone et al. 2022; Tabandeh et al. 2022, 2024), the field of wildfire risk analysis remains relatively nascent (Elhami-Khorasani et al. 2022). Current methodologies often concentrate on isolated aspects—such as hazard modeling or loss estimation—without providing an end-to-end solution that links ignition, fire propagation, and infrastructure-level consequences (Sullivan 2009a; Johnston et al. 2012). This fragmentation limits the ability of researchers, policymakers, and industry practitioners to anticipate and respond effectively to wildfire threats in real-world contexts.

Modeling wildfire propagation has been central to wildfire risk analysis. The main challenge is balancing accuracy with computational efficiency, ensuring models are both precise and feasible for real-time use. Physics-based models (e.g., FIRETEC, WFDS) offer deep insights into combustion and fluid mechanics (Linn et al. 2002; Mell et al. 2007), yet their high computational demands constrain full-scale applications and real-time forecasting, particularly in a probabilistic formulation needed to account for the many uncertainties (Morvan 2011; Mandel et al. 2011). Meanwhile, empirical or semi-empirical approaches (e.g., Rothermel 1972; Sullivan 2009b) are computationally more tractable but often struggle with limited accuracy—especially when real-time, high-resolution data on wind conditions, vegetation types, and fuel properties are difficult to obtain or assimilate. Even where semi-empirical methods can run quickly, their outputs may be undermined by uncertainties in environmental data, forcing operational systems to accept trade-offs between fidelity and speed.

Another open challenge is related to the underdeveloped link between fire behavior models and broader socio-economic consequences (Maranghides et al. 2015). Integrating advanced fire modeling with large-scale infrastructure assessments remains challenging due to a lack of standardized frameworks, the computational intensity of coupling multiple simulation tools, and limited datasets. As wildfires encroach on urban and suburban areas, the demand grows for end-to-end risk analysis tools capable of (1) simulating propagation in near real-time, (2) dynamically updating environmental data, (3) evaluating the vulnerability of built environments, and (4) quantifying cascading socio-economic impacts under uncertainty. Addressing these interdisciplinary challenges requires advancements in computational modeling, data integration, and risk-informed decision-making that unify elements from combustion science, meteorology, engineering, and economics.

We have been addressing some of these challenges by developing a tool for wildfire risk analysis that is both scientifically rigorous and practical for operational use. This tool builds on several decades of experience in risk analysis of the built environment under various natural hazards, such as earthquakes, hurricanes, and floods. However, it is specifically designed to address the unique complexities of wildfire risk analysis. Its modular design facilitates expansion and continuous improvement with new methodologies, bridging the gap between academic research and practical needs. By leveraging advanced mathematical methods and robust data-processing capabilities, the tool enables stakeholders to assess wildfire impacts on infrastructure services—both before and during an event. Before wildfires, the tool can support proactive measures by simulating the outcomes of different intervention strategies, enhancing community and infrastructure preparedness. During wildfires, it can provide real-time predictions of fire behavior and facilitate 'what-if' scenarios to guide rapid response and containment efforts. The tool is designed for two types of users. Basic users will receive automated predictions that update continuously as wildfire evolves, providing real-time insights without requiring direct interaction. Advanced users, on the other hand, can run customized ‘what-if’ scenarios by modifying conditions to explore different intervention strategies. This capability is particularly relevant for intervention strategies, such as evaluating the effects of controlled burns on future fire spread or assessing the impact of containment efforts before deployment.

The remainder of this report is structured as follows: Section 2 highlights the growing wildfire problem, including its causes, impacts, and the need for advanced risk analysis. Section 3 discusses the financial, health, and environmental cost of wildfires. Section 4 reviews current solutions and intervention strategies for wildfire mitigation and suppression, highlighting pre-fire planning and during-fire response measures. Section 5 identifies key gaps in existing solutions, with a focus on modeling challenges and limitations in real-time decision-making. Section 6 introduces a tool for wildfire risk analysis, designed to address these challenges through real-time data integration, dynamic simulation capabilities, and infrastructure impact assessments. Finally, the last section concludes with a summary of key findings and discusses potential future directions to enhance wildfire management and infrastructure resilience.

2. Understanding the Wildfire Problem

Wildfire activity in the United States has increased dramatically over the past decades, with fires becoming larger, more frequent, and more destructive. Figure 1 shows that between the 1980s and the 2010s, the average number of acres burned annually in the U.S. more than doubled, and this trend continues to accelerate (NIFC 2025). Multiple factors contribute to this heightened risk: environmental changes, human activity, and the expansion of communities into fire-prone areas. Climate change plays a central role in this shift, contributing to prolonged fire seasons and more extreme fire behavior (IPCC 2023). Warmer temperatures, changing precipitation patterns, and prolonged drought conditions have significantly dried out vegetation, making it more susceptible to ignition. Since the mid-1980s, the fire season has lengthened by nearly 78 days, turning what was once a seasonal hazard into a year-round threat in many regions (Westerling et al. 2006). These extended windows of vulnerability strain firefighting resources and increase the potential for catastrophic fires. The combination of hotter, drier conditions and shifting precipitation patterns has created a "new normal" for wildfire activity.

The Western U.S. is particularly affected, with California, Oregon, and Washington experiencing some of the most intense wildfire seasons on record (Reidmiller et al. 2018). Strong seasonal winds—like the Santa Ana winds in Southern California—further exacerbate the problem by carrying embers over long distances and pushing flames into urban areas. While lightning remains a key natural ignition source, human activity is responsible for the majority of wildfires (Balch et al. 2017). Downed power lines, vehicle sparks, campfires, and arsons are among the common ignition causes. This human component is especially concerning in areas with high population density and poor infrastructure maintenance. For instance, aging power lines that snap during wind events have been linked to several large and destructive wildfires in

California (CAL FIRE 2022). Decades of fire suppression policies have led to an overaccumulation of dry, dense vegetation in many forests (Steel et al. 2015). This fuel buildup, combined with invasive species like cheatgrass in the Great Basin or flammable shrubs in chaparral ecosystems, makes it easier for small ignitions to expand rapidly. As a result, once a fire starts, it can grow at alarming speed, threatening both wildlands and nearby communities.

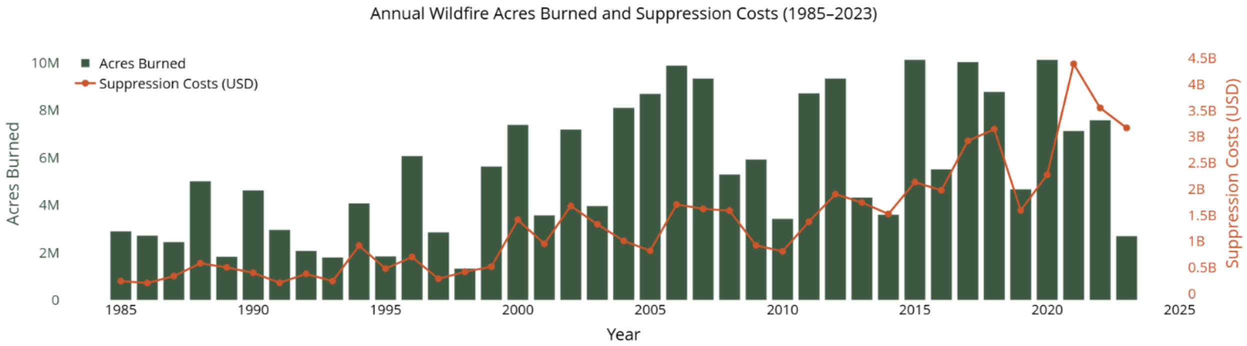


Figure 1: Trend of increasing wildfire impact: Annual acres burned, and suppression costs have risen over the years, reflecting the growing severity and frequency of wildfires. This increase is driven by factors such as longer fire seasons, climate change, and expanding wildland-urban interfaces.

One of the most concerning trends is the rapid expansion of the Wildland-Urban Interface (WUI), where human development meets undeveloped wildlands. As more homes and communities are built in high-risk areas, the exposure of people and property to wildland fires increases dramatically. Over 32% of new housing developments in the U.S. between 1990 and 2010 were constructed in the WUI (Radeloff et al., 2018). This expansion puts millions of people at risk and complicates firefighting efforts due to issues like limited road access and proximity to flammable vegetation. Structures built in the WUI are often not designed to withstand wildfire conditions. Key risk factors include flammable roofing materials, inadequate defensible space, and older construction methods that do not meet modern fire-resistant building codes (IBHS 2025). Infrastructure networks such as roads, power lines, and water supplies can be quickly compromised, adversely impacting both evacuation and firefighting operations. For example, narrow or winding roads in hillside developments can make evacuation challenging and make it difficult for emergency vehicles to access affected areas in time. Beyond direct destruction, wildfires in the WUI can trigger a chain reaction of economic impacts. Businesses may suffer extended closures, supply chains can be disrupted, and entire industries—such as tourism or agriculture—may face significant losses (III 2025a). Even once the flames are contained, widespread evacuations and displacement of residents can prolong business closures, further compounding revenue losses for local economies.

3. Understanding the Financial, Health, and Environmental Costs of Wildfires

3.1. Financial costs

Suppression costs for large wildfires can exceed $100 million per incident, and federal suppression expenditures have increased dramatically over the past two decades. In addition, the broader societal costs, including economic losses, health impacts, and long-term recovery—can be five to 30 times higher (NIFC 2025).

The financial value of assets at risk in wildfire-prone areas is staggering. In California alone, billions of dollars' worth of homes, infrastructure, and natural resources lie within high-risk zones (CAL FIRE 2025a). Even a single, large wildfire can threaten thousands of structures and cause widespread economic disruption. For example, the 2018 Camp Fire destroyed over 18,000 structures and caused $16.5 billion in damage, illustrating the growing vulnerability of communities in the WUI (Maranghides et al. 2020).

Beyond the cost of the physical damage, business interruptions, lost tourism revenue, and reduced property values can have long-lasting effects on local economies. It is estimated that indirect costs can be up to 15 times higher than direct suppression expenses (Dale 2010). For instance, the economic impact of the 2017 wildfires in California was estimated at $180 billion, driven by property losses, business closures, and infrastructure damage. Moreover, preventive power shutoffs, implemented by utilities to reduce the likelihood of fire ignition, have themselves imposed substantial costs on local communities. One analysis estimated that widespread Public Safety Power Shutoffs in 2019 generated as much as $2.5 billion in economic losses due to forced business closures, lost wages, and disrupted supply chains (Reuters 2019). This underscores how measures aimed at mitigating wildfire risk can inadvertently exacerbate financial burdens, further highlighting the complex and interconnected nature of wildfire-related economic impacts.

3.2. Health costs

One of the most significant but less visible impacts of wildfires is the effect of smoke on public health. Wildfire smoke contains fine particulate matter (PM2.5), which can exacerbate respiratory and cardiovascular conditions, particularly among vulnerable populations such as children, the elderly, and those with pre-existing health issues (Johnston et al. 2012). During the 2020 wildfire season, hospitals in California reported a marked increase in emergency room visits for respiratory ailments, resulting in millions of dollars in additional healthcare costs (Rosenthal et al. 2021).

3.3. Environmental costs

Wildfires release vast amounts of carbon dioxide and other greenhouse gases, contributing to global climate change. They also destroy forests and vegetation that would otherwise sequester carbon, compounding the greenhouse effect over time (IPCC 2023). Post-fire erosion and runoff can degrade water quality, threatening aquatic ecosystems and increasing the risk of mudslides—especially on steep, fire-scorched hillsides (Moody and Martin, 2009). The “True Cost of Wildfire” report estimates that the combined environmental and health costs of a large wildfire can easily exceed $1 billion (CWFL 2022).

3.4. Notable examples

Some of the notable examples of such destructive wildfires in the recent past are the 2018 Camp Fire in Northern California, and the 2025 Palisades and Eaton Fires in Southern California. The 2018 Camp Fire, which destroyed the town of Paradise, remains one of the most tragic examples of the true cost of wildfire. The fire burned over 153,000 acres, destroyed 18,804 structures, and resulted in 85 fatalities (Maranghides et al. 2020). The direct suppression costs exceeded $150 million, but the total economic impact was far higher. Long-term losses from Camp Fire are estimated at $16.5 billion, including property damage, lost business revenue, and recovery expenses.

In January 2025, Los Angeles faced two significant wildfires: the Palisades Eaton Fires. These events underscored the complex interplay between climate change, urban development, and escalating wildfire costs. Palisades Fire ignited on January 7, 2025, near the Pacific Palisades neighborhood. Strong Santa Ana winds and dry conditions fueled rapid spread across 23,707 acres, destroying over 6,800 structures and resulting in 12 fatalities. Eaton Fire began on the same day in Eaton Canyon in the San Gabriel Mountains. It burned 14,021 acres, devastated the community of Altadena, destroyed more than 9,400 structures, and caused 17 deaths. Together, the Palisades Eaton Fires caused total damage and economic losses estimated at over $250 billion (The Guardian 2025). This figure potentially marks them as among the costliest natural disasters in U.S. history, once property destruction, business interruptions, and long-term environmental damage are accounted for. Beyond the immediate destruction, the fires led to massive smoke emissions, severely degrading air quality and posing serious health risks to millions of residents across the region. The loss of vegetation also heightened the risk of mudslides and erosion, especially with the onset of winter storms. Recovery efforts have been extensive but remain challenging. Significant resources are needed for debris removal, rebuilding, and reestablishing essential services. Thousands of residents faced prolonged displacement, exacerbating the housing shortage in the Los Angeles area. The fires also sparked renewed discussions about strengthening building codes, developing more resilient infrastructure, and rethinking land-use planning to mitigate future wildfire risks.

4. Current Solutions and Intervention Strategies

The increasing frequency, severity, and cost of wildfires highlight the urgent need for more effective and sustainable management strategies. As financial, health and environmental costs escalate and WUI communities keep growing, current approaches show clear limitations. Risk analysis must encompass the entire wildfire lifecycle—from ignition sources and propagation mechanisms to the impacts on buildings, infrastructure, regional economy, and public health. Tackling these challenges requires 1) improved land-use planning, including restricting development in high-risk areas, 2) enhanced infrastructure resilience, such as updating power grids, roads, and water systems to withstand wildfire threats, 3) effective modeling and prediction tools that leverage all available data to predict and manage fire risk more effectively, and 4) community engagement and preparedness, such as educating residents on defensible space, evacuation procedures, and the long-term benefits of prescribed burns or fuel treatments. By integrating these strategies, policymakers, communities, and stakeholders can work toward a future where wildfires, while inevitable in fire-adapted ecosystems, do not have to be as destructive or costly.

Current efforts to mitigate and manage wildfires have evolved significantly over the past decades, driven by a growing recognition that fires are a complex natural phenomenon rather than an external threat that can be eliminated. A useful starting point for understanding current solutions is the “wildfire triangle,” which conceptualizes wildland fires as the product of three interacting elements, fuel, weather, and topography (Finney et al. 2021) (see Figure 2). Each of these components can be influenced—though not always controlled—by specific strategies designed to either reduce fire intensity or channel fire behavior in less destructive ways. Early twentieth-century policy in the United States, motivated by large and devastating events like the Great Fire of 1910, held a “10 a.m. policy” that dictated every fire to be contained by 10 a.m. the day after it was detected (Pyne, 2017). This led to an aggressive, long-lasting strategy of total suppression, which often viewed all wildland fires as immediately dangerous, regardless of ecological context. Although this approach temporarily curtailed large-scale fires, it also disrupted natural fire regimes, allowing significant accumulations of fuels such as dead wood, litter, and dense undergrowth (Steel et al. 2015). These built-up fuels effectively turned many forests into powder kegs that, when ignited under severe weather conditions, produce extreme fire behavior that far exceeds the capacity of conventional firefighting.

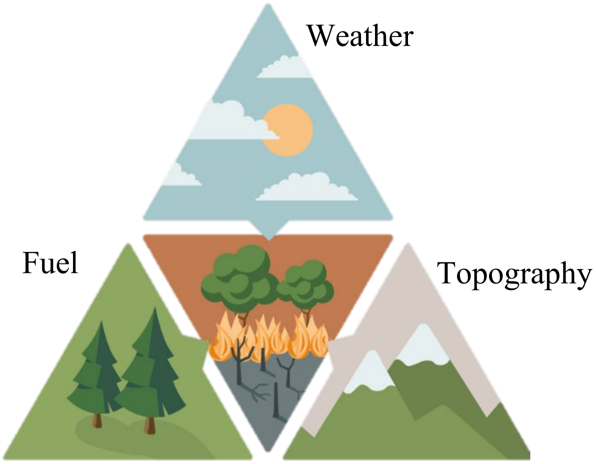


Figure 2: Wildfire triangle illustrating the three key factors influencing wildland fire behavior: fuel, weather, and topography. While all components interact to shape fire dynamics, intervention strategies primarily focus on modifying fuel to reduce fire intensity and mitigate fire spread.

In response, modern fire science and policy have begun embracing a multi-phase approach that includes both pre-fire interventions intended to mitigate risks before a wildfire starts and during-fire interventions designed to contain the blaze once it is active. Pre-fire strategies focus significantly on reducing or managing the fuel load, since this directly affects fire spread and intensity. Tables 1 summarizes the common strategies currently used for pre-fire interventions, while Figure 3 illustrates their implementation in practice. One widely used technique is the prescribed or controlled burn, in which low-intensity fires are set under carefully monitored conditions to consume understory vegetation, leaf litter, and other combustible materials

(Finney et al. 2021). By orchestrating these burns in cooler, moist seasons, managers can limit potential fire spread and restore ecological processes that natural fires once provided. Mechanical fuel reduction—often by thinning out smaller trees and dense underbrush—is another important method, particularly around WUI, to create defensible space that can slow or redirect an approaching fire (Radeloff et al. 2018). Both prescribed burns and mechanical thinning, however, can face community resistance due to concerns over air quality, aesthetics, and costs, along with the logistical challenges of carrying them out safely (Stephens et al. 2020).

An equally crucial mitigation strategy is structural hardening, which aims to make buildings and infrastructure more resistant to ignition. Over the last decade, revised building codes have mandated the use of fire-resistant materials—such as non-combustible roofing and ember-resistant vents—and required that defensible space be maintained within a certain perimeter around structures (IBHS 2025). These measures, though insufficient to stop a wildfire entirely, can significantly reduce the likelihood of home ignition, particularly from ember showers that can precede the main flame front by miles. Economic tools, such as tying insurance premiums or coverage availability to adherence to fire-safe practices, further incentivize property owners to adopt preventative measures (III 2025b).

Early detection and monitoring also play a critical role before a fire breaks out, as advanced tools for predicting fire propagation allow land managers to simulate how a potential fire might spread, guiding the placement of fuel breaks or the timing of strategic ignition operations. For instance, high-resolution, AI-enabled cameras mounted on towers or drones continuously scan for anomalies such as rising smoke plumes, allowing for near-real-time alerts to fire agencies. Infrared sensors and thermal imaging cameras, often integrated into satellite networks, can detect subtle heat signatures in remote or rugged areas, alerting authorities long before a fire is visible to the naked eye. In addition to these passive detection systems, ground-based sensor networks—which measure variables such as temperature, humidity, and wind speed—can feed data into fire spread simulators, helping predict fire behavior under a range of conditions.

Policy and land use planning also form a pivotal part of the pre-fire intervention strategies. By restricting construction in high-risk fire zones, requiring multiple ingress and egress routes in new subdivisions, and mandating the incorporation of fire-adapted landscaping, local jurisdictions can limit the exposure of human communities to wildfire threats (Radeloff et al. 2018). Municipalities and utility companies are additionally investing in infrastructure hardening—such as upgrading power lines or installing advanced weather monitoring systems—to reduce the chance of ignitions during extreme wind events (CAL FIRE 2025b). In regions prone to catastrophic wildfires, preventive power shutoffs (often referred to as Public Safety Power Shutoffs, or PSPS) have emerged as a critical policy instrument. By temporarily de-energizing power lines under hazardous conditions, utilities aim to prevent infrastructure-related ignitions; however, such shutoffs come with significant social and economic costs that require careful planning, regulatory oversight, and community engagement. Furthermore, public health measures, like setting up "clean air shelters" with high-efficiency filtration systems, help communities cope with episodic smoke pollution (Johnston et al. 2012). These strategies illustrate a broader shift away from the historical mindset that all fires must be immediately suppressed, favoring instead an approach that balances ecological benefits with the need to protect communities and resources.

Table 1: Common pre-fire intervention or mitigation strategies

Category		Description
Fuel management		Strategies aimed at reducing available combustible material to limit fire spread and intensity
	controlled burn	intentionally setting low-intensity fires under controlled conditions to reduce excess vegetation
	mechanical fuel reduction	physically removing vegetation using chainsaws or other equipment to reduce fuel loads
Structural hardening		Enhancing buildings and infrastructure to be more resistant to wildfires
	fire-resistant building	using ember-resistant vents and non-combustible roofing materials
	defensible space regulation	requiring the clearance of vegetation within a designated perimeter around structures
Early detection and monitoring		Detecting and tracking wildfires at early stages for rapid response
Policy and land use planning		Restricting construction in wildfire-prone areas and enforcing fire-resistant building codes

Figure 3: Strategies for wildfire mitigation and management. Prescribed Burning (left)—shows controlled low-intensity fires set under monitored conditions to reduce fuel load and restore ecological balance. (b) Mechanical Thinning (middle)—shows the removal of smaller trees and underbrush to create defensible space around the Wildland-Urban Interface (WUI). (c) Structural Hardening and Defensible Space (right)—shows a hardened home with defensible space, demonstrating how fire-resistant materials and maintained perimeters reduce ignition risk during wildfire events.

Despite these proactive efforts, significant intervention is often still required once a wildfire has ignited, especially under extreme conditions. Tables 2 summarizes the common strategies currently used for these during-fire interventions, while Figure 4 illustrates their implementation in practice. As summarized in Table 2, current suppression strategies typically involve direct and indirect attacks, which include ground-based crews working on the fire's edge using hand tools and water hoses in lower-intensity conditions or creating control lines at a safer distance when fire behavior is more severe (Steel et al. 2015). Where feasible, backburning—intentionally setting a smaller fire from a containment line—consumes the fuel in the main fire's path and can reduce its intensity (Stephens et al. 2020). In large or remote areas, aerial suppression plays a key role, with aircraft dropping water or fire retardants to slow the fire's forward progression or cool particularly volatile sections of the flame front. Managers must constantly weigh real-time factors such as wind shifts, humidity, and topography to decide where to allocate resources, prioritizing the protection of life, critical infrastructure, and environmentally sensitive areas (NIFC 2025).

Table 2: Common during-fire intervention strategies

Category	**Description**
Direct attack	Firefighters work directly at the fire's edge using hand tools, water hoses, and other equipment to suppress flames. Most effective on smaller or low-intensity fires
Indirect attack	Creating control lines (firebreaks) at a safe distance from the fire, usually in safer areas for firefighters. Firebreaks may use natural barriers (rivers, roads) or bulldozers to clear vegetation
Backburning	Starting a controlled fire ahead of the main wildfire, on the downwind. Even though the controlled fire is ignited downwind, it moves upwind toward the main fire due to the heat and low-pressure zone created by the main fire. By the time the two fires meet, the fuel in between is already burned, preventing further spread
Aerial suppression	Using aircraft to drop water, fire retardants, or foam directly onto the fire or ahead of it to slow its spread

Figure 4: Wildfire intervention strategies illustrated through four distinct approaches: (Top Left) Direct Attack – fire crews work directly at the fire edge to suppress the flames. (Top Right) Indirect Attack – firebreaks are created ahead of the fire to remove vegetation and stop its spread. (Bottom Left) Backburning – a controlled fire is set downwind to consume fuel and meet the main wildfire front upwind, limiting its advance. (Bottom Right) Aerial Suppression – aircraft drop water or retardant on the fire to reduce its intensity and assist ground operations.

Coordinating these during-fire interventions typically involves multiple agencies at local, state, and federal levels, each contributing specialized crews, equipment, and expertise. Evacuation orders are timed to prevent bottlenecks on roads and allow emergency responders to access threatened neighborhoods. Communications systems, ranging from wireless emergency alerts to traditional siren networks, have become indispensable for issuing evacuation routes and distributing rapid updates about fire behavior. Decisions about triage—

where to defend structures versus where to focus on stopping the spread—are informed by advanced modeling tools, historical fire data, and the real-time intelligence gathered from ground-based observation and aerial reconnaissance (Calkin et al. 2011). During the most severe fire seasons, when multiple large wildfires burn simultaneously, resource allocation can become a critical challenge, underscoring the importance of consistent interagency planning and shared protocols.

Equally important are the economic and community-level mechanisms that connect these suppression strategies to broader resilience objectives. For instance, some jurisdictions mandate developers to include “shelter-in-place” structures in new developments situated in fire-prone regions. Infrastructure operators deploy automated power shutdowns or invest in insulating electrical lines when high-wind events coincide with extreme fire weather to prevent accidental ignitions (CAL FIRE 2025b). Public health systems also respond by preparing local clinics and hospitals for a possible surge in respiratory ailments linked to wildfire smoke, with telemedicine playing an increasing role in addressing less severe cases (Johnston et al. 2012). In many cases, these measures illustrate a paradigm shift that acknowledges the need to coexist with wildfires, focusing on reducing their destructiveness rather than attempting to eradicate them entirely (Finney et al. 2021).

Ultimately, these approaches reflect a transition from viewing wildfires strictly as emergencies to be suppressed as quickly as possible to understanding that fire is an integral component of many ecosystems. By differentiating between beneficial low-intensity fire and catastrophic megafires, land managers strive to reduce the accumulations of fuels that drive extreme fire behavior. The integration of advanced fire behavior modeling, remote sensing, and economic incentives has helped policymakers and communities plan more effectively and invest in preventative measures that mitigate the worst impacts of wildfires. Figure 5 illustrates how effective wildfire intervention spans both pre-fire mitigation (i.e., prescribed management to control vegetation, structural hardening to protect buildings, early detection for rapid response, and land-use planning) and during-fire response (i.e., creating firebreaks, backburning to remove fuel ahead of the main fire, and aerial suppression to slow fire spread). This continuum of wildfire management underscores the importance of coupling preventative strategies with coordinated suppression efforts to minimize wildfire impact. Nonetheless, as the climate continues to warm and populations expand into once-remote wildlands, large-scale fire events will pose ongoing challenges, emphasizing the importance of evolving strategies that couple scientific understanding with practical, on-the-ground actions (Stephens et al. 2020). No single intervention can fully eliminate the risk posed by wildfires, but by uniting structural hardening, fuel management, early detection and monitoring, and coordinated suppression tactics, communities can achieve a more balanced coexistence with fire's natural role in the landscape.

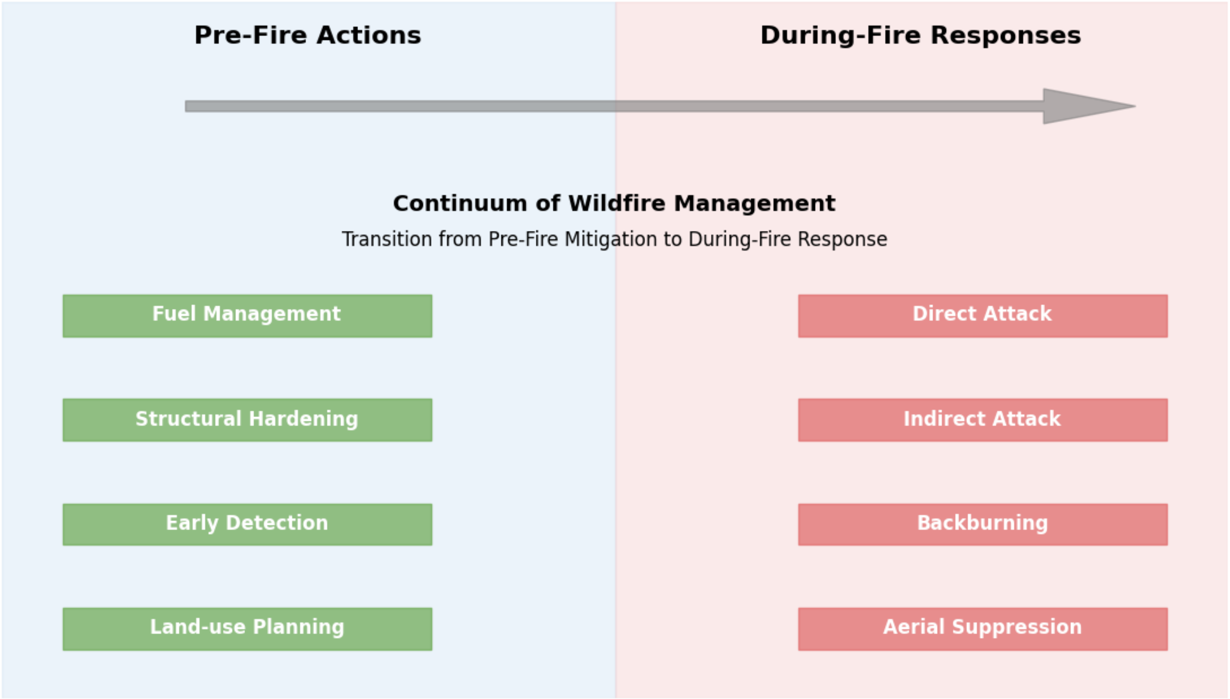


Figure 5: Effective wildfire intervention requires a comprehensive approach that spans both pre-fire mitigation and during-fire response strategies. Pre-fire actions focus on reducing wildfire risk and increasing resilience through methods such as prescribed management to control vegetation, structural hardening to protect buildings, early detection for rapid response, and land-use planning to minimize vulnerability. During an active wildfire, containment efforts shift to direct and indirect attack methods, including the creation of firebreaks, backburning to remove fuel ahead of the main fire, and aerial suppression to slow fire spread and support ground operations. Together, these interventions form a continuum of wildfire management aimed at minimizing wildfire impact

5. Challenges and Gaps in Existing Solutions

Despite notable progress in wildfire management and prevention, a range of challenges and gaps persist in current solutions, particularly in the domain of modeling and operational interventions. Wildfires are dynamic, multi-scale processes that emerge from the complex interplay of fuel, weather, and topography, and their behavior can shift dramatically over short time spans (Finney et al. 2021). This inherent complexity poses substantial obstacles for scientists and practitioners attempting to predict fire spread accurately, estimate potential damages, and coordinate timely suppression efforts. Moreover, as climate change extends fire seasons and intensifies drought conditions, the shortcomings in our collective capacity to anticipate and respond to extreme events have become increasingly apparent (IPCC 2023). These circumstances not only highlight the risk of underestimating mega-fire scenarios but also emphasize the importance of refining existing models and closing methodological gaps.

A significant challenge in wildfire modeling arises from the need to characterize inputs that are both spatially heterogeneous and highly variable in time. Wind, for instance, can shift direction or escalate in speed with minimal warning, carrying embers well beyond established perimeters (Andrews 2018). Fire behavior models such as FARSITE and BehavePlus rely on inputs specifying wind speed, direction, and gust frequency, yet real-world conditions often deviate from idealized assumptions, thereby introducing significant uncertainties into predicted rates of spread and flame lengths (Finney 1998). In complex terrain, topographical factors further complicate wind patterns, channeling or amplifying gusts that accelerate fire movement along ridgelines or through steep canyons (Clark et al. 1996). These local wind phenomena can outpace what standard forecast models capture, challenging firefighting crews who must allocate limited resources swiftly and effectively. Even seemingly comprehensive data sets from remote sensing platforms, weather stations, and aircraft reconnaissance can become outdated within hours in rapidly changing conditions, illustrating the fragile reliance on snapshots of meteorological information.

Fuel heterogeneity is another major source of complexity, as it can vary dramatically over short distances. Different vegetation types—ranging from grasslands to chaparral to dense coniferous forests—carry distinct thermal properties, fuel load densities, and moisture levels (Rothermel 1972). This variability influences how quickly a fire ignites and spreads, and it is further shaped by past management strategies, historical fire return intervals, and invasive species proliferation (Steel et al. 2015). While standardized fuel models exist (e.g., the Anderson fuel classification system) and can be integrated into simulation tools, these frameworks sometimes struggle to incorporate transient changes in fuel moisture or the presence of finer-scale phenomena such as pockets of high-density shrubs within what is otherwise considered a low-fuel area (Anderson 1982). The result is that seemingly similar landscape patches can burn in unexpectedly different ways. Although field sampling, LiDAR data, and aerial imagery have improved the resolution at which fuels can be mapped, the mismatch between model assumptions and actual conditions on the ground remains a persistent source of prediction error (Finney et al. 2021).

Topography completes the wildfire triangle, and its effects can be both direct and indirect. Directly, features such as slope angle influence the rate of fire spread, since fires move more rapidly uphill as the flames preheat higher vegetation layers (Finney et al. 2021). Indirectly, ridgelines and canyons create microclimates where temperature inversions or wind tunnels accelerate spread in particular directions. Some models address topographic detail by incorporating digital elevation data and algorithms for spotting, where embers are lofted by convective currents and transported downslope or across valleys (Albini 1979). However, each additional layer of complexity—from changes in slope to the presence of obstacles like roads or rivers—requires more computational power, creating a tradeoff between model resolution and the speed with which simulations can be produced. This tension is crucial during active fire events, when delayed or overly complex simulations may not be operationally useful for real-time decisions regarding evacuation or resource deployment (Clark et al. 1996).

Another set of challenges emerges when researchers and practitioners attempt to validate wildfire models and quantify their uncertainty. Fire events are difficult to replicate in controlled experimental settings at scale, and existing laboratory experiments often involve small plots that do not capture the multi-scale interactions present in large wildfires (Sullivan 2009b). For instance, flame vortices, convective columns, and the regional wind feedback mechanisms that characterize mega-fires seldom manifest at small scales. As a result, empirical findings from laboratory burns may not scale in a straightforward way to real-world infernos that can cover tens of thousands of acres (Stephens et al. 2020). Consequently, validation exercises often rely on post-hoc assessments of historical fire perimeters against simulated outcomes, and these can only gauge model performance under specific historical conditions — and even then, they typically require detailed information on intervention strategies that are typically not be readily or consistently available. Such retrospective studies are valuable for identifying major discrepancies between observed and predicted fire behavior, but they do not always illuminate where in the model chain errors arise—whether from input data, parameterizations of combustion processes, or simplifications of atmospheric coupling. Furthermore, each real incident unfolds within a unique confluence of vegetation states, meteorological regimes, and ignition patterns, making direct comparisons across fires prone to confounding factors (Sullivan 2009b).

Uncertainty also proliferates through the many assumptions and approximations needed to create any practical model. For example, the direction and speed of fire spread may hinge on assumptions about fuel moisture, yet actual moisture content can fluctuate drastically in a single forest stand depending on slope aspect, time of day, and shadowing from the canopy (Andrews 2018). Coupling that uncertainty with inherent variability in the wind field can produce wide confidence intervals around model outputs, complicating decisions about where to deploy firefighting assets or when to issue evacuation orders. These uncertainties become even more pressing for “mega-fires,” events that surpass typical ranges for energy release and resultant spotting distances (Stephens et al. 2020). Such large-scale conflagrations can generate their own weather systems, including powerful updrafts that launch embers miles ahead of the main fire front. Standard models not specifically designed to account for these feedback mechanisms may underestimate the rate of fire growth and the geographical scope of potential impact (Finney et al. 2021). This underestimation can be catastrophic for incident managers, forcing them to play catch-up instead of proactively mitigating risk.

In addition to these modeling difficulties, operational interventions during an ongoing event often hinge on forecasts that must be both accurate and timely. Delays in running computationally intensive models might render the output irrelevant if conditions change or the fire transitions from a ground-based surface fire to a more volatile crown fire (Finney 1998). Moreover, real-time decision-making generally requires probabilistic predictions that incorporate not just a single estimate of fire location or intensity, but a range of potential outcomes with associated likelihoods. Providing such probabilistic predictions is challenging because it requires multiple model runs, each with varying initial conditions and parameter settings to reflect uncertainty in wind, fuel moisture, and ignition sources. Generating ensemble predictions for large, complex fires within the narrow decision windows available to emergency responders can strain computational resources, particularly if local agencies do not have dedicated supercomputing capabilities or high-bandwidth data streams (Sullivan 2009b).

Various modeling paradigms attempted to address these constraints. Deterministic models, epitomized by the Rothermel equations for surface fire spread, focus on average conditions and yield straightforward, operationally compatible outputs (Rothermel 1972). However, they lack the capacity to simulate rapid transitions to extreme fire behaviors. Semi-empirical approaches, like those employed in FARSITE, integrate fuel models, slope data, and weather forecasts to predict fire growth over time but can struggle with capturing complex atmospheric dynamics (Finney 1998). Coupled fire-atmosphere models, such as those using computational fluid dynamics (CFD) algorithms, aim to resolve interactions between fire-induced convection and ambient winds, offering more realistic simulations at the expense of very high computational requirements (Clark et al. 1996). Each approach—deterministic, semi-empirical, or fully coupled—introduces significant tradeoffs regarding usability, speed, resolution, and accuracy, that make such approaches of limited practical value.

So, the pursuit of new models continues because of the tremendous potential these tools can have to serve as “digital twins” of the real wildfire environment. If models could be run quickly and reliably, decision-makers could use them to test a suite of interventions—ranging from specific suppression tactics, like backburns in designated locations, to large-scale evacuations—before committing resources in the field. By experimenting within a virtual environment, incident commanders might foresee detrimental chain reactions or discover a more efficient way to corral the fire. This vision hinges on closing important modeling gaps that currently hamper the practical use of such models. Further improvements in sensor networks, data assimilation techniques, and advanced machine-learning methods for predictive modeling could enhance the accuracy and speed of real-time forecasts, mitigating uncertainty to a degree.

The challenges and gaps in existing wildfire solutions center on the difficulty of capturing the full complexity of wildland fire behavior in models and interventions designed for real-time operations. The physical processes underlying fire ignition, spread, and extinction are deeply intertwined with atmospheric dynamics, heterogeneous fuels, and variable terrain. Gaps in our understanding of fuel moisture dynamics, wind-field variability, and large-scale turbulent combustions affect the accuracy of predictive models, while the lack of robust validation data for mega-fire scenarios adds another layer of uncertainty. From a management perspective, these modeling uncertainties directly affect how decisions are made during an active event, potentially constraining evacuation timing and the strategic positioning of firefighting resources. Yet these same models, if improved and implemented at scale, hold the promise of serving as digital test beds in which multiple interventions can be simulated swiftly, allowing emergency managers to refine their approaches and minimize loss of life, property, and vital ecosystems. It is precisely this tension between the current limitations and future potential of wildfire modeling—coupled with the ecological necessity of fire in many landscapes—that motivates ongoing research and innovative solutions aimed at reconciling the natural role of wildland fire with the imperative to protect human communities and infrastructure.

6. Proposed Solution: A New Tool for Wildfire Risk Analysis

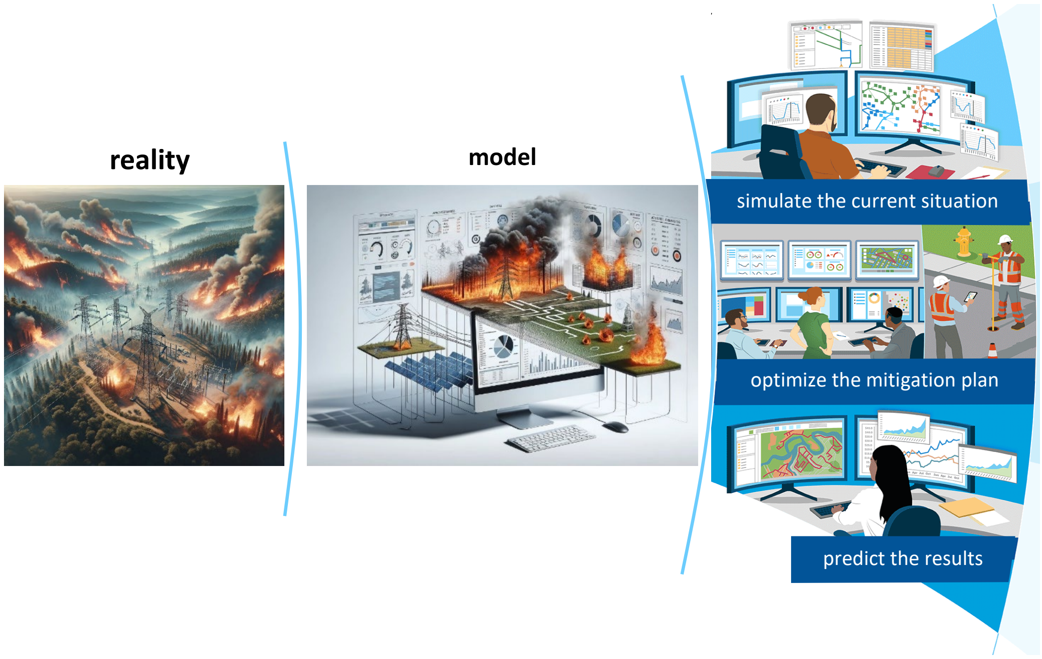
We are developing a new tool for wildfire risk analysis that addresses some of the key challenges discussed in Section 4. This is in response to the broader realization that existing wildfire models and intervention strategies, while advancing in many aspects, still struggle to capture the fast-evolving complexities of real-world fire behavior. As described in the previous sections, challenges such as incomplete data, rapidly changing meteorological conditions, and fuel heterogeneity often conspire to undermine both the accuracy of predictions and the effectiveness of on-the-ground responses. The tool integrates multiple data sources, modeling techniques, and intervention analyses into a single, user-friendly system that addresses some of the most persistent gaps identified in contemporary wildfire management.

At its core, the tool functions as a “digital twin,” a dynamic modeling environment that mirrors real-time fire conditions and can be updated continuously as new information becomes available. The tool captures major drivers of wildfire behavior—fuel load, weather patterns, and topography—without overwhelming users with excessive computational complexity. By consolidating data from satellite imagery, ground-based sensors, and meteorological forecasts, the system mitigates the lag between actual field conditions and the assumptions embedded in predictive models. This approach addresses one of the key issues discussed earlier: the frequent mismatch between static input parameters and the dynamic reality of how quickly fire perimeters can shift, or how abruptly wind and humidity can change.

A central design priority is to facilitate immediate operational decision-making while still providing the depth needed by researchers to refine long-term strategies. In many large wildfires, incident commanders and local agencies must allocate scarce firefighting resources within narrow windows of opportunity. By automating the ingestion of updated weather and fuel data, the tool offers real-time simulations of how a fire front might evolve in the next few days, thereby helping planners decide whether to prioritize direct attack, indirect containment lines, or targeted aerial drops. Equally important, this same system could serve as a platform for "pre-incident" scenario testing, where researchers or land managers experiment with various prescribed burn strategies or mechanical thinning plans in a virtual environment before implementing them on the ground. Rather than viewing scientific modeling and field operations as two separate domains, the tool bridges them through a shared interface, one in which adjustments to parameters can show both immediate and longer-term implications for fuel loads, structural vulnerability, and fire spread.

Transforming Wildfire Risk Management with Digital Twins

A digital twin in wildfire risk analysis allows us to simulate and visualize the ultimate impact of hazards and the effects of intervention strategies. These digital twins contribute to more inclusive and transparent risk reduction decisions, improving how we manage critical infrastructure services during emergencies. By offering a detailed, real-time view of potential wildfire scenarios, digital twins empower stakeholders to make informed, proactive decisions that improve community safety and infrastructure resilience. This technology ensures that mitigation strategies are effectively tailored and resource-efficient, significantly enhancing the speed and efficacy of emergency responses and recovery efforts post-wildfire.



Equally crucial, the tool attempts to address the variable success rates of different suppression strategies. The tool incorporates time-stamped and georeferenced data on containment lines, backburn operations, or aerial suppression drops. The tool can reflect real-world firefighting conditions, wherein plans often must pivot in response to on-the-ground reports and shifting weather forecasts. By capturing these nuances, the tool reduces the disconnect between laboratory-derived models and fast-changing conditions that characterize large-scale wildfires.

Realism remains a guiding principle, so the tool explicitly recognizes that wildfires do not act in isolation from the built environment. Drawing on research that underscores the interdependence of power grids, road networks, and water distribution lines, it links simulated fire progression to potential impacts on critical infrastructure. If utility lines run through a high-risk corridor, for instance, or if an essential water pumping station lies directly in the projected path of the fire, the model can highlight these vulnerabilities in real-time. Users can then explore interventions—such as rerouting power flow or strategically positioning backup generators for water pumps—to see how quickly a localized disruption might ripple through larger service areas. This system-of-systems perspective does not pretend to erase all the cascading risks of a major wildfire event, but it does offer a mechanism for incident managers and planners to recognize bottlenecks and vulnerabilities before they compound into wider crises.

The user interface is designed to accommodate a range of expertise levels, from trained fire behavior analysts to local officials or insurance representatives seeking a higher-level understanding of evolving threats. Rather than presenting a monolithic output, the dashboard organizes data layers—such as live wind vectors, updated humidity profiles, or newly formed hotspots on the fire perimeter—so that users can selectively investigate the information most pertinent to their role. Researchers might, for example, delve into fine-grained data on flame lengths or heat release rates, whereas an emergency manager might focus on neighborhoods at high risk of ember spotting and the time window for safe evacuation. By matching the complexity of the output to user needs, the tool aims to enhance both operational effectiveness and broader risk communication.

A particularly forward-looking aspect involves the tool's modular architecture, which opens the door to integrating emerging technologies and datasets as they become available. Satellite imagery is becoming more frequent and higher in resolution; machine learning methods are advancing in areas like fuel moisture estimation and anomaly detection. Meanwhile, improvements in sensor hardware could provide more granular readings of temperature, humidity, or even local wind gusts. By abstracting these data streams into interchangeable modules, the tool need not remain static; it can evolve alongside broader technological and scientific breakthroughs, whether those come in the form of better atmospheric coupling algorithms, more extensive sensor networks, or advanced remote sensing platforms. This adaptability is not a luxury but a necessity, given the persistent pace of climate change and the associated shifts in fire regimes that can outdate even the best models if they remain static.

The tool stands as a step toward more integrated, adaptive, and evidence-based wildfire management, drawing on the extensive groundwork laid by existing models and the urgent need outlined throughout this report to refine both pre-fire planning and during-fire response. It will not singlehandedly eliminate the dangers posed by wildfires, especially in the face of evolving climatic extremes and the continual expansion of the Wildland-Urban Interface. However, by seamlessly combining real-time data assimilation, advanced modeling, infrastructure impact analysis, and user-friendly visualization, it makes significant progress in bridging the gap between theoretical research and practical action. In so doing, it acknowledges the complex reality that, while wildfires may be an inevitable part of many ecosystems, the devastation they impose on communities and landscapes can be curbed through better-informed, faster-adapting, and more collaborative intervention strategies.

7. Summary and Conclusions

Over the past decades, wildfire activity in the United States has escalated, driven by climate change, prolonged droughts, human activity, and expanding communities in fire-prone areas. Wildfires are now larger, more frequent, and more destructive, with the Western U.S. being particularly affected. The increasing vulnerability of the Wildland-Urban Interface (WUI) exposes millions to significant risks, including structural damage, economic disruption, and public health crises from smoke exposure. Climate change has lengthened fire seasons, transforming what was once a seasonal threat into a year-round challenge. Wildfire mitigation strategies have shifted from a suppression-only approach to a more comprehensive framework that includes pre-fire and during-fire interventions. Pre-fire strategies focus on fuel management, structural hardening, early detection, and policy changes to reduce risks, while during-fire strategies involve direct and indirect firefighting tactics, including firebreaks, backburning, and aerial suppression. Despite these advancements, significant gaps remain in wildfire modeling and operational response due to the dynamic nature of wildfires and the complexity of integrating real-time data. To address these challenges, a tool for wildfire risk analysis is under development at the University of Illinois Urbana-Champaign. The tool functions as a "digital twin," integrating real-time data from satellites, sensors, and weather forecasts to predict fire behavior and assess risks to critical infrastructure. It offers modular architecture for adaptability, a user-friendly interface for diverse stakeholders, and scenario-testing capabilities for proactive planning and designing various novel intervention strategies. By bridging the gap between research and practice, the tool aims to improve real-time decision-making, reduce uncertainty, and enhance wildfire management in the face of evolving fire regimes.

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References

Abatzoglou, J. T. and Williams, A. P. (2016). "Impact of anthropogenic climate change on wildfire across western US forests," *Proceedings of the National Academy of Sciences*, 113 (42), 11770-11775.

Albini, F. A. (1979). *Spot fire distance from burning trees: a predictive model*. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture.

Anderson, H. E. (1982). *Aids to determining fuel models for estimating fire behavior*. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-GTR-122.

Andrews, P. L. (2018). *The Rothermel surface fire spread model and associated developments: A comprehensive explanation*. General Technical Report, RMRS-GTR-371, Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Balch, J. K., Bradley, B. A., Abatzoglou, J. T., Nagy, R. C., Fusco, E. J., and Mahood, A. L. (2017). "Human-started wildfires expand the fire niche across the United States," *Proceedings of the National Academy of Sciences*, 114 (11), 2946-2951.

Berg, N. and Hall, A. (2015). "Increased interannual precipitation extremes over California under climate change," *Journal of Climate*, 28 (16), 6324-6334.

CAL FIRE. (2025a). "Fire statistics and incident information," Retrieved from https://www.fire.ca.gov/our-impact/statistics

CAL FIRE. (2025b). "The department of forestry and fire Protection," Retrieved from https://www.fire.ca.gov

Calkin, D. E., Thompson, M. P., Finney, M. A., and Hyde, K. D. (2011). "A real-time risk assessment tool supporting wildland fire decision-making," *Journal of Forestry*, 109 (5), 274-280.

CDFFP (California Department of Forestry and Fire Protection). (2023). "CalFire stats and events," Retrieved from https://www.fire.ca.gov/our-impact/statistics.

CFSC (California Fire Science Consortium). (2020). "Expansion of the wildland-urban interface," Retrieved from https://www.cafiresci.org/research-publications-source/category/wildland-urban-interface.

Clark, T. L., Jenkins, M. A., Coen, J., and Packham, D. (1996). "A coupled atmosphere-fire model: Role of the convective Froude number and dynamic fingering at the fireline," *International Journal of Wildland Fire*, 6 (4), 177-190.

CWFL (Coalition Wester Forestry Leadership). (2022). The True Cost of Wildfire in the Western U.S. 2022 Report. Available from: https://www.thewflc.org/sites/default/files/TrueCostofWildfire.pdf

Dale, L. (2010). *The true cost of wildfire in the Western U.S*. Western Forestry Leadership Coalition, Lakewood, CO.

Elhami-Khorasani, N., Ebrahimian, H., Buja, L., Cutter, S. L., Kosovic, B., Lareau, N., Meacham, B.J., Rowell, E., Taciroglu, E., Thompson, M.P., and Watts, A.C. (2022). "Conceptualizing a probabilistic risk and loss assessment framework for wildfires," *Natural Hazards*, 114 (2), 1153-1169.

Finney, M. A. (1998). *FARSITE, Fire Area Simulator--model development and evaluation*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Finney, M. A., McAllister, S. S., Forthofer, J. M., and Grumstrup, T. P. (2021). *Wildland fire behavior: Dynamics, principles and processes*. CSIRO publishing.

Gardoni, P., Murphy, C. and Rowell, A. (Eds.) (2016). *Risk analysis of natural hazards*. Springer International Publishing, Switzerland.

Gardoni, P. (Ed.). (2019). *Routledge Handbook of Sustainable and Resilient Infrastructure*. Routledge, New York, NY.

Guzman-Morales, J. and Gershunov, A. (2019). "Climate change suppresses Santa Ana winds of Southern California and sharpens their seasonality," *Geophysical Research Letters*, 46 (5), 2772-2780.

Iannacone, L., Sharma, N., Tabandeh, A., and Gardoni, P. (2022). "Modeling time-varying reliability and resilience of deteriorating infrastructure," *Reliability Engineering & System Safety*, 217, 108074.

IBHS (Insurance Institute for Business & Home Safety). (2025). "Wildfire prepared home," Retrieved from https://wildfireprepared.org/

III (Insurance Information Institute). (2025a). "Wildfire facts and statistics," Retrieved from https://www.iii.org/fact-statistic/facts-statistics-wildfires

III (Insurance Information Institute). (2025b). "Insurance for wildfires," Retrieved from https://www.iii.org/article/insurance-for-wildfires

IPCC (Intergovernmental Panel on Climate Change). (2023). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., Kinney, P., Bowman, D. M. J. S., and Brauer, M. (2012). "Estimated global mortality attributable to smoke from landscape fires," *Environmental Health Perspectives*, 120 (5), 695-701.

Linn, R., Reisner, J., Colman, J. J., and Winterkamp, J. (2002). "Studying wildfire behavior using FIRETEC," *International Journal of Wildland Fire*, 11 (4), 233-246.

Mandel, J., Beezley, J. D., and Kochanski, A. K. (2011). "Coupled atmosphere-wildland fire modeling with WRF-Fire version 3.3," *Geoscientific Model Development*, 4 (1), 497-545.

Maranghides, A., McNamara, D., Vihnanek, R., Restaino, J., and Leland, C. (2015). *A case study of a community affected by the Waldo fire event timeline and defensive actions*. NIST Technical Note 1910, Gaithersburg, MD.

Maranghides, A., Mell, W., Hawks, S., Wilson, M., Brewer, W., Link, E. D., Brown, C. U., Murrill, C. P., and Ashley, E. (2020). *Preliminary data collected from the Camp Fire reconnaissance*. NIST Technical Note 2128, Gaithersburg, MD.

Mell, W., Jenkins, M. A., Gould, J., and Cheney, P. (2007). "A physics-based approach to modelling grassland fires," *International Journal of Wildland Fire*, 16 (1), 1-22.

Moody, J. A. and Martin, D. A. (2009). "Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States," *International Journal of Wildland Fire*, 18 (1), 96-115.

Morvan, D. (2011). "Physical phenomena and length scales governing the behaviour of wildfires: A case for physical modelling," *Fire Technology*, 47 (2), 437-460.

Moritz, M. A., Parisien, M. A., Batllori, E., Krawchuk, M. A., Van Dorn, J., Ganz, D. J., and Hayhoe, K. (2012). “Climate change and disruptions to global fire activity,” *Ecosphere*, 3 (6), 1-22.

NIFC (National Interagency Fire Center). (2025). “Wildland fire statistics and trends,” Retrieved from https://www.nifc.gov/fire-information/statistics/wildfires

Nocera, F., Tabandeh, A., Guidotti, R., Boakye, J., and Gardoni, P. (2019). “Physics-based fragility functions: Their mathematical formulation and use in the reliability and resilience analysis of transportation infrastructure,” In: Paolo Gardoni (Ed.) *Routledge Handbook of Sustainable and Resilient Infrastructure*, pp. 239-260, Routledge.

Pyne, S. J. (2017). *Fire in America: A cultural history of wildland and rural fire*. University of Washington Press.

Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., Bustic, V., Hawbaker, T. J., Martinuzzi, S., Syphard, A. D., and Stewart, S. I. (2018). “Rapid growth of the US wildland-urban interface raises wildfire risk,” *Proceedings of the National Academy of Sciences*, 115 (13), 3314-3319.

Reidmiller, D. R., Avery, C. W., Easterling, D. R., Kunkel, K. E., Lewis, K. L., Maycock, T. K., and Stewart, B. C. (2018). *Fourth National Climate Assessment: Volume II – Impacts, risks, and adaptation in the United States*. Washington, DC.

Reuters (2019, October 10). “In California, food spoils, businesses close as power outages imposed,” Retrieved from https://www.reuters.com/article/california-wildfire-pge/in-california-food-spoils-businesses-close-as-power-outages-imposed-idUSL2N26V1C1/

Rosenthal, A., Stover, E., and Haar, R. J. (2021). “Health and social impacts of California wildfires and the deficiencies in current recovery resources: An exploratory qualitative study of systems-level issues,” *PloS ONE*, 16 (3), e0248617.

Rothermel, R. C. (1972). *A mathematical model for predicting fire spread in wildland fuels*. Intermountain Forest & Range Experiment Station, Forest Service, U.S. Department of Agriculture.

Sharma, N., Tabandeh, A., and Gardoni, P. (2020). "Regional resilience analysis: A multiscale approach to optimize the resilience of interdependent infrastructure," *Computer-Aided Civil and Infrastructure Engineering*, 35(12), 1315-1330.

Steel, Z. L., Safford, H. D., and Viers, J. H. (2015). "The fire frequency-severity relationship and the legacy of fire suppression in California forests," *Ecosphere*, 6 (1), 1-23.

Stephens, S. L., Westerling, A. L., Hurteau, M. D., Peery, M. Z., Schultz, C. A., and Thompson, S. (2020). "Fire and climate change: conserving seasonally dry forests is still possible," *Frontiers in Ecology and the Environment*, 18 (6), 354-360.

Sullivan, A. L. (2009a). "Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models," *International Journal of Wildland Fire*, 18 (4), 349-368.

Sullivan, A. L. (2009b). "Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models," *International Journal of Wildland Fire*, 18 (4), 369-386.

Tabandeh, A., Sharma, N., and Gardoni, P. (2022). "Uncertainty propagation in risk and resilience analysis of hierarchical systems," *Reliability Engineering & System Safety*, 219, 108208.

Tabandeh, A., Sharma, N., and Gardoni, P. (2024). "Seismic risk and resilience analysis of networked industrial facilities," *Bulletin of Earthquake Engineering*, 22 (1), 255-276.

The Guardian (2025, February 1). "Los Angeles Palisades and Eaton fires contained," Retrieved from https://www.theguardian.com/us-news/2025/feb/01/los-angeles-palisades-eaton-fires-contained

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W. (2006). "Warming and earlier spring increase western US forest wildfire activity," *Science*, 313 (5789), 940-943.

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