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"Bending the Risk Curve: Protecting Californians from Wildfire Risk"

May 12, 2026

1:30 PM

1021 O Street, Room 2100

The Impact of Climate Change Catastrophes on Californians

1. Amy Bach, Executive Director, United Policyholders

Bending the Risk Curve

1. Nancy Watkins, Principal and Consulting Actuary, Milliman
2. Michael Wara, Ph.D., J.D., Senior Director for Policy, Sustainability Accelerator, Doerr School of Sustainability, Stanford University; Director, Climate and Energy Policy Program and Senior Research Scholar, Woods Institute for the Environment

Modeling for Fire Risk

1. Frank Frievalt, Director, Wildland-Urban Interface Fire Institute, California Polytechnic State University, San Luis Obispo
2. Michael Gollner, Ph.D., Associate Professor of Mechanical Engineering, University of California, Berkeley

Scaling Solutions

1. Dan Dunmoyer, President and Chief Executive Officer, California Building Industry Association

Concluding Thoughts and Departmental Perspective

1. Commissioner Ricardo Lara, California Department of Insurance

Enhancing California's Resiliency to Natural Catastrophes

In February 2026, the California Earthquake Authority issued its Senate Bill 254 Information and Recommendations Report in response to SB 254 (2025) authored by Senator Becker. The report was a part of Executive Order N-34-25 that requires the Office of Emergency Services (CalOES), the Department of Forestry and Fire Protection (CalFIRE), the Office of Energy Infrastructure Safety, the California Public Utilities Commission (CPUC), and the California Department of Insurance (CDI) to "provide options and recommendations to the Wildfire Fund Administrator for enactment of programs to reduce the risk of wildfires spreading and becoming high-severity catastrophes, including improved state and local catastrophic event response capability, home fire risk reduction standards, vegetation management practices, and communitywide wildfire hardening requirements."

This report found that California is underprepared for the growing frequency of dangers exacerbated by climate change. Additionally, the entities which help the State manage this growing risk, including insurance carriers, the California Fair Access to Insurance Requirements Plan (FAIR Plan), and the California Wildfire Fund have been stressed at a rapidly rising rate. As such, the report focuses on reducing risk before disasters happen, accelerating recovery after catastrophe, and spreading financial risk more equitably across stakeholders including utilities, customers, insurers, and the government.

History of California Wildfires and Management Efforts by the State

Wildfire catastrophes in California are growing in number and frequency. Recent fires include the Camp Fire in 2018 which destroyed 153,000 acres and led to 85 deaths, as well as the Eaton and Palisades Fires which destroyed 38,000 acres, over 16.000 structures, and killed 31 people according to CalFIRE. These fires are also occurring in more urban areas due to climate change and the expansion of residential developments that are not designed for the surrounding wildfire risks.

The CEA's report found that the State needed enhanced response to catastrophe after the 2017-2028 Wildfires that devasted Northern California. These fires caused billions of dollars in damage and subsequently had significant negative impacts on the insurance market in the form of surging exposure and claims. For Californians, these losses led to a contracting insurance market due to increased risk which in turn led to reduced insurance affordability and access. As risk has grown, so have insurance premiums and the unwillingness of many insurers to continue writing policies in high risk areas of the state.

In response to the 2017-2018 Wildfires, California passed SB 901 (Dodd, 2018) which established a commission to study catastrophic wildfire cost and recovery. However, the timing of this study and the subsequent bankruptcy filed by PG&E, made some of the findings incomplete. As a result, the Governor established an Energy Strike Team to address how to resolve this crisis and still promote clean energy. The Governor partnered with the Legislature to enact AB 1054 (Holden, Burke, and Mayes; Dodd and Hertzberg, 2019). This bill established the California Wildfire Fund to stabilize Investor Owned Utilities' (IOUs) credit ratings and invest in electrical grid enhancements, in addition to providing a reserve for IOU reimbursement after paying damages for fires they caused. Some of these damages were paid to insurers who had pursued legal action against the utilities for claims paid out to policyholders affected by such fires. Furthermore, the California Wildlife & Forest Resilience Task Force developed an action plan released in January 2021 that had four primary goals: increase mitigation, strengthen protection of communities, manage forests in balance with economic and environmental goals, and drive innovation and accountability.

In January 2025, the Palisades and Eaton Fires demonstrated the urgency of establishing broader community resiliency and enhanced coordination across all levels of government. Electrical utility credit rating agencies emphasized the need for state action to restore the Wildfire Fund's ability to help reimburse for damages since the Eaton Fire, as there was concern the Fund was at risk of being depleted.

The FAIR Plan, which serves as an insurer of last resort, rapidly expanded due to insurers declining to write policies in, and/or leaving high-risk areas. As of March 2026, the FAIR Plan's total exposure is $750 billion, with 684,388 policies. This amounts to a 242% increase in exposure and a 152% increase in policies since September of 2022. The Los Angeles Fires strained the FAIR Plan's reserves to the point where a $1 billion assessment of the admitted insurers who make up the Plan became necessary, under statute. In turn, those insurers were permitted to pass on half of the assessment amount to policyholders, known as recoupment.

While the Sustainable Insurance Strategy implemented by the Insurance Commissioner and CDI has begun to incentivize insurers to write more policies in the state, including in high-risk areas, in exchange for the ability to file for rate increases, factor in reinsurance costs, and make use of catastrophe models, there is still more work to be done to help manage risk and make insurance more affordable and available in the state.

Recommendations Moving Forward

According to the SB 254 report, California needs long-term, sustainable solutions to prepare adequately for future wildfires. One of the report's recommendations highlights the value of community hardening. In 2018 and 2019, the state legislature invested billions of dollars in community hardening. Through this initiative, California has developed capacity to manage wildfire behavior in certain landscapes, but the state is still less prepared to contain large-scale, structure-to-structure fires in wildland-urban interface communities. Effective hardening relies on better coordination between state and local governments, landowners, individual businesses, and homeowners to improve landscape conditions. Beginning in 2008, mandatory home-hardening standards were enacted for new construction due to promote resiliency. The SB 254 report emphasizes the need to adopt hardening retrofit standards for existing homes that can also be cost-effective to implement.

In 2025, the legislature passed two bills that were designed to improve hardening – AB 1143 (Bennett, 2025) and SB 616 (Rubio, 2025) – but both efforts were vetoed by the Governor. This year, Assemblymember Bennett has introduced AB 1934, which requires the State Fire Marshal's Wildfire Mitigation Advisory Committee to develop an implementation plan for a home hardening certification program.

Other states have also undertaken resiliency efforts. For example, in Alabama, programs to make homes more resilient against hurricanes have been highly successful, resulting in significant discounts from insurers and state grants to help cover upgrade costs. The Alabama Department of Insurance set a mandatory insurance discount for fortified homes and policies that encourage rebuilding to stronger fortified standards after disaster. Insurers must provide significant premium reductions based on the level and age of the fortification certification, and coastal homeowners can purchase an endorsement that requires damaged homes to be rebuilt to the fortified standards. Alabama also created the Strengthen Alabama Homes grant program which helps homeowners pay for reroofing upgrades using funds from insurance industry fees. The program has provided nearly $86 million to retrofit about 8,700 homes and also helped build a strong local network of trained contractors, evaluators, and inspectors. Studies have shown that these homes suffer less damage and have fewer claims.

Legislative efforts continue in California. As the Chair of the Insurance Committee, Senator Steve Padilla has authored SB 876 which would comprehensively reform the insurance claims process. It expands coverage for rebuilding, and broadens options for using additional living expenses benefits. Insurers must also provide updated rebuilding cost estimates and allow policyholders to combine coverages to rebuild. Finally, the bill requires insurers to maintain disaster response plans for the California Department of Insurance and increases penalties and restitution authority for unfair insurance practices. Other key bills include SB 877 and SB 878 authored by Senator Pérez which regulate insurance business practices. SB 877 expands the definition of claim-related documents to include all records related to loss amounts, covered damage, and repair costs, whether preliminary or final. SB 878 establishes strict timelines for insurers to pay claims following a total loss, requiring actual cash value payments within 30 days of the loss and undisputed replacement cost payments within 30 days after specified conditions are met. If insurers fail to meet these deadlines, interest accrues on overdue payments.

Approach in this Hearing

This hearing will be an opportunity to discuss and learn about keeping California residents safe from the scourge of wildfires, with a focus on the importance of bending the risk curve by mitigating fire risk, thus strengthening the insurance market and making insurance more available and affordable.

We will hear from the Insurance Commissioner to understand the nature of the risk facing Californians and the insurance industry. We will delve into the Commissioner’s perspective on how best to reduce risk in the state and by extension help stabilize the insurance market. Priority will be placed on how disaster risk affects California’s residents and insurance policyholders, and the urgent need to address these risks and protect the lives and homes of Californians.

The committee will also hear from academic and subject matter experts who have undertaken extensive research and work on the nature of wildfire risk, including actuarial and modeling perspectives, and ways in which this risk can be mitigated and scaled to the community level. By reducing risk, the potential for insurability, and the affordability thereof, can be increased. To provide applied perspectives about home and community defensibility, we will hear from home builders and those with experience in fire science and resiliency.

Ricardo Lara, California Insurance Commissioner

Raised in East Los Angeles by immigrant parents, Commissioner Ricardo Lara made history in 2018 by becoming the first openly gay person elected to statewide office in California's history. Commissioner Lara previously served in the California Legislature, representing Assembly District 50 from 2010 to 2012 and Senate District 33 from 2012 to 2018. Commissioner Lara earned a BA in Journalism and Spanish with a minor in Chicano Studies from San Diego State University.

During the COVID-19 pandemic, Ricardo has directed insurance companies to return health care and auto insurance premiums. His actions resulted in cost savings of over $1.75 billion for California drivers so far.

In response to the climate crisis, Ricardo continues to lead efforts to protect Californians from the impacts of climate change — including wildfires, floods and heatwaves — by pushing the insurance industry to be part of the solution, not part of the problem. Ricardo wrote the nation's first climate insurance law, SB 30, and following unprecedented wildfire disasters, he used his authority to protect more than 2 million policyholders from non-renewal when insurers tried to flee the marketplace. He created the nation's first Climate and Sustainability Branch within the Department of Insurance, and also sponsored legislation to allow wildfire survivors to better access their benefits.

Amy Bach, Co-Founder and Executive Director, United Policyholders

Amy Bach is an insurance consumer advocate and attorney and a leading voice for policyholders in California and across the nation. She co-founded United Policyholders (“UP”) in 1991 and serves as the organization's Executive Director, shaping and overseeing its Roadmap to Recovery™, Roadmap to Preparedness, and Advocacy and Action programs.

In response to California’s property insurance crisis, Bach launched and leads a Wildfire Risk Reduction and Asset Protection (“WRAP”) initiative, working group and online mitigation help resource center. Through this work, UP is helping increase home hardening and defensible space in communities across the state as a strategy for making homes more resilient and restoring a competitive marketplace where consumers will be able to find affordable, reliable protection for their assets. This work includes ongoing coordination with stakeholders including the California DOI, agents, realtors, CalFire, insurers and insurer trade associations, fire scientists, Fire Safe Councils, Firewise communities and mitigation professionals.

A nationally recognized expert on property insurance, regulation, law and public policy matters, Bach is an official Consumer Representative with the National Association of Insurance Commissioners, an appointed member of the Federal Advisory Committee on Insurance to the U.S. Treasury and a frequent speaker at meetings of the National Council of Insurance Legislators.

Nancy Watkins, Principal and Property & Casualty Consulting Actuary, Milliman

Nancy Watkins is a principal and consulting actuary with Milliman in San Francisco. At the forefront of innovation in catastrophic risk, Nancy consults for insurers, regulators, trade groups, and community/government entities. Her recent engagements include supporting the CDI for the implementation of its Sustainable Insurance Strategy, developing a methodology to create wildfire mitigation credits for ratemaking for the Casualty Actuarial Society, research for a WUI Data Commons on behalf of IBHS and CalChiefs, and a study exploring ways to rebuild the Town of Paradise to promote climate resilience.

Widely known as a thought leader in property insurance availability and affordability, Nancy leads the global Milliman Climate Resilience Initiative. She served on the California Office of the State Fire Marshal Risk Modeling Advisory Workgroup and was appointed by the U.S. Treasury Financial Stability Oversight Council as a member of its Climate-related Financial Risk Advisory Committee. She is frequently asked to testify as an expert by state and federal legislators, regulators, and other policymakers trying to address insurance and climate risk issues.

Michael Wara, Director of the Climate and Energy Policy Program, Stanford University Woods Institute for the Environment

Michael Wara, JD, PhD, Directs the Climate and Energy Policy Program at the Stanford Doerr School of Sustainability. His team conducts multidisciplinary, policy relevant research on issues related to wildfire, insurance, electric utilities, the energy transition, and food systems. He has played a role in the development of utility wildfire liability frameworks, prescribed fire policy, cap-and-invest, a western regional electricity market, and the low carbon fuel standard. Wara is also the Senior Director for Policy at the Stanford Sustainability Accelerator, where he leads efforts to translate Stanford research into sustainability policy impact at scale.

Frank Frievalt, Director, Wildland-Urban Interface FIRE Institute

Chief Frievalt (ret.) has served since 1979 with Special District, City, County, State, and Federal fire agencies in roles from Firefighter to Fire Chief. He holds a M.S. from Oklahoma State University in Fire and Emergency Management Administration, and currently serves as Director of the Wildland-Urban Interface Fire Institute at Cal Poly, San Luis Obispo. Frank is an SME for the Gordon and Betty Moore Foundation Wildfire Advisory Council, and previously served as a Senior Policy Advisor to the Western Fire Chiefs Association, with an emphasis on the development of resilient Wildland Urban Interface (WUI) communities. His work is grounded in aligning key stakeholders around a core set of parcel and community level mitigations that will disrupt the fire pathways which lead to conflagration. He is pursuing the actuarial valuation of risk mitigations, for both the public and private sectors, because we share the same desired outcome, minimizing property loss to the peril of wildfire.

Director, Wildland-Urban Interface FIRE Institute: April 2023 - Present Provide overall visionary leadership and strategic management for the direction, coordination, and oversight of the new WUI FIRE Institute. Responsible for building a dynamic, results-oriented Institute that crosses industry and academic borders in California and beyond. Responsible for administering the Institute’s research, outreach and educational missions and will serve as the primary external face of the Institute.

Michael Gollner, Fire Science Researcher and Professor, UC Berkeley

Dr. Michael Gollner is an Associate Professor, Deb Faculty Fellow and Vice Chair for Graduate Studies in the Department of Mechanical Engineering at the University of California, Berkeley where he leads the Berkely Fire Research Lab. He received his Ph.D. in Mechanical Engineering from the University of California, San Diego and was previously an Associate Professor of Fire Protection Engineering at the University of Maryland, College Park, MD from 2012-2019. Dr. Gollner studies how fires ignite and spread within the wildland-urban interface (WUI), the physics and dynamics of wildland fire spread, the processes by which structures ignite from embers, and emissions and associated health effects from wildfire smoke. Dr. Gollner has authored over one hundred peer-reviewed publications in leading international journals and over a hundred other presentations, articles, and reports related to these topics.

Dr. Gollner is currently a principal member of the NFPA Wildland and Rural Fire Protection and Spaceports committees and has testified to the US House of Representatives on wildfire policy. He serves as Associate Editor for the journals *Fire Technology* and *Proceedings of the Combustion Institute* and has served on the boards of the International Association of Wildland Fire, the International Association of Fire Safety Science, and served as past Chair of the Research Advisory Board of the NFPA Fire Protection Research Foundation. He has served on committees and as an advisor to the California Department of Insurance, US Forest Service, CAL FIRE, and the GAO. He has been awarded the NSF CAREER award, Tsuji Early Career Award by the Combustion Institute, Proulx Early Career Award from the IAFSS, IAWF Early Career Award in Fire Science, and the Fire Protection Research Foundation Medal.

Dan Dunmoyer, President and CEO, California Building Industry Association

Dan Dunmoyer serves as the President and CEO of the California Building Industry Association. A proven and dedicated leader, Dunmoyer brings a wealth of experience in both the public and private sector. As the President and CEO of CBIA, Dunmoyer oversees and manages all aspects of the association. A respected and recognized leader, he is strongly committed to ensuring that the organization continues to be the leading voice of housing in California and efforts to ensure the American Dream of homeownership is attainable for all Californians. The son of a small home builder from Southern California and a veteran of California public policy issues, Dunmoyer has been closely involved in California's unique political culture for years.

MILLIMAN REPORT

State of Insurance for Wildfires

Issue Brief on behalf of Alliance for Wildfire Resilience

August 2025

Authors
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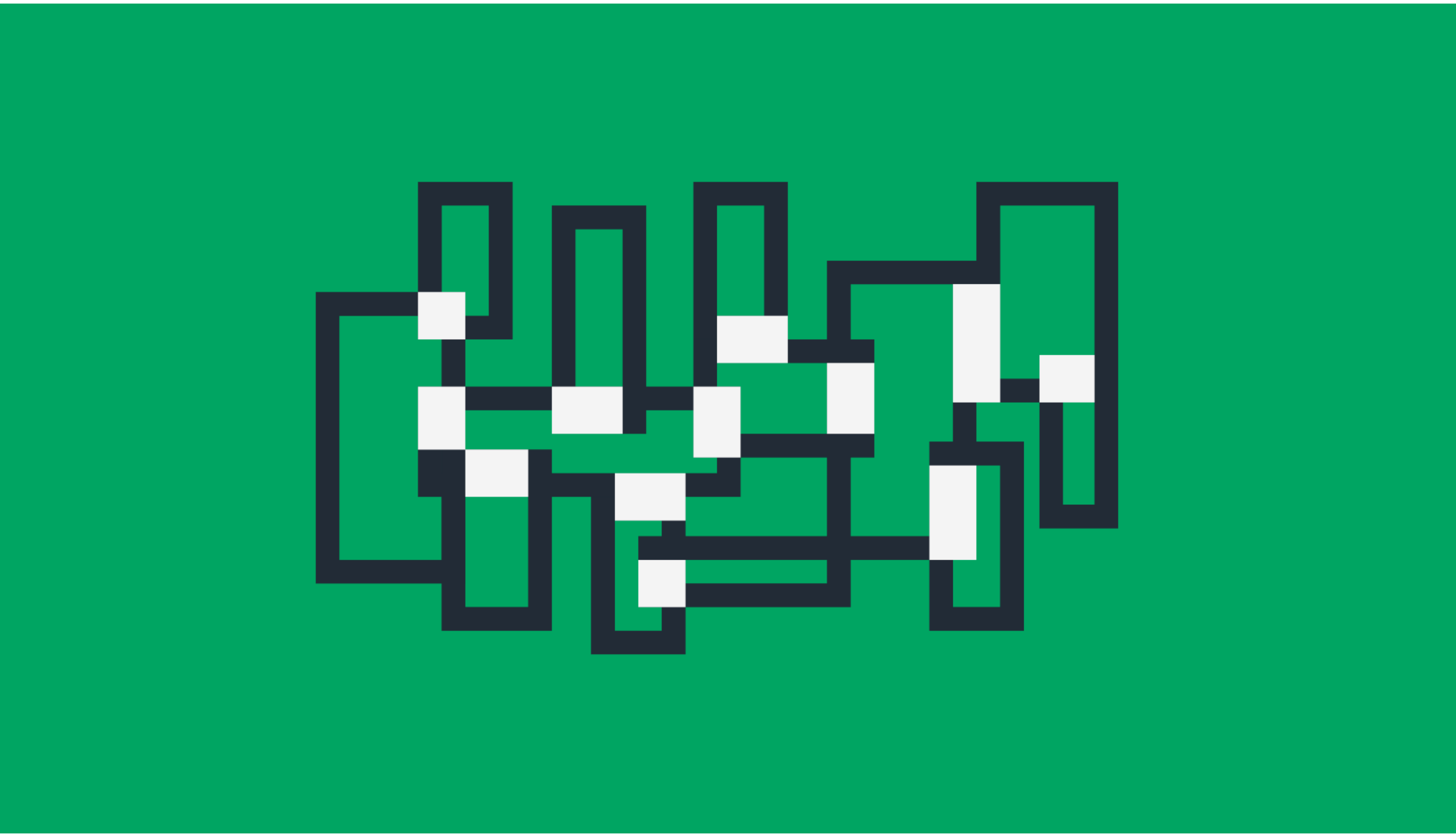

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Purpose of Report

In many areas of the U.S., communities are facing unprecedented challenges associated with wildfires, principally urban conflagrations, which have become more frequent and destructive over the past decade. Escalating wildfire risk has destabilized insurance markets, leading to cascading economic effects such as delayed real estate transactions, stalled new construction, and property value decreases.

Many legislators and regulators are hearing from constituents who have experienced unplanned premium increases or the inability to secure coverage. Policymakers are striving to understand how wildfire affects homeowners' access to insurance and what interventions may work to address the problems.

Alliance for Wildfire Resilience ("AWR") was formed with the goal of reducing the long-term consequences of wildfires in the United States by fostering partnerships to achieve meaningful and lasting changes in wildfire policy. AWR engaged Milliman, Inc. ("Milliman"), an independent actuarial consulting firm, to prepare this issue brief as an educational resource designed to be used by federal policymakers.

The purpose of this brief is to summarize at a high level the issues faced by U.S. homeowners in wildfire-exposed areas and the current challenges in managing wildfire risk today. It explains how wildfire risk is affecting the sustainability of the property insurance market that serves as a critical financial safety net for individuals, businesses, and communities. This brief also offers insights on ways federal policymakers can help effect meaningful change in order to reduce risk and restore sustainable insurance in wildfire-exposed areas, with benefits to economic resilience and stability.

Throughout the brief we have included references to more detailed documents that might be useful in gaining a deeper understanding of the concepts discussed. Milliman and AWR are available to answer any questions about this brief.

1 How is Wildfire Risk Impacting Homeowners and Communities?

1.1 URBAN CONFLAGRATION RISK IS INCREASING

While "wildfire" is commonly used to describe all types of fires occurring in wholly or partially natural areas, it is crucial to distinguish fires occurring in vegetative landscapes from urban conflagrations. These fires may start as wildfires burning in vegetation but, as the fires enter urban or suburban communities and spread uncontrollably from structure to structure, they are more accurately known as urban conflagrations. Although traditional wildfires remain a significant threat to ecosystems and infrastructure, the modern wildfire crisis is increasingly driven by urban conflagrations resulting in widespread structural loss.

Urban conflagrations have become larger, more frequent, and more severe, primarily due to a combination of factors:

- *Changing atmospheric conditions*. Warming temperature trends, persistent droughts and changes in precipitation patterns have created environments where fuels dry more quickly and remain combustible for longer periods throughout the year.[1] As a result, fire seasons have lengthened by an average of 84 days since the 1970s across the Western United States.[2]
- *Historic fire suppression.* Past land use and decades of wildfire suppression have led to changes in vegetation that have increased the potential for extensive areas of high-intensity wildfires.[3] This "fire deficit" has disrupted natural ecological processes that historically limited fuel loads through regular, low-intensity burns and has promoted the growth of invasive fire-intolerant plant species.[4] The combination of these factors has created conditions where fires burn hotter, spread faster, and threaten more communities with unprecedented intensity.
- *Increased construction of vulnerable structures in fire-prone areas.* Countrywide, the number of housing units in areas designated as Wildland Urban Interface ("WUI") increased 25% (35.8 million to 44.7 million) from 2000 to 2020.[5] The top five states in terms of percentage increase in number of homes over that time period were Nevada (98%), Utah (59%), Arizona (54%), Florida (52%), and Texas (52%); California had an increase of 22%. Much of this development occurs with vulnerable construction within and adjacent to fire-prone wildlands and with little preparation for fire.[6] The expansion of the built environment into fire-prone areas has not only increased exposure to wildfire but also increased the probability of human-driven ignitions within areas already prone to fire.[7]

> More than half of the communities with the greatest potential for catastrophic urban wildfire events are not in the West: Florida, Texas, Oklahoma, and Alabama are among the top 10 states when ranked by communities with high urban wildfire risk factors.

Although California has experienced recent notable destruction, wildfire is reaching into more communities and impacting more people. A recent Headwaters Economics analysis shows that more than 1,100 communities in 32 states across the U.S. share similarities with communities recently devastated by urban wildfires. More than half of the communities with the greatest potential for catastrophic urban wildfire events are not in the West: Florida, Texas, Oklahoma, and Alabama are among the top 10 states when ranked by communities with high urban wildfire risk factors.[8]

The occurrence of "fast fires" has also become more prevalent and is predicted to increase in the future. Many of the most deadly and destructive fires share the common characteristic of extremely rapid growth under extreme weather conditions when it is hot, dry and windy. Based on a study of more than 60,000 fires from 2001 to 2020, these "fast fires" represented 2.7% of all events but accounted for 89% of the structures damaged or destroyed. Among the top 20 fastest growing fires, only two originated primarily as forest fires, with 16 in grassland and two in closed shrubland. Five of the top 20 fastest fires were in California, with the other 15 distributed across Oklahoma, Kansas, Oregon, Washington, Texas, Idaho, Nevada and Utah.[9]

1.2 CASCADING IMPACTS ON BROADER ECONOMY

The risks associated with wildfire and other catastrophes are owned by residents and communities, but the financial uncertainty of these risks can be transferred in exchange for an insurance premium with a more certain cost if there is a well-functioning insurance market. However, rising risk can disrupt the insurance market and have cascading impacts on home ownership, wealth, tax bases and investment.

1.2.1 Housing Market

Housing markets in wildfire-prone regions have begun to show signs of price adjustments associated with the rising risk. A study published in *Landscape and Urban Planning* found that major wildfires caused a 2.2% drop in home values in nearby neighborhoods that were not burned.[10]

Homeowners need to obtain insurance to secure most mortgages, and insurance issues can impact both sales of existing homes and new construction. According to a report from the California Association of Realtors, 13% of realtors in California had a sales transaction canceled in 2024 because insurance was unavailable or unaffordable, almost double the 6.9% reported a year earlier.[11] According to the California Building Industry Association, construction in less developed areas has been slowed because homebuilders cannot figure out how to insure new developments at a price that customers can afford, and multi-family condominium projects have been particularly affected.[12]

According to a report from the California Association of Realtors, 13% of realtors in California had a sales transaction canceled in 2024 because insurance was unavailable or unaffordable, almost double the 6.9% reported a year earlier.

1.2.2 Mortgage Lending

Increasing wildfire risk and disruptions in the insurance market may be affecting the mortgage industry. A study by the Federal Reserve Bank of Philadelphia found increases in mortgage delinquencies among households impacted by fires.[13] Another paper by the Federal Reserve Bank of Dallas found that rising insurance premiums are associated with increased probabilities of default and prepayment within 12 months after premiums change.[14] Drops in home values can increase the risk of mortgage defaults, as experienced in the 2008 mortgage crisis.

1.2.3 Municipal Bonds

As rising risk leads rating agencies and other financial institutions to incorporate climate and catastrophe risk metrics into their underwriting models, the cost of issuing debt to municipalities and public entities in high-risk areas will increase.

As rising risk leads rating agencies and other financial institutions to incorporate climate and catastrophe risk metrics into their underwriting models, the cost of issuing debt to municipalities and public entities in high-risk areas will increase. Research published in the *Journal of Financial Economics* documented that counties with high exposure to climate risks are paying more in underwriting fees and initial yields to issue long-term municipal bonds compared to counties with low exposure, reflecting investors' growing concerns about climate-related fiscal challenges.[15] This increase in the cost of borrowing then flows through the government's finances, ultimately being borne by the taxpayers of that jurisdiction.

Municipal bonds fund 70% of U.S. infrastructure, and higher borrowing costs would make it more difficult for wildfire-exposed communities to improve aging infrastructure and rebuild following disasters. Notably, S&P Global Ratings recently downgraded the credit rating of the Los Angeles water and power utility, citing “the increasing frequency and severity” of wildfires and signaling a potential watershed moment for a market that has ignored climate change and the risk of a disaster wiping out a city's property tax base and forcing a bond default.[16]

1.3 IMPACTS ON INSURANCE SUSTAINABILITY

A sustainable insurance market rests on three pillars: availability, affordability, and reliability:

- Availability signifies that there are enough private insurers willing to offer insurance in a market so that customers can readily obtain the coverage they need.
- Affordability signifies that policyholders are willing and able to pay the premiums charged in order to transfer their risk.
- Reliability signifies that insurers are confident in the market and their ability to remain solvent and pay claims associated with the risks they have insured, given the environment in which they operate.

Escalating wildfire risk is causing cracks in all three of these pillars, disrupting the insurance market and potentially resulting in a lack of available and affordable insurance options that consumers can rely on.

1.3.1 **Availability**

The primary factors that can restrict availability in the private insurance market are 1) inability to measure risk, 2) inability to manage overall risk and 3) inability to match the price to the risk and earn a reasonable return.

1.3.1.1 MEASURING RISK

Sometimes the inherent risk perceived in a market can increase rapidly, leading to short-term market shocks. Catastrophic events are a common catalyst for such changes in risk assessment, potentially triggering a widespread repricing of the risk due to the realization that the hazard was much higher than previously believed. For many years, the most destructive U.S. wildfire on record was the 1991 Oakland Hills fire; it was possible to consider that catastrophe as an anomaly and unlikely to occur again. However, the 2017 and 2018 wildfire seasons caused a fundamental reassessment of wildfire risk by many insurance professionals and fire management experts.

Insurers and reinsurers have become increasingly reliant on sophisticated catastrophe (“CAT”) models to help measure catastrophe risk. Without such tools, wildfire coverage would likely be unavailable across broad geographic regions as insurers would lack a sufficient basis for risk management and pricing. In general, although they are currently the best available tools for the purpose, CAT models for wildfire are less mature than models for other perils, such as earthquakes and hurricane.[17] Due to this factor and the relatively small number of events with which to validate models, insurers and reinsurers may be less confident about wildfire model predictions and more conservative with capacity allocation, underwriting, and pricing for wildfire risk.

1.3.1.2 MANAGING RISK

Moreover, wildfires now result in additional exposure beyond direct fire damage, including widespread smoke damage affecting properties far from actual flames, higher additional living expense costs due to prolonged evacuations, labor shortages that cause longer rebuilding timelines, and post-wildfire mudflow and debris flow risks, which can cause significant secondary losses in burn scar areas. These changes have rapidly transformed wildfire from a secondary peril, historically considered manageable through geographic diversification, to a primary catastrophe risk that can threaten insurer solvency.

Insurers need to manage their overall exposure to catastrophic events to stay solvent and ensure the ability to pay claims. Insurance generally relies on the “pooling principle”, which is the idea that a portfolio of many policies is less risky than a single policy due to the independence of individual risks. In areas threatened by natural catastrophes, individual risks are far less independent and insurers are at greater risk of simultaneous losses affecting a large percentage of their policies. Thus, insurers typically limit their concentration in certain areas and seek additional protection through reinsurance and/or other risk transfer options such as catastrophe bonds.[18] When risk increases, insurers may need to reduce their exposure (through non-renewals, limits on new business or market withdrawals) and/or purchase additional reinsurance to maintain their financial strength. Financial strength is important to avoid ratings downgrades, which could potentially impact consumers if their homeowners insurance is not deemed sufficiently reliable to meet the requirements of mortgage lenders.

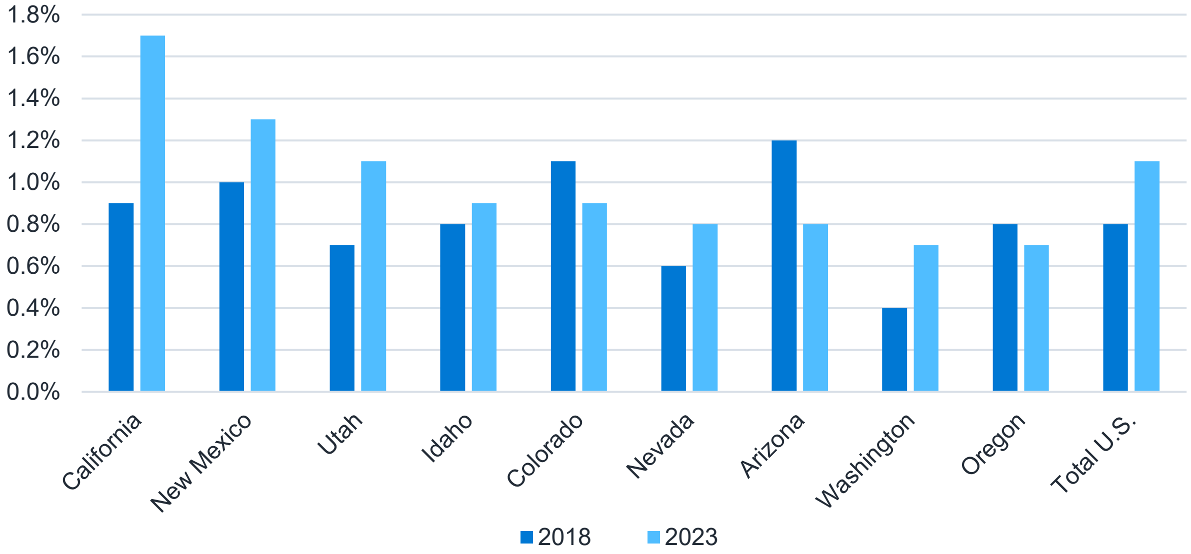
1.3.1.3 PRICING RISK

Availability also depends on insurers’ ability to charge a price corresponding to the risk. Homeowners insurance pricing is regulated at the state level, with each state operating independently and resulting in a wide range of regulatory practices across the country. Especially in a rising risk situation, the target of state regulators and consumer advocacy groups is often to delay or suppress premium increases, rather than to address the underlying risks faced by residents that underlie those increases. Insurers in many states with high wildfire risk have faced significant hurdles when attempting to secure actuarially sound rates that reflect current risk levels.

Over a prolonged period, inadequate rates eventually erode insurer surplus, increasing the risk of insolvencies. If insurers are not able to charge a price that earns a reasonable profit for some segments of the market, they may restrict or withdraw availability in those segments.

California historically has promoted some of the most restrictive regulatory constraints, including a prohibition on incorporating wildfire catastrophe models and reinsurance costs in the calculated rate need, and rate hearings that delay rate approval and often result in rates that are much lower than requested.[19] The lengthy and uncertain approval process for rate filings can create a mismatch between risk exposure and premium. Given these constraints, insurers may determine that a more viable strategy is to reduce their risk by retreating or receding from the market rather than pursue full rate indications. The chart below shows how California experienced a much steeper increase in non-renewal rates since 2018 versus several Western states and the U.S. average:

FIGURE 1: HOMEOWNERS INSURANCE NONRENEWAL RATES BY STATE AND TOTAL US: 2018 VS. 2023



Sources: U.S. Senate Budget Committee Staff Report for December 2024. Total U.S. average calculated as exposure-weighted average, using earned house-years by state from National Association of Insurance Commissioners (NAIC) homeowners reports for years 2017 and 2022.

1.3.1.4 NON-ADMITTED INSURANCE

Historically, most property owners obtain insurance coverage through the “admitted” market. For homeowners unable to obtain coverage through the admitted market, the next option is often to seek coverage from “non-admitted” insurers. Non-admitted insurers operate outside state regulatory authority, giving them more flexibility in rates and policy provisions. The non-admitted market grew by double digits for six consecutive years through 2023 due to increasing demand from catastrophe-exposed properties and complex liability risks who could not find coverage in the admitted market.[20] In California, non-admitted insurers wrote 4% of the homeowners insurance premiums in 2023, compared to 0.4% a decade earlier in 2013.[21] Non-admitted insurance is useful to cover unique or high-risk situations and can help to fill the coverage gap created when admitted market availability recedes. However, it offers fewer customer safeguards such as state guaranty fund protection, leaving consumers more vulnerable if the insurer goes insolvent.

1.3.1.5 RESIDUAL MARKETS

When consumers are unable to find coverage in the admitted or non-admitted private markets, many states have established entities to offer insurance directly as a last resort; this is referred to as the “residual market”. For property insurance, these often take form as Fair Access to Insurance Requirements (“FAIR”) plans, which are state-mandated entities formed and administered by private insurers. A less common type of residual market entity is a “public option”, where the state legislature creates a free-standing insurance entity operating under substantial governmental oversight and control, such as the California Earthquake Authority and Florida Citizens Property Insurance Corporation.[22] Residual markets typically offer less flexibility in coverage options and often require subsidization in the form of contingent funding from taxpayers, from policyholders of private insurers, or both.

Residual markets typically offer less flexibility in coverage options and often require subsidization in the form of contingent funding from taxpayers, from policyholders of private insurers, or both.

One response to insurance availability problems in the West has been the expansion of residual market coverage. As directed by the California insurance commissioner, the state's FAIR Plan has significantly increased commercial property coverage limits in 2025.[23] Following years of market contraction in high-risk areas, Colorado recently formed a new FAIR plan, which was signed into law in May 2023.[24] Additional states, including Nevada, Utah, Idaho, Montana, and South Dakota are also exploring new FAIR plans.[25]

According to A.M. Best, policy counts in property residual markets have nearly doubled from 2018 to 2023. The California FAIR plan policy count grew by 276% from 2018 through 2024, with a 15-fold increase in premiums over the same period.[26]

FAIR plans and other residual market solutions are necessary to provide availability when insurance is not readily or consistently available in the private market. However, using residual markets to address affordability concerns is misdirected; a residual market with rates that are inadequate will likely experience disproportionate growth, increased likelihood and size of deficits and assessments, and ultimately will not be financially self-sustaining.[27]

1.3.2 Affordability

Within the context of a sustainable insurance market, affordability refers to whether customers are generally willing and able to buy insurance at the price offered. That said, it is important to note that private insurers are precluded from establishing rates based on their policyholders' ability or willingness to pay, although governmental programs could theoretically contain subsidies based on means testing or some other determination. Actuarial ratemaking standards and state regulations direct actuaries to base rates on the expected value of all future costs associated with an individual risk transfer.

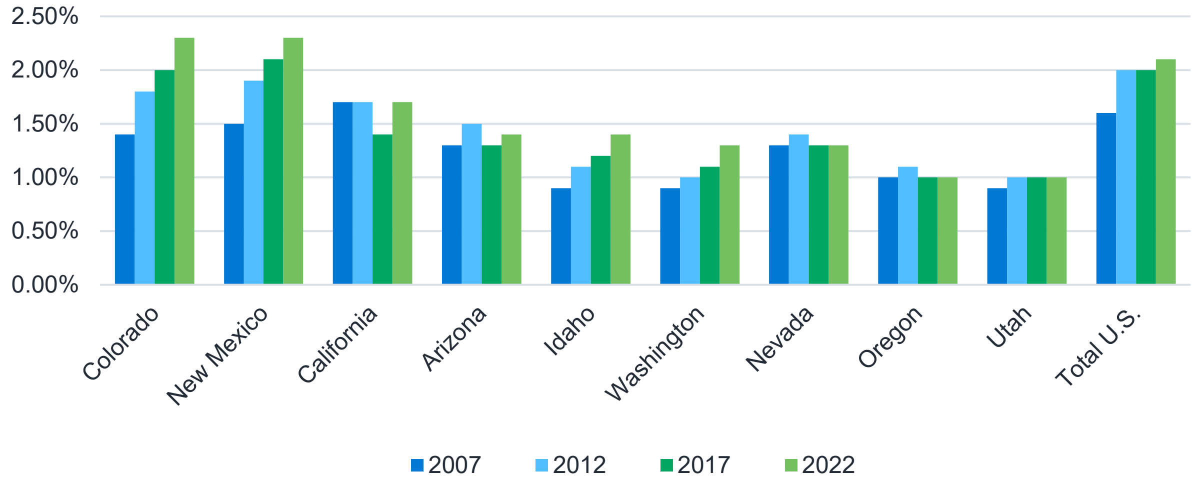
Affordability challenges can arise from unplanned increases in the price of the insurance, as we have seen in areas where wildfire risk is rapidly increasing. Beyond wildfire risk there have been other factors, such as the rising costs of building materials and labor, simultaneously driving up insurance premiums and exacerbating the struggle to maintain affordability.

As consumers face increasing financial strain, it can be tempting for regulators and legislators to focus on delaying or suppressing insurance premium increases. However, while affordability is desirable, efforts to keep prices artificially low can result in unintended consequences. For example, prior to December 2024, California rate regulations specified that a minimum 20-year average of historical catastrophe losses must be used to calculate catastrophe provisions in homeowners rates. However, this methodology resulted in catastrophe rate indications that failed to respond to rising risk until the extreme wildfire events in 2017 and 2018 led to drastic increases within a short timeframe.[28]

Increased competition generally helps affordability, since a greater variety of options for consumers to choose from make it more likely for them to find a lower price point. As previously noted, the inability to match price to risk can potentially lead insurers to limit writings and, in some cases, withdraw entirely from markets. In high-risk areas this can create a cascading effect where each insurer's retreat reduces competition and further hurts affordability.

The chart below shows one useful metric for affordability, the statewide average homeowners premium as a percentage of the median household income for several Western states and the U.S. average:

FIGURE 2: HOMEOWNERS AVERAGE PREMIUM AS A PERCENT OF MEDIAN INCOME: 2007 - 2022



Sources: Data for 2007-2021 from Insurance Information Institute archive of NAIC reports. Data for 2022 from NAIC. Median Household Income by State from US Census Bureau, Historical Income Tables: Households, Table H-8.

In 2022, the average cost for homeowners insurance ranged from 1.0% to 2.3% of median household income for Western states, versus 2.1% for the U.S. in total. However, these statewide averages do not represent the full picture, particularly the experience in high-risk areas.

Affordability issues can financially stress households and cause them to underinsure (by buying policies with high deductibles, insufficient limits, or inadequate coverage provisions), or, in the worst cases, fail to secure coverage at all*.* While underinsuring or reducing coverage can improve affordability, it leaves homeowners more financially vulnerable to displacement in the event the property is damaged or destroyed. After a disaster, widespread underinsurance can have follow-on impacts to the tax base of entire communities if properties are abandoned, rebuilding is delayed, and homelessness increases.

Regulatory frameworks have struggled to address underinsurance, as most states lack systematic data collection on coverage adequacy, the extent of underinsurance, or the relationship between premium affordability and coverage decisions. The NAIC has taken steps to develop a standardized data call to help fill these knowledge gaps, reduce inconsistencies across states and better address compliance costs and confidentiality concerns.

> Affordability issues can financially stress households and cause them to underinsure (by buying policies with high deductibles, insufficient limits, or inadequate coverage provisions), or, in the worst cases, fail to secure coverage at all.

1.3.3 Reliability

Reliability refers to a long-term expectation that an insurance market will function properly, both in terms of insurers being able to operate within a stable and predictable system and policyholders being able to count on insurers meeting their commitments.

Aspects of regulation, legislation, and/or the legal environment deemed materially adverse by insurers can cast doubt on the market and cause reliability challenges. For example, if courts deviate from longstanding precedents regarding coverage interpretations or award amounts, or if the system precludes insurers from effectively addressing pervasive fraud, then this can contribute to an environment of uncertainty and unreliability. Another aspect of unreliability includes conditions contributing to widespread insurer insolvency and/or residual market expansion that may transfer additional risk to admitted insurers, their policyholders, and taxpayers in the state.

A company near or in insolvency may close, enter conservatorship, and have remaining funds paid to creditors and claimants. Once the insurer's capital is exhausted, state guaranty funds may serve as backstops for the affected policyholders; however, guaranty funds can trigger assessments that increase costs for other insurers in the market and their policyholders. Often, the policyholders of insolvent insurers may end up insured in the residual market. For example, when more than 20 companies folded or left Louisiana after a series of hurricanes in 2020-2021, more than 100,000 policies were added to Louisiana Citizens Property Insurance, the state-run insurance market of last resort.[29]

Assessments that are recoupable from taxpayers and non-residual market policyholders in the state may have a negative and unplanned effect on insurance affordability.

Expanding residual markets with high concentrations of risk may create a "death spiral" effect, where increasing assessments drive further market exits, impacting availability and concentrating more risk in the residual market.

Growth in residual markets can also affect the financial health of insurers, which in turn harms the financial stability of homeowners, communities, and local economies. Residual plans generally have some provision that member insurance companies provide funds to cover deficits in the event that losses exceed the plan's surplus and reinsurance recoveries. In some states, portions of the deficits are funded by taxpayers and/or partially recoupable by insurers via premium surcharges to policyholders. However, a recent study found that only 12 of 36 state plans had explicit provisions that prevent insurers from solely bearing the burden of funding deficiencies. As long as the plans are relatively small, this may not present an issue, but uncertainty around assessment and recoupment becomes more significant for residual market plans whose size could represent material risks to member insurers.[30] Further, assessments that are recoupable from taxpayers and non-residual market policyholders in the state may have a negative and unplanned effect on insurance affordability for those households.

Growth in residual market exposure increases the risk of assessments. Expanding residual markets with high concentrations of risk may create a "death spiral" effect, where increasing assessments drive further market exits, impacting availability and concentrating more risk in the residual market.[31]

1.4 INSURANCE MARKET DISRUPTION IS THE SYMPTOM, NOT THE PROBLEM

Currently, insurance capacity is an issue in many wildfire-exposed areas of the U.S., leading some people to believe that federally backed insurance is needed to fill the gap. However, if the federal government steps in and provides a substitute for private insurance without regard to the underlying drivers, that action may make the problem worse.

Federal insurance programs are subject to significant political interference and uncertainty from administration to administration. Additionally, they establish a status quo that is often unresponsive to evolving situations, and can discourage private insurers from expanding in high-risk areas if government sets rates to be artificially low instead of being truly reflective of risk. That does not necessarily make for the best outcomes to serve at-risk communities. Although there can be a role for government to provide premium subsidies, this never actually reduces costs; it just creates a mechanism where the costs are shifted from some people/places/times to others.

Although there can be a role for government to provide premium subsidies, this never actually reduces costs; it just creates a mechanism where the costs are shifted from some people/places/times to others.

Public discourse and regulatory responses around the wildfire crisis have often mischaracterized insurance as the problem rather than recognizing it as a symptom of a larger problem – too much risk for the market to bear. Risk-based insurance premiums communicate the relative safety of an area and drive behavior. If homeowners cannot get affordable insurance, they may act to mitigate their risk, or they may decide that it is too risky to live there.

When insurance becomes widely unavailable, unaffordable, or both, a necessary part of any effective solution is to reduce the risk.

Policy actions that are intended to change insurer behavior without reducing risk can actually force the underlying pillars out of balance and accelerate the collapse of the insurance market. They may also have the unintended outcomes of delaying recognition of the risk, disincentivizing early intervention, putting more families in harm's way and ultimately increasing costs. Therefore, when insurance becomes widely unavailable, unaffordable or both, a necessary part of any effective solution is to reduce the risk.

2 Challenges and Suggestions for Wildfire Risk Reduction

This section explores some of the challenges involved in reducing wildfire risk and suggests ways federal policymakers can play an effective role.

2.1 EFFECTIVE MITIGATION MUST BE MULTILAYERED

According to the Insurance Institute for Business & Home Safety ("IBHS"), there are four elements that all conflagrations share:[32]

- Typically preceded by or occur during drought conditions.
- Include densely packed structures with combustible exterior and framing materials.
- Weather conditions with winds of at least 20–30 mph.
- Fuels (such as ornamental vegetation, wooden privacy fences and sheds) that connect the dense structures together, providing a pathway of fire.

> To slow fire spread, neighborhoods must function as fuel breaks rather than fuel sources.

IBHS notes that the combination of an active wildfire and a built environment conflagration can be too dangerous for direct fire suppression tactics, especially in situations where weather conditions are so extreme that aerial fire suppression resources cannot be used in coordination with ground resources. To slow fire spread, neighborhoods must function as fuel breaks rather than fuel sources. Neighborhoods must resist ember attacks as wildfire approaches as well as break the chain of fire spread through flame contact and radiant heat.

Consistent with this research and the previously mentioned "fast fires" study, a recent report on preventing urban conflagration recommends focusing on time as the common denominator of the problem of urban disaster fires in order to craft effective risk mitigation strategies. Community ignition time can be altered through home hardening and defensible space, especially at likely fire entry points. Additionally, fire arrival into the community can be delayed through strategic vegetation management.[33]

Utility-caused ignitions have driven many of the recent destructive wildfire events and tend to occur in proximity to populated areas, creating immediate threats to communities and minimal warning time. Accordingly, utility hardening and safety is another important component of reducing exposure to conflagration, but regulatory oversight of utility mitigation varies dramatically by state.[34] California and Oregon have mandated a framework for utilities companies to develop Wildfire Mitigation Plans (WMPs) and implement comprehensive utility wildfire safety programs, including Public Safety Power Shutoffs (PSPS) during extreme fire weather. Additionally, some utilities operating in other states have created analogous WMPs and PSPS plans and made them publicly available even where they are not required by law or regulation to do so. However, many utilities in the Southeast, Gulf Coast, and Upper Midwest lack even a public plan describing their implementation of wildfire mitigation or safety shutoffs. States with minimal or no specific regulatory requirements addressing utility wildfire mitigation may be underprepared for their wildfire exposure.[35]

POSSIBLE SOLUTIONS:

Improve land use planning: The federal government could create incentives to encourage local governments to improve land use planning to reduce wildfire risk.[36] Federal support for improved land use planning and defensible space requirements would help local governments develop and implement more effective wildfire risk reduction ordinances.

Provide assistance for strategic vegetation management: Additional funding focused on strategic fuel management around WUI communities would complement existing forest management efforts. By focusing specifically on this interface, such a program would create more effective buffers around vulnerable communities, such as wetlands, urban greening, or other forest strategies to limit fire spread or change fire behavior.[37]

Increase adoption of utility wildfire mitigation plans: The federal government could also develop standards for electricity utility wildland fire mitigation plans and encourage the adoption of those plans by all electric utilities.[38]

2.2 NEED FOR STAKEHOLDER COLLABORATION AND COORDINATION

Effective wildfire risk management involves collaboration among numerous public entities at various levels (federal, state, and local) and with diverse expertise (forestry, land use planning, fire service, building codes, etc.) as well as private entities like utility companies. These agencies/entities have traditionally operated independently, creating coordination challenges that impede effective risk management. Meaningful risk reduction will require new partnerships taking collective, coordinated actions.

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In densely built areas, mitigated parcels may continue to be exposed to significant risk due to conditions present on surrounding parcels, meaning that collective action at a neighborhood or community scale is required to be truly effective.

Wildfire is different than other perils because the home propagates the risk itself; therefore, interruption of that propagation requires home mitigation. In densely built areas, mitigated parcels may continue to be exposed to significant risk due to conditions present on surrounding parcels, meaning that collective action at a neighborhood or community scale is required to be truly effective. However, the benefits and costs of mitigation are not always distributed equally across a community.[39]

The possibilities and challenges are different for new versus existing construction. New developments can be planned using fire-resistant construction techniques and with parcel layouts and defensible space requirements reducing connective fuels between structures. Existing communities will require retroactive mitigation, which is much more expensive and difficult.

Influencing individual risk management decisions represents more than just an information deficit problem. A number of barriers must be addressed in order to increase consumer acceptance and uptake of necessary actions:

- *Limited time and resources:* Implementation of recommended actions is limited by competing financial priorities, with many consumers facing cost constraints and time limitations as barriers. It is often difficult to know which actions are most critical. Effective wildfire risk reduction requires prioritized support and resources to assist the most vulnerable and/or disadvantaged areas. Even well-resourced communities are constrained in their financial and physical ability to mitigate, making it important to develop a prioritized plan based on a risk assessment that focuses on activities with the greatest potential to reduce the likelihood of community-scale losses.[40]
- *Unrealistic expectations about efficacy of other actions:* Many homeowners in high-risk areas contend that improving fire suppression will adequately protect their properties. Some may believe that the burden lies entirely upon utilities to eliminate the risk through grid hardening. However, as was dramatically demonstrated in the recent Los Angeles fires, under extreme high-wind drought conditions these activities can prove insufficient to prevent large-scale conflagrations.
- *Unrealistic expectations about insurance:* Homeowners may refuse to take action unless they are guaranteed insurance availability and/or premium discounts that pay for the cost of the mitigation. Although insurers would typically charge higher premiums to higher risk policies and lower premiums to lower risk policies, the differential may have no relationship to the cost of home hardening, especially over the short term.
- *Resistance to external control:* Homeowners may reject efforts to impose new requirements as an unnecessary and improper infringement of their property rights. They may feel very strongly about their ideal

home and landscape aesthetic, and resist departing from it. In densely populated areas, however, their failure to mitigate can increase the risk to their neighbors, much as secondhand smoke can pose a threat to nonsmokers. Collective action at scale can be more readily achieved if each individual homeowner can be motivated to reduce the vulnerability of their home and those of their neighbors.

Effective wildfire risk reduction also requires clear and consistent mitigation directives that stakeholders at all levels can understand and implement. As discussed in a recent CAL FIRE Risk Modeling Advisory Working Group Report, a municipality might have specific ordinances that homeowners must follow to reduce their wildfire risk, and while these ordinances exceed state minimums, they might not align with the mitigations recognized in rating or underwriting by insurers, none of which might align with the latest available science and understanding of wildfire risk.[41] For example, multiple defensible space standards have historically been promulgated in California, with conflicting guidance on critical areas such as "Zone Zero" (0-5 feet from structures). This inconsistency extends to community-level designations such as Firewise USA® and other state-specific resilience designations.

Effective wildfire risk reduction also requires clear and consistent mitigation directives that stakeholders at all levels can understand and implement.

The insurance industry has responded to the wildfire crisis through support for mitigation standards and legislative action, including forest management and community protection programs, to reduce risk. IBHS launched its Wildfire Prepared Home program in 2022, establishing the first comprehensive, science-based standard for wildfire-resistant construction and landscaping. The program has been expanded to include community-level designations through the Wildfire Prepared Neighborhood initiative, recognizing the importance of collective risk reduction.[42]

These programs and frameworks will take time to scale, and any standards will need to be reinforced through governmental mechanisms such as building codes, defensible space requirements and enforcement in order to maximize their effectiveness.

Additional frameworks such as “Fire Adapted Communities” and “Ready, Set, Go!” have been created to address additional aspects of adaptation to fire, such as evacuation planning and wildfire response. However, these programs and frameworks will take time to scale, and any standards will need to be reinforced through governmental mechanisms such as building codes, defensible space requirements and enforcement in order to maximize their effectiveness.

POSSIBLE SOLUTIONS:

Coordinate mitigation among federal agencies: A coordinated partnership among stakeholder agencies could better facilitate governmental efforts to address wildfire risk reduction actions and increase ignition resistance within the built environment.[43]

Encourage safe new construction: Continued scientific research and innovation is needed in the fields of building design, community design, landscape architecture, and safe and sustainable building practices to create more ignition-resistant structures and communities.[44]

Retrofit existing construction: While addressing new construction through building codes represents an important component of long-term risk reduction, a comprehensive approach must include strategies and requirements for retrofitting existing structures and communities. Mitigations can be planned and prioritized at points where changes in the presence of combustible material (or fuels) will have the greatest potential impact on the community’s risk.[45] Grant programs can provide financial assistance to implement mitigation for low-income, high-risk homeowners.

National Wildfire Resilience Certification Program: A federal "stamp of approval" program, similar to Energy Star but focused on wildfire resilience, could provide easier recognition for mitigation efforts.

2.3 NEED FOR BETTER WILDFIRE DATA, MODELS AND METRICS

In order to make better decisions around mitigation, there is a need for better data, models and metrics with which to assess the impact of mitigation actions on urban wildfire risk.

While publicly available hazard maps from agencies like the U.S. Forest Service and state fire agencies provide valuable context for land management, they are updated infrequently, sometimes on five-year cycles or longer. This makes them less useful for capturing recent changes from development, previous fires, or vegetation management efforts. Fire footprints, which are the geographic boundaries of historical wildfires, offer important insights but suffer from inconsistent collection methods across jurisdictions and time periods. These sources also lack the granularity of data needed for property-specific risk assessment.

As discussed in the CAL FIRE Risk Modeling Advisory Working Group Report, wildfire models have been in use for decades and come in many forms, depending on the intended use cases and available input. For example:

- Fire managers use fire simulation models to prioritize and plan for wildfire mitigation actions, such as prescribed fire, mechanical thinning, managing suppression resources, and identifying egress routes.
- Insurance companies rely on multiple sources of data and models to assess wildfire risk. Their focus is on managing and pricing the risks associated with their insured portfolios.
- Electric utilities deploy consequence models that estimate the impact of a wildfire should a utility asset cause an ignition, to inform operational and asset-hardening decisions.

However, none of these models were designed to evaluate the effectiveness of current and prospective mitigations within and outside communities to reduce the risk of urban conflagration. In order to do so, it is critical to consider how fire spreads in the built environment. Structural ignition can occur in multiple ways, including ember intrusion, radiant heat and direct flame contact. Modeling these effects is hindered by a lack of detailed historical and current data on parcel- and community-level data regarding factors such as building materials, defensible space, and other mitigation actions.

In order to make better decisions around mitigation, there is a need for better data, models and metrics with which to assess the impact of mitigation actions on urban wildfire risk.

Current wildfire models often have difficulty distinguishing the risk of structure-to-structure transmission for unmitigated versus well-mitigated homes. Even if the data and models were available, communities may not have the resources to license the models, or the expertise to evaluate results. There is also a lack of guidance and targeted benchmarking metrics (e.g. vulnerability to fast fires) with which to evaluate the costs and benefits of different options.

These gaps lead to several problematic outcomes. Public agencies struggle to prioritize mitigation investments without a clear understanding of where risk is highest and how different mitigation actions might reduce it. Insurers cannot see what mitigation has been done or what needs to be done and reflect it in their risk assessments, and homeowners receive mixed signals about their risk and the most effective mitigation actions to take.

POSSIBLE SOLUTIONS:

Invest in tools for community risk assessment and management: Communities need more sophisticated tools to understand the areas that are most vulnerable to incoming wildfire and structure-to-structure ignition, assess fire response capabilities, and identify the quantity, types, and locations of risk reduction activities that will create the greatest return on investment. Similar risk assessment tools could be applied at a national level to identify communities with the highest wildfire exposure and greatest need.

Provide a framework and resources for continuous evaluation: Funding is needed to regularly assess fire pathways, implement strategic mitigations, monitor results, and continue to improve outcomes. Specific metrics designed around fast fires may help prioritize use of scarce resources and allow more targeted and effective mitigations. If the community’s capacity to mitigate is substantially lower than the investment needed, federal and state grant programs could provide financial resources needed to achieve meaningful risk reduction.

Make mitigation actions visible to insurers: To accurately gauge the state of wildfire risk in communities located in fire-prone areas, there needs to be a common ground truth upon which various consumers of data can rely. A public/private effort is underway to collect and manage previously unavailable data on parcel- and community-level mitigations to help stakeholders engaged in risk measurement and/or risk reduction, which could be supported via federal funding and resources.[46]

3 Conclusion

Today's wildfire crisis represents a daunting challenge, but it is not an unprecedented one. Urban conflagrations like the ones experienced by Chicago, Baltimore, and San Francisco over a century ago seemed unavoidable, yet they were virtually eradicated through transformative changes in building codes developed in collaboration with engineers and the insurance industry

Ignoring the escalating wildfire risk and managing from crisis to crisis reduces the number of options available and drives up the costs of reaction at various levels. State and local policy efforts, with the involvement of the private sector, are crucial to effect meaningful change, but there may be effective actions the federal government can take.

We have the scientific understanding, technological capabilities, and economic motivation, and can direct these toward adapting communities to exist with fire as an enduring element of our landscape. Managing wildfire risk will require aligning many stakeholders, making difficult decisions, finding the necessary resources and implementing solutions at scale, but it is fundamentally a solvable problem.

4 Limitations

This report was commissioned by AWR and is intended to summarize, at a high level, the issues faced by U.S. homeowners in wildfire-exposed areas and the current challenges in managing wildfire risk today. It may not be appropriate, and should not be used, for other purposes. The data and exhibits in this report are provided to support the findings contained herein, limited to the scope of work specified by AWR, and may not be suitable for other purposes. Milliman does not intend to benefit or create a legal duty to any other recipient of this work.

In preparing this report, we relied upon the information obtained from publicly available sources. We did not audit, verify, or review the data and other information for sampling bias, reasonableness, and consistency. Such a review is beyond the scope of our assignment. If the underlying data or information is inaccurate or incomplete, the results of our analysis may likewise be inaccurate or incomplete. In that event, the results of our analysis may not be suitable for the intended purpose.

The materials in this document represent the opinion of the authors and are not representative of the views of Milliman, Inc. Milliman is available to answer any questions regarding this report or any other aspect of our review.

Acknowledgements

The authors would like to thank the following individuals for their contributions as peer reviewers to this paper:

- Kimiko Barrett, PhD – Headwaters Economics
- Karen Collins – American Property Casualty Insurance Association
- Bob Roper – Western Fire Chiefs Association
- Michael Wara, JD, PhD – Stanford University

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Endnotes

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Measure twice, cut once: A state-level framework for effective wildfire risk mitigation

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Executive summary

Amid rising wildfire risk, western U.S. states face an urgent need to protect fire-exposed communities. With limited time and money to act, they must go beyond fire suppression activities and implement proven mitigation measures with verifiable outcomes.

This paper outlines a risk-based framework guiding states to focus their efforts where they are more likely to see results: the built environment, particularly existing structures and surrounding vegetation, and electricity infrastructure. The framework consists of six steps:

1. Inventory the universe at risk.
2. Establish metrics for quantifying risks and damages.
3. Determine the key physical risks to mitigate and the appropriate actions needed to address each of them.
4. Assess the cost of mitigations and potential funding sources.
5. Secure stakeholder buy-in.
6. Create an action plan prioritizing mitigation methods and targets.

State leaders are likely to face many obstacles when pursuing wildfire mitigation, including consumer resistance to change, misconceptions about risk, and concerns about funding. This framework helps stakeholders anticipate challenges and mobilize populations to adopt the necessary steps that will reduce wildfire risk, improve insurability, and lead to sustainable communities.

Introduction: Why fire-prone states must create a wildfire mitigation framework

Wildfire-caused losses in the built environment are a major and increasing driver of economic, social, and health impacts across western states. But fire is a permanent and necessary feature of the landscape in which many communities have been built. Further, while fire suppression is necessary to help protect communities in immediate danger, these efforts cannot go far enough to avoid devastating fires now or in the future; the firefighting agencies in Southern California are among the best-equipped in the world, yet they could not prevent the losses in the 2025 Los Angeles wildfires.

Amid limited budgets and a growing urgency to protect fire-exposed communities, states must go beyond fire suppression activities and implement proven mitigation measures that will yield the greatest return on investment.

Instead, communities—including cities and suburbs far from the wildland-urban interface (WUI)—must adapt to this natural phenomenon by implementing adaptation strategies as outlined in this document. In fact, hardening homes, creating defensible space, strategically reducing fuels adjacent to communities, and implementing other risk-reduction measures increases the effectiveness and cost-efficiency of fire suppression by reducing fuel loads and making structures more resistant to wildfire.

Previous mitigation initiatives have mostly failed to deliver resilience, for multiple reasons. Some did not insist on verifiable outcomes and simply celebrated activities that turned out to have little impact on community risk. Others neglected to educate stakeholders—including homeowners and utility ratepayers—about their role in funding solutions. Others targeted perfection in ways that limited scalability. Still other attempts have fallen short because states have, perhaps unintentionally, focused on risk-reduction activities in unpopulated areas, which is often a politically easier choice but one that has not proven effective at protecting homes and people from wildfire.

Amid limited budgets and a growing urgency to address this problem, states must direct their resources toward strategies that will yield the greatest return on investment. Based on the authors’ expertise in utility wildfire risk management, firefighting, and risk modeling, this paper outlines a decision-making playbook to help states conduct risk-based mitigation planning and risk-targeted spending. It details how to create a mitigation framework that can be customized to local conditions to help protect communities from fire across the West and beyond.

Landscape management vs. community risk

This mitigation framework is focused on reducing wildfire risk to human life and property in the built environment. Although modifying vegetation adjacent to communities is a vital component of our recommendations, broader landscape management and forest health—a related and important topic—is distinctly different and requires a separate set of mitigation measures. Because most wildfire agencies are responsible for land management, these parallel concerns of forest health and community wildfire safety have historically been conflated, but that approach has often impeded progress in both areas.

Our framework outlines how to reduce wildfire risk in communities. Specifically, it focuses on measures to protect communities from fast fires, which are characterized by rapid, wind-dominated fire spread that outpaces the firefighting response to points of entry capable of initiating urban fires. Wildfire mitigation outside these locations is beyond the scope of this paper.

The state wildfire mitigation framework: A six-step process for reducing community wildfire risk

1. INVENTORY THE UNIVERSE AT RISK.

Begin with the two areas that contribute the most to wildfire-driven losses: communities and the electric grid.

First, assess the community.

Wildland-initiated urban fires are more likely to occur in dense urban and suburban areas in fire-dependent landscapes where fast-moving, wind-driven fires occur and the community is exposed to extremely dry vegetation. The risk associated with these conditions is often exacerbated by long-term drought, which increases the combustibility of vegetation.

Identify densely populated areas.

We define “density” in terms of structure separation distance (SSD). For example, consider where properties are close enough together that radiant heat and direct flame contact under high winds can cause structure-to-structure fire spread. Note that “density” may be subjective and often correlates with home values, as more expensive properties tend to have more land around them. It is also important to look beyond the traditional WUI; recent fires such as the 2025 urban conflagrations in Los Angeles and the 2021 Marshall Fire in Colorado show that suburbs and cities may face as much risk as rural areas.

Wildland-initiated urban fires are more likely to occur in dense urban and suburban areas in fire-dependent landscapes where fast-moving, wind-driven fires occur and the community is exposed to extremely dry vegetation.

Considerations for new construction vs. retrofitting existing communities

For those jurisdictions that have adopted modern WUI building codes, wildfire-informed approaches to community design, and associated hazard maps to guide the application of these code requirements, new communities are relatively well-prepared for wildfire exposure. The much larger and more challenging problem is the millions of existing homes built without consideration for wildfire, which require prioritized retrofits at meaningful scale to achieve a degree of wildfire adaptation.

This framework focuses on the steps needed to undertake large-scale, prioritized mitigations to achieve neighborhood-scale adaptation of existing structures. These same steps should be followed when rebuilding a community after a catastrophic wildfire.

Tally the properties at risk.

Focus on the number of dwelling units rather than storage sheds, isolated cabins, and other buildings not inhabited full time. Structures built before 2008 building code upgrades in California (or WUI code adoption in other states) will face higher wildfire risk than new developments, as will new structures not built to WUI code standards. However, even for properties built to the WUI code, yards and attached wooden structures such as fences and decks can be important ignition sources and create substantial vulnerability in urban fires.

Assess nearby vegetation.

Assess fuel loads, both within and immediately outside communities, that are capable of igniting and carrying fast fires into residential areas. Note that fast fires occur more frequently and spread more rapidly in grasslands or shrubs/brush, not forests.

Determine travel routes.

Communities with fewer roads in and out have reduced opportunities for people to evacuate and for firefighting crews to enter via vehicle. Evaluate the capacity of these road networks to handle simultaneous evacuation (egress) and fire response (ingress).

Calculate the probability of high-risk weather conditions.

Dry days with low humidity and wind speeds exceeding 55 miles per hour create the most dangerous conditions for fires to spread rapidly. While these weather conditions may be most common in the West, they can also occur in other parts of the country at any time of year. The number of areas experiencing at least a few days a year with these extreme conditions appears to be rising.

Evaluate the electricity grid.

Although utility companies are actively upgrading infrastructure and implementing other protective measures, such as public safety power shutoffs (PSPS) on days at high risk for fire, the grid remains the most likely current cause of ignitions under dangerous conditions. About half of all structure loss in California in the past decade has been associated with ignitions related to the electric system.

Assess the operational practices of electric utilities.

Best practices of electric utilities require situational awareness of wind speeds at pole height as well as weather forecasting sufficient to prepare for operational interventions to reduce risk. Best practices also require developing a nuanced understanding of ignition risk at the circuit or sub-circuit level, so that utilities know both where and when to focus risk-reduction efforts.

Utilities should be prepared—and have prepared their customers—for three types of interventions:

1. Disabling reclosers—systems that reenergize distribution circuits after a fault.
2. Enabling “fast-trip” settings on high-risk distribution circuits. These settings turn off circuits quickly enough to prevent ignitions but significantly compromise reliability.
3. PSPS for conditions in which the grid is simply unsafe to operate. Practicing for these conditions is essential.

Assess the condition of local distribution and transmission infrastructure.

To date, most effective mitigation efforts have addressed the electric utility distribution system, which connects substations to homes. Typical hardening involves (1) installing advanced controls that allow for the operational changes previously described; (2) sectioning distribution circuits to allow more targeted use of fast-trip and PSPS processes; and (3) hardening these circuits using covered conductors (insulated wires), undergrounding, and other technologies.

Utility risk reduction in the electric transmission system works very differently than for electric distribution. Transmission lines, because they provide bulk power system reliability, are very rarely deenergized during very high winds, when the rate of wildfire spread is very difficult for firefighters to manage and fire aviation assets are generally ineffective if not grounded. Instead, transmission system hardening consists of enhanced inspection and maintenance of towers and conductors to spot mechanical wear and tear that can lead to component failure. This approach depends critically on the ability to spot problems before they occur in equipment that is often 50 and sometimes as much as 100 years old.

Consider other high-value assets at risk.

States may also factor in potential fire-caused harm to the local water supply, business supply chains, and other assets. In addition, they should consider and prepare for the impact of electric infrastructure operational safety practices (PSPS and fast trip) on the operation of critical infrastructure and emergency response.

2. ESTABLISH METRICS FOR QUANTIFYING RISKS AND DAMAGES.

Amid limited budgets, states should direct spending to areas with the greatest amount of value at risk, where mitigation efforts will yield the highest return. However, this valuation step is complicated, as some measurements are currently uncertain, the various vulnerabilities may equate to comparing apples and oranges, and the absence of a large-loss fire in any given year does not amount to success. Success can really only be judged by estimating changes in the underlying risk and associated damages.

> States should direct spending to areas with the greatest amount of value at risk, where mitigation efforts will yield the highest return.

Stakeholders should consider the following factors and keep equity top of mind, as different segments of the population may be impacted more or less severely by the same events.

Decide which damages to consider.

These may include human health and safety (in terms of lives lost and increased morbidity); property and infrastructure; community impact; and other economic and social impacts.

Determine how to value these damages.

Note that some losses may be difficult to quantify in terms of dollars. Likewise, it may be challenging to find a valuation metric that applies across all categories.

Consider loss of life.

This may be particularly fraught and challenging. Evacuation routes can be used as a surrogate, as a community with compromised or limited evacuation routes is more likely to experience higher fatalities during a wildfire than an area with more or better evacuation options. Likewise, communities with high concentrations of older adults—who are significantly more likely to die in a wildfire—face disproportionate risk.

The effects of wildfire and toxic smoke on community health, especially over the long term, are equally significant and concerning and even less certain.

Count the number of structures at risk of damage or loss.

This is preferable to estimating replacement costs, which will over-index wealthy communities. Note that remediating smoke damage to structures not destroyed by fire has emerged as a particularly challenging type of damage to evaluate, as seen in the aftermath of the Los Angeles wildfires.

Consider additional impacts.

These may include number of PSPS days, insurability, economic interruption on various timescales, and economic disruption to local government, particularly through loss of parcel tax revenue. Although states can factor in the known economic repercussions beyond property loss, quantifying each individual impact may not be necessary.

Determine modeling requirements.

A modeling framework will need to be created in tandem with the mitigation framework. When specifying modeling requirements, states must strike a pragmatic balance between complexity and cost. More extensive modeling does not always result in better guidance. Developing and maintaining an elaborate system may not be feasible for states with smaller budgets, but less expensive, high-level models may be sufficient. If we know where the risk of structure loss is high and which interventions are most likely to reduce that risk, we do not need to model every structure's risk to know which set of interventions will be optimal. However, we do need to model the network effects through which unmitigated structures threaten other structures.

Different models may be more suitable for different aspects of mitigation management. For example, fully probabilistic models may be more suitable for quantifying dollars of expected property loss under a range of ignition and weather scenarios. Other models might be appropriate for evaluating the effectiveness of utility investments to reduce ignitions. Still other models may be more useful to assess how rapidly fire might spread within a community under various mitigation scenarios, given an ignition in high-wind conditions. Note that model choices should be periodically reevaluated because the field is rapidly advancing.

Once models are selected/established at the statewide level, communities should be given access to the necessary tools and training to perform cost–benefit analyses that comport with the metrics promulgated within the state mitigation framework.

3. DETERMINE THE KEY PHYSICAL RISKS TO MITIGATE AND THE APPROPRIATE ACTIONS NEEDED TO ADDRESS EACH OF THEM.

In fire-dependent landscapes, fires are valuable and unavoidable. Further, in populated areas, ignitions of various types are inevitable. Rather than solely attempting to prevent all fires, states should also focus on reducing the negative consequences of these fires and consider mitigations that reduce their damage once they approach or enter communities. Cost-efficient, effective wildfire mitigation requires matching the mitigation to the mechanism of ignition.

Review utility-caused ignition risks.

Consider how to trade off ignition risk versus the consequences of ignition. Utilities are currently spending tens of billions of dollars of their customers’ money to reduce utility-sparked wildfire ignitions to zero or near-zero, but attempting to reach this goal may be futile and not yield the most effective use of limited societal mitigation resources.

In populated areas, ignitions of various types are inevitable. Rather than solely attempting to prevent all fires, states should also focus on reducing the consequences of these fires and consider mitigations that reduce their damage.

Utilities should implement operational practices that reduce ignitions during dangerous times, balancing the need to improve safety against reduced reliability and implementing cost-effective interventions to mitigate the impacts of PSPS on their customers. Mitigations may require new infrastructure investments, such as underground power lines and covered conductors, that reduce ignition risks.

Plan for additional sources of ignition.

Even when electricity grids are fully upgraded, wildfire will remain a risk, with other types of human and natural causes likely to be responsible for ignitions. Wildfire ignitions are correlated with population density up until the built environment becomes so urbanized that wildfires cannot propagate due to lack of fuel.

Map fire pathways.

Assess areas with vegetation that will bring fires to the community and the entry points that will receive them.

Plan for vegetation management.

The effectiveness of mitigation efforts such as fuel breaks to modify vegetation will benefit from being sited close to the community. Distant vegetation treatments run the risk of an ignition occurring downwind or in a location that causes the fire to bypass the treated area. Very near community mitigations can serve to change the exposure of perimeter homes to ground component fire such that they only require ember resistance, reducing the mitigation effort required by residents.

Review the structures capable of initiating urban fire.

Some homes may be exposed to grass, brush, and/or timber, while others may have exposure to blown embers and firebrands but not to a ground component fire. All of these create different hazards requiring different mitigation measures.

Note that structure loss typically occurs under extreme drought and wind conditions, and these must be the focus of mitigation efforts. During average conditions, modest fuel breaks combined with fire suppression will likely prove effective; however, these approaches alone cease to provide protection under the weather conditions capable of generating extreme fire behavior.

Determine mitigations to residential dwellings.

These will depend on the potential source of ignition. If the mechanism of ignition is the adjacent structure, this risk cannot be mitigated at the parcel level, and risk-reduction efforts are better spent mitigating risk factors upstream to prevent the initiation of urban fire.

Most homes will require some retrofits, but the question is to what extent and at what cost; for example, if all homes already have a Class A roof, mitigations become cheaper. However, not all treatments are equally effective, and they must be grouped and matched to the mechanism of ignition at the appropriate scale to reduce risk. The approach that will be effective for densely packed homes in urban or high-density suburban locations is not the same approach that should be used for low-density areas:

Structure loss typically occurs under extreme drought and wind conditions, and these must be the focus of mitigation efforts. Not all treatments are equally effective, and they must be grouped and matched to the mechanism of ignition at the appropriate scale to reduce risk.

- **Low-density homes with exposure to wildfire** should have defensible space to reduce fire intensity and break up vegetative continuity, as well as home-hardening retrofits and Zone Zero/Home Ignition Zone mitigations to create ember resistance.

- **Homes at the edge of high-density areas** need the same mitigations as low-density homes, as they will be exposed to the same wildfire conditions.
- **Homes that are within the ember deposition zone but not on the edge of high-density areas** need home-hardening retrofits and Zone Zero/Home Ignition Zone mitigations to create ember resistance. Because these homes do not have direct exposure to ground component fire, they do not generally benefit from traditional defensible space work.
- **Homes that are outside the ember deposition zone** do not need retrofits, as risk is reduced by mitigating those upstream structures that could carry urban fire to their location.

In the case of new community construction, this approach can be further enhanced through the thoughtful placement of non-burnable community amenities such as parks, golf courses, water features, roads, bike paths bordered by non-combustible walls, and parking lots to compartmentalize the community and limit the consequences of structural ignitions.

Consider workforce needs.

Consider the potential availability of and need to hire specialized staff. For example, “mow and blow” crews require less skill and can establish Zone Zero spaces, while much more highly trained electrical workers, who are in limited supply, are needed for grid upgrades. State university systems may be a good potential resource for training and developing new workforces to meet the need for planning, designing, implementing, modeling, inspecting, and maintaining resilient structures and communities.

4. ASSESS THE COST OF MITIGATIONS AND POTENTIAL FUNDING SOURCES.

Creating a sustainable funding model for a risk-assessment framework and the necessary mitigations for homes, the electric grid, and other areas will require contribution from multiple public and private sources. Again, matching the mitigation measure to the method of home and/or community ignition will help prevent wasted resources and thereby reduce costs.

Property owners.

Homeowners must be made aware that they are responsible for funding home-hardening measures, and the government will not be the primary payer. States must mobilize homeowners’ capital and cooperation through public awareness, enforcement of regulations, and financial incentives, including access to insurance coverage and mortgage credit.

Note that these same households will contribute to grid-related mitigation measures through higher electricity bills and to community mitigation through state and local taxes. And, if left untreated, high wildfire risk will likely contribute to escalating insurance premiums and reduced availability of coverage.

State government.

The state’s primary investments may be in education, risk assessments, and assistance for property owners and local governments. States may also fund or guarantee low-interest loans, with the option to borrow against real estate transfer taxes. In addition, states may provide resources to enhance community-level fuels management, particularly when state firefighting resources have primary responsibility for fire suppression.

Local government.

These bodies typically focus on community-level preparedness, planning, and enforcement of building codes and defensible space ordinances. Local governments can also fund fuels management activities adjacent to communities to disrupt fire pathways where low SSDs make home-level mitigations an ineffective strategy.

Utilities ratepayers.

Evidence suggests that investor-owned utilities are better able to raise funds than rural and municipal utilities. However, costs are ultimately borne by ratepayers. These costs are spread across all ratepayers, meaning that communities with low risk end up subsidizing risk reduction in high-risk communities. This raises important equity questions, particularly if low-risk communities are also in hot climate zones with high electric bills related to air conditioning costs.

> Creating a sustainable funding model for a risk-assessment framework and the necessary mitigations will require contribution from multiple public and private sources. Homeowners must be made aware that they are responsible for funding home-hardening measures, and the government will not be the primary payer.

With utility upgrades effectively paid for by community residents through higher electricity costs, determine whether it might be preferable to raise this money through higher taxes or insurance premiums. We note that these mechanisms for raising money are more challenging to implement politically but also allow for a more diversified set of mitigation actions that may be more cost-effective.

Unlikely source: the federal government.

Contrary to public assumptions, the U.S. Forest Service does not provide funding in areas without federal lands. Limited federal dollars may be available for post-fire recovery and other wildfire-related activities, or via grants for community-level fire-prevention measures and infrastructure projects. However, states and communities should not expect significant federal contributions to mitigation efforts.

Additional potential sources.

Funding may also come from public partnerships with private capital and resilience bonds. In California, tax increment financing is an option for local governments that form Climate Resilience Districts. Insurance premium taxes may also help cover mitigation costs, and in rare circumstances carriers themselves may contribute to mitigation efforts. For example, in some communities insurers have opted to fund the installation of screens on vents in vulnerable homes because this has been deemed a smaller expense than covering losses if those homes remain unprotected and burn during a wildfire.

Realistic expectations on costs.

Past rebuilding schemes after wildfires have perpetuated the narrative that every home costs $200,000 to mitigate. This is false—and underscores the need to match the mitigation measure to the method of ignition.

Hardening some homes may require only minimal, inexpensive landscaping changes. Not every house will require a new roof, new siding, double-paned windows, and other extensive and expensive modifications. In these cases, the majority of the expense may be associated with the materials selected for replacement and not the cost of removing the existing combustive material. The costs can further be reduced by planning community-wide efforts that allow materials and labor to be more efficiently purchased and deployed.

Maintenance costs.

Note that, for any vegetation treatment or defensible space mitigation, the cost of original implementation is likely to far exceed the cost of maintenance. However, absent a sustainable mechanism to fund and ensure maintenance, the value of the treatments will diminish over time. A realistic expectation should be that vegetation treatments must receive maintenance as often as once a season and no less frequently than once a decade, depending on vegetation type. This maintenance cycle inherently limits the number of acres that can be sustainably modified, further emphasizing the need for careful targeting.

5. SECURE STAKEHOLDER BUY-IN.

To implement effective mitigation measures, states must involve many stakeholders and organizations. Securing their buy-in and agreement may prove challenging. The following considerations can help.

Enlist champions to foster an enabling political climate.

Identify and engage with leaders in the community who can act as high-visibility first movers and inspire others to act. Consider neighborhood organizers, city council members, fire chiefs, real estate agents, and other stakeholders.

Consider whether certain existing governance structures create conditions more receptive to implementing the necessary changes. For example, it may be more effective to first pursue mitigations in communities with willing subcommunity entities, such as homeowners' associations (HOAs) or FireWise neighborhoods, to demystify the process and outcomes.

It is vital to educate the public that suppressing all fires, hiring more firefighters, and other popular but insufficient strategies will have no incremental impact on community wildfire risk. Reducing community vulnerability is the most necessary and least costly mitigation that will help.

Communication also can help create the political climate needed to proceed. The public, and the elected officials that respond to but can also influence public opinion, must learn that suppressing all fires, hiring more firefighters, and other popular but insufficient strategies will have no incremental impact on community wildfire risk. It is vital to educate the public that reducing community vulnerability is the most necessary and least costly mitigation that will help.

Identify strategies to increase the cooperation of property owners.

Promulgating the necessary interventions via building codes can enhance resilience going forward, but this will only affect new construction and therefore does not address the largest part of the problem. Owners of existing homes are likely to be surprised to face and may resist any new hardening requirements, as standard land-use policy only requires homes to be brought up to code when a major building permit is needed.

To reduce resistance, look to tie mitigation requirements to existing opportunities where decisions and investments are already being made. For example, owners are often more motivated to comply when they need government and/or HOA signoff before a sale. Requiring a subset of mitigation actions to be implemented when properties are bought and sold, when homes are being rebuilt after a fire, or when permitting is required for other home renovations, helps to overcome the social, political, and financial challenges of retrofitting existing communities.

It is critical to communicate with owners about risk, especially the impact to property values from wildfire risk and rising insurance costs. In addition, owners should be educated about the spillover effects of home mitigation—both positive and negative—to bring social pressure to bear on holdouts.

Consider the insurance implications.

To the extent that insurance premiums signal the true cost of risk, improved cost of and access to insurance can reinforce the benefits of risk reduction; conversely, a disconnect between effective mitigation and insurance outcomes is a strong deterrent to taking action.

Public misconceptions about the role of insurers in wildfire risk mitigations are widespread, so education will also be crucial here. Dispel the notion that insurers will fund mitigations, and plan to educate homeowners on the value of retaining access to insurance policies in high-risk communities. In addition, expect confusion about the potential impact of mitigation strategies on insurance premiums, and aim to set realistic expectations up front that mitigations are unlikely to lead to substantial reductions in current premiums in most places. Mitigation may be able to stabilize future costs, not take us back to a pre-climate change era.

> Improved cost of and access to insurance can reinforce the benefits of risk reduction; conversely, a disconnect between effective mitigation and insurance outcomes is a strong deterrent to taking action.

The public also must learn that addressing an entire community's wildfire risk through proven hardening measures will have the most meaningful impact on insurance costs. Note that in order for hardening to impact future insurance premiums, insurers must have visibility into hardening measures, which can be facilitated via the establishment of a public/private mitigation data exchange.

Require accountability.

Tie incentives to outcomes, for example by providing grants or other funding only on the condition that appropriate mitigation measures are implemented and documented via inspection. Identify levers available to enforce mitigations, including new zoning laws and building codes and mandatory inspections of defensible space. Consider additional laws or regulations that can compel mitigation, such as requirements to comply with defensible space requirements and harden a home before a sale, as previously suggested.

6. CREATE AN ACTION PLAN PRIORITIZING MITIGATION METHODS AND TARGETS.

Consider portfolios of strategies.

Certain baskets of mitigation measures must be implemented together in order to be effective. In addition, other mitigations are non-negotiable baselines, and if these are not properly implemented all other measures will be ineffective. For example, homes within the ember deposition zone must implement ember-resistant mitigations including Class A roof covering or assembly, ember-resistant vents, and a non-combustible Zone Zero.

Model the scenarios under consideration.

Alternative mitigation scenarios can be modeled at the statewide level to estimate their impacts on the underlying risk. Access to appropriate models at the local level can help community leaders with decision-making.

The models and the underlying data will need to be refined and updated over time. Some high-level models, such as state wildfire hazard maps, may need to be updated only once a decade, while more detailed models may require more frequent updates.

Perform a cost–benefit analysis.

Determine which approaches are feasible given the funding available. Factor in the time required to complete each potential mitigation step. If a measure takes decades to implement, even if it is highly cost-effective, a high-risk community may burn prior to its completion.

Consider additional factors.

Leaders must weigh trade-offs, such as the introduction of grid updates that have caused poor electricity reliability in some rural areas. In addition, it is vital to avoid embracing technology fallacies: No single “savior” technology, such as drones or artificial intelligence, will reduce wildfire risk on its own.

At every stage, be mindful of equity. As noted earlier, certain valuation metrics may direct mitigations toward higher values at risk, which may be the more expensive homes in more expensive areas. Take steps to ensure mitigation measures are distributed so that occupants of less-expensive homes will be able to recover from catastrophic wildfires.

Be honest with stakeholders about the potentially achievable risk reduction given available funds, and the remaining risk that will still exist for a community. Wildfire risk reduction is analogous to seatbelts in that it will reduce but not eliminate losses.

Set a timeline for implementation.

It may be tempting to set an ambitious goal for 10 years in the future, but this will not come to fruition without a detailed plan for how to achieve this end state. Instead, establish a series of gates for achieving incremental, measurable progress along this path, and set interim goals (e.g., the first 3–5 years, 5–10 years, and beyond). Bear in mind that government and organizational budgets are often set annually, so each one-year budget must factor in the incremental steps needed to achieve the desired endpoint multiple years in the future.

Conclusion: Effective wildfire risk mitigation requires a plan

As the climate crisis escalates, devastating wildfires—including urban conflagrations—are becoming increasingly common. To reverse this trend, states must pursue effective mitigation measures to protect their communities. This framework offers a path forward.

Any plan must go beyond simply requiring mitigation steps, as the past decade of fires has proven that activity alone does not reduce risk. A mitigation framework must insist on measurable and verifiable outcomes.

The process will not be easy. Change is challenging and disruptive, and policymakers must make difficult choices. Older communities, not new construction, are the most at risk and thus require the most change, raising complicated implementation issues. Spending limited resources in one area likely means diverting funds from another, perhaps extremely worthy, area. But without the appropriate mitigations, applied at scale within the at-risk, dense communities, any action will fall short of what is needed. If this occurs, states should expect to face the dire and costly outcome of losing more and more residents and communities to fire.

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Article

https://doi.org/10.1038/s41467-025-63386-2

Fire risk to structures in California's Wildland-Urban Interface

Received: 13 January 2025

Accepted: 15 August 2025

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The destructive impacts of wildfires on people, property and the environment have dramatically increased, especially in the Wildland-Urban Interface (WUI) in California. In these areas structures are threatened by both approaching flames and lofted embers which spread fire into and within communities. While independent factors influencing structure fire protection are well known, their combined effects remain largely unquantified, limiting the accuracy of risk assessments and mitigation strategies. Here, we examine five major historical WUI fires—2017 Tubbs, 2017 Thomas, 2018 Camp, 2019 Kincade, and 2020 Glass Fires—utilizing machine learning (ML) analysis of on-the-ground post-fire data collection, remotely sensed data, and fire reconstruction modeling to assess patterns of structure loss and mitigation effectiveness. We show that the spacing between structures is a critical factor influencing fire risk, highlighting the importance of structure arrangement, while fire exposure, the ignition resistance (hardening) of structures, and clearing around structures (defensible space) work in combination to mediate fire risk. Utilizing an XGBoost classifier, structure survivability can be predicted to 82% accuracy. Results highlight the effectiveness of hardening and defensible space, with a hypothetical 52% reduction in losses. Our findings emphasize the need for community-level mitigation to reduce structure loss in future WUI fires.

Globally, the frequency, severity, and size of wildland fires has been increasing, resulting in extreme events that have led to dramatic losses in terms of people, property and the environment[1,2]. A majority of these impacts on people occur where houses and other urban development intermingle with undeveloped wildland vegetation, an area termed the WUI. This area has grown dramatically in recent years[3,4] with one-third of all new homes in the US built in the WUI[5]. The western United States has witnessed a 246% increase in structures lost to wildfires from 2010–2020 compared to the previous decade[6]. California, despite its long fire history, has experienced recent increases in the number of very large fires (over 100,000 ha) resulting in massive losses of lives and property[7]. Between 2013 and 2018, approximately 47,000 structures have been damaged or destroyed and 189 fatalities have been attributed to wildfires in California[8]. This increasing risk has consequences that jeopardize the economic stability, well-being of local residents, and the environment in affected communities[9].

Central to preventing future destruction has been the development of mitigation measures aimed at reducing the likelihood of ignition and spread in the WUI[10–14]. Improvements in building features and materials (hardening) and clearing surrounding vegetation and other flammable materials (defensible space) play important roles mitigating fire spread into the WUI[15–18] but differ in their characteristics

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because structures and vegetation have different heat release rates, durations of burning, and responses to external exposure including direct flame contact, radiation, and firebrands[19]. For instance, Ondei et al.[20] synthesize a zonation strategy for defensible space, focusing on removing dead vegetation within 1.5 meters of a house and managing fuel connectivity up to 30 meters. Similarly, studies like Carton et al.[21] stress the importance of fire-resistant construction, vegetation management, and the need for specific wildfire codes, particularly addressing the unique needs of Indigenous communities and heritage properties in Canada. While effective mitigation strategies have been developed based on past testing and investigations[22], their combined effectiveness under different exposure conditions is not yet known[5].

Previous geospatial studies have demonstrated the critical influence of spatial arrangement and biophysical factors[23–25], with defensible space around structures playing a substantial, albeit secondary, role[26,27]. The role of building materials has also been examined, revealing mixed findings[27–29]. For instance, Syphard and Keeley[28] found structural features like enclosed eaves and vent screens were crucial, while others (Price et al., Metz et al., Knapp et al.)[30–32] identified factors such as spacing and arrangement as more important, suggesting determinants of loss are often beyond homeowners' control. A later study of the Woolsey Fire suggests that proximity to destroyed structures and building materials, such as multi-pane windows and enclosed eaves, are key factors in determining survival.[27] Large structure loss datasets, such as those from the Camp fire, show that homes built before 1997 had markedly lower survival rates compared to those built after, underscoring the importance of construction standards[32]. The 2021 Marshall Fire also highlights the significance of neighborhood and parcel characteristics in housing survival, revealing the impact of jurisdictional differences in building codes and planning[31]. Collectively, these studies underscore that while defensible space is important, building features and surrounding vegetation, as well as proactive mitigation strategies, are critical to improving wildfire resilience.

Despite these advances, the majority of studies focus on single events, and lack a comprehensive quantitative analysis of how mitigation measures, such as home hardening and defensible space, interact and influence fire risk. In order to safeguard communities and stem the current trend of destruction, we must quantitatively understand how features influence fire risk to structures, particularly in relation to fire exposure, surrounding vegetation, the proximity of neighboring structures, and properties of the structures themselves. We hypothesize that the combined effects of structure hardening, defensible space, and structural separation can substantially reduce the risk of structure loss, with the most substantial benefits occurring when changes are made to both the structure itself and the surrounding vegetation. Furthermore, changes to individual structures may not be sufficient to reduce risk when structures are arranged at high density, requiring community-wide mitigation.

Here, we combine the largest existing structure loss database from California with simulated fire and ember exposure conditions to structures across multiple large-loss events, providing a methodology to quantify and compare the combined influence of exposure and mitigations such as defensible space and home hardening on fire risk. Unlike past studies, fire reconstruction modeling that includes urban fire spread is used to quantitatively estimate the effect of flame and ember exposure on structures. Geospatial assessments of vegetation surrounding structures are added using both LiDAR and visual imagery to assess the level of defensible space (vegetation) surrounding structures. The database is then fit using a multivariate analysis similar to refs. 27,31 that distinguishes between the interrelated effects of exposure, structure hardening, and defensible space. A parameter importance analysis reveals the strong role both structure separation and exposure play, distinguishing wildfire from other natural hazards that are not affected by neighboring conditions, highlighting the importance of a community approach to mitigation. The model developed is strongly predictive when incorporating all the above features and is also used to assess the impact of recommended mitigation measures on homes. It is found that it is most impactful to make changes both to the structure itself and surrounding fuels, especially vegetation and other flammable materials within 1.5 m (5 ft) of the structure (zone 0) to achieve the maximum benefit.

Results

In this study we took advantage of the Damage INSpection (DINS) Dataset collected by on-the-ground CAL FIRE crews from structures damaged, destroyed, or affected by wildfires in California during post-fire investigations between 2013–2022 (California Department of Forestry and Fire Protection (CAL FIRE))[33]. Figure 1 shows all fires in the DINS dataset between 2017–2022 as well as five of the largest loss fires in this dataset (2017 Tubbs and Thomas, 2018 Camp, 2019 Kincade, and 2020 Glass fires) selected for further analysis based on data availability and the number of structures exposed and destroyed. We combined records of damage state and building features from this dataset with remotely-sensed assessment of surrounding vegetation (akin to defensible space) and structure footprints (to assess building separation) of undamaged, damaged, and destroyed structures within the final fire perimeter (CAL FIRE Historic Fire Perimeters), including a 91 m (300 ft) buffer around any burned areas[34]. Post-fire reconstruction modeling was then used to add local fire exposure by both flames (flame length) and embers (ember load) to the dataset resulting in a more complete picture of fire exposure and effects.

Data from 5 selected fires were extracted from the overall DINS dataset (~90,000 structures) by combining/stacking the five fire datasets after preprocessing. Additional structures that were unburned but exposed to fire were added to the dataset (Tubbs ~14,000, Thomas ~ 6000, Camp ~24,000, Kincade ~2000, and Glass ~5000 structures). We employed a resampling process to balance the samples, resulting in a total of approximately 47,000 structures and 45,947 unique data points. We simplified the damaged, non-damaged, and destroyed classifications in the original DINS to a binary classification of Survived and Damaged categories because >90% of damaged structures are destroyed.

Post-fire reconstruction

Five fires were reconstructed using a level-set model (ELMFIRE) that included both wildland[35,36] and urban fire spread[37] to re-create fire spread conditions and estimate critical missing exposure data (flame length and ember deposition) from these events. While reconstruction can never perfectly mirror on-the-ground conditions, these results provide reasonable estimates taking into account spatiotemporal variability in fuels, topography and weather. Figure 2 shows the modeled fires and resulting flame length (in meters) and ember load (in terms of number of embers deposited per meters squared). These are extracted adjacent to each of 47,000 structures in our dataset and distributions are shown in terms of flame and ember exposure as probability density functions (PDF) in Fig. 3. These distributions reveal a 27% and 39% overall decrease in exposure to flames and embers, respectively for structures that survived vs. those that were damaged. The decrease in exposure, however, is small in comparison to the difference in total number of structures destroyed and suggests that other features may play a role in determining which are more or less likely to survive.

Feature contribution to structure loss

We applied an XGBoost[38] Classifier to our dataset and then utilized a SHapley Additive exPlanations (SHAP) model to explore the importance of various features on structure destruction. By looking at the stacked results from all 5 fires (Fig. 4), we found that structure density, which is determined by the distance between structures (SSD), is one of the most important features in structure destruction. The second

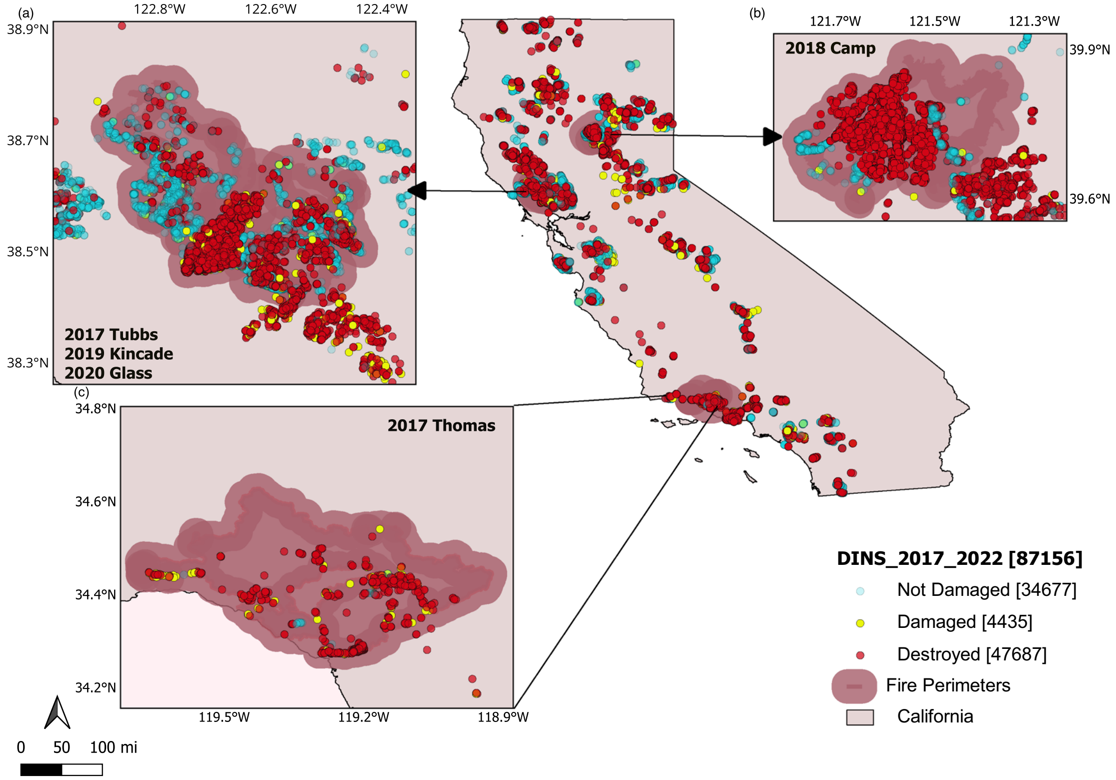

Fig. 1 | Spatial distribution of damage to structures in California. CAL FIRE Damage Inspection (DINS) data (2017–2022; $n = 87{,}156$) overlaid on fire perimeter polygons (semi-transparent rose shading) for five of the most destructive WUI fires before the 2024–2025 Los Angeles area fires. Insets show details for **a** 2017 Tubbs, 2019 Kincade and 2020 Glass fires (left panel), **b** 2018 Camp fire (upper right) and **c** 2017 Thomas fire (lower center). Symbols denote building damage state: cyan circles, Not Damaged ($n = 34{,}677$); yellow circles, Damaged ($n = 4435$); red circles, Destroyed ($n = 47{,}687$). The California state boundary is outlined in black. Coordinates are in degrees latitude and longitude; scale bar in miles. Map created using the Free and Open Source QGIS.

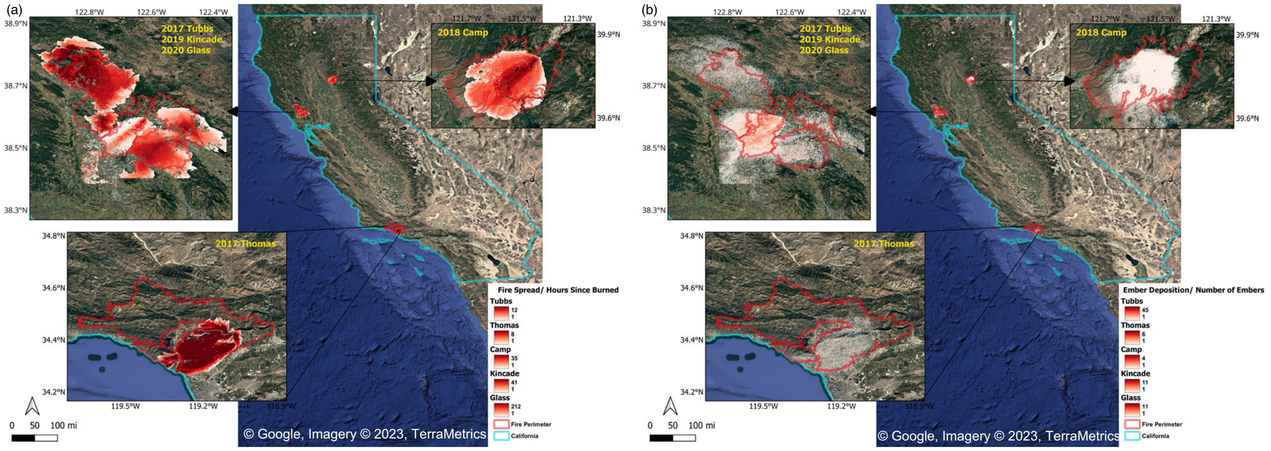

Fig. 2 | Simulation of fire spread and ember deposition for the 5 fires, overlaid with fire perimeters. a Fire spread (shaded based on time of arrival) illustrates fire progression in each event, while **b** ember deposition illustrates the large reach and stochastic nature of generated firebrands. Fire spread and ember deposition outputs generated using the ELMFIRE model with the HAMADA urban fire spread extension from elmfire.io (https://github.com/lautenberger/elmfire). In fire spread maps each pixel is colored by hours since burned or time of arrival (white = 1 h; dark red = maximum hours shown). Cumulative ember deposition used to show the average number of embers per cell (white = 1; dark red = highest mean). Fire perimeters (red outline) and the California state boundary (cyan outline) were overlaid in QGIS. Insets show details for 2017 Tubbs/2019 Kincade/2020 Glass (left), 2018 Camp (upper right) and 2017 Thomas (lower left).

most important contributor to the classification results from the XGBoost estimator was exterior siding, representative of the materials used in construction, followed by Year Built. Note, in the DINS database year built indicates the year that the primary structure in the parcel was constructed. Year built has therefore been identified as a confounding variable ultimately combining the effects from different parameters such as hardening (e.g., materials used for roof construction, eaves, vent screen, window pane, exterior siding), vegetation, and surrounding features (e.g., defensible space/vegetation separation distance and nearby structures/structure separation distance). Hence, considering Year Built as a single factor for determining vulnerability is inaccurate, and our results recommend adopting a holistic approach in such determinations. Results underscore the importance of hardening structures, structure density, and

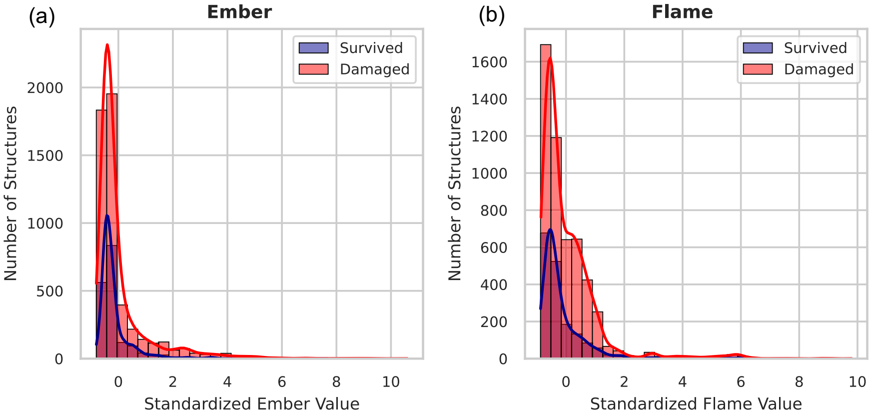

Fig. 3 | Number distribution showing structure damage based on standardized flame and ember values. Number distributions of structure damage versus standardized ember and flame values ($n = 47{,}742$). Histograms with overlaid kernel-density estimates display counts of surviving (blue) and destroyed (red) structures for **a** standardized embers and **b** standardized flame. These distributions highlight the pronounced effect of simulated ember and flame exposures on the destruction of structures in large WUI fires.

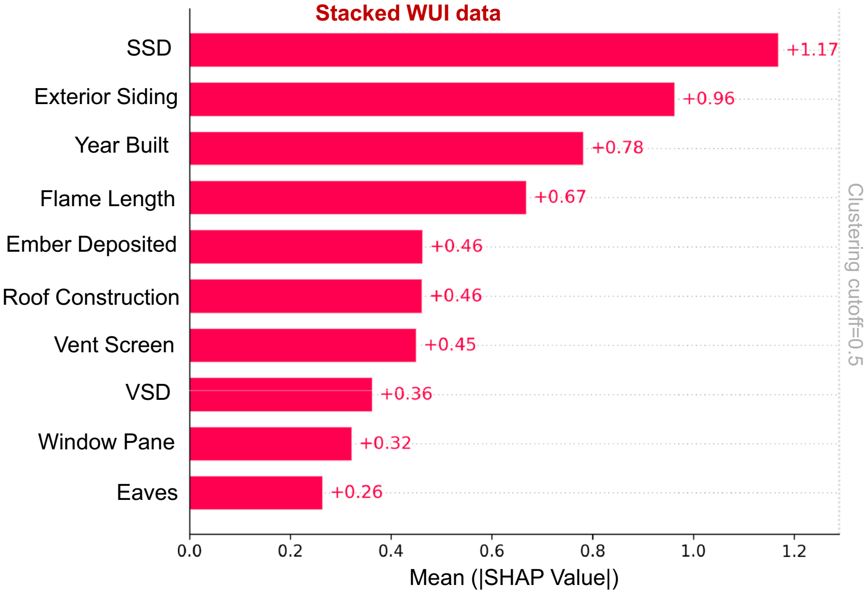

Fig. 4 | SHAP aggregation results characterizing the contribution of features for the entire (stacked) WUI data from five fires. Mean absolute SHAP values from an XGBoost classifier ($n = 47{,}742$ structures) trained on merged WUI data from five fires. Bars show the average |SHAP| for each predictor, ranked by contributions: structure separation distance (SSD), exterior siding, year built, flame length, ember deposition, roof construction, vent screen, vegetation separation distance (VSD), window pane and eaves. Higher |SHAP| indicates greater contribution to the model's prediction of structure destruction. The vertical dotted line marks the clustering cutoff (0.5) used to identify redundant features. SSD is the single strongest driver of predicted loss, followed by exterior siding and year built.

building arrangements in WUI areas to mitigate fire risk and potential destruction. These results are consistent with already-established engineering knowledge[22,32,39]. Furthermore, these insights are based on the available data rather than being drawn from direct experiments or detailed numerical simulations at the flame scale.

Exposure was still important in predicting damage from past WUI fires, specifically considering flame length and ember load derived from fire spread simulations. Flame length, which indicates the height and intensity of flames, can directly influence the severity of damage to structures and vegetation in its path. Ember load, representing the number and size of burning embers carried by the wind, also substantially contributes to the spread of the fire and subsequent structure loss, as these embers can ignite spot fires far beyond the main fire front. The intensity and reach of flames, as well as the quantity of embers, played pivotal roles in the extent of damage and structure loss observed in these fires.

SHAP values provide a unified measure of feature importance in a predictive model. Based on the evaluation metrics, the XGBoost model emerged as the most effective estimator, demonstrating superior skill in predicting losses. This finding is supported by its higher average SHAP values for key features compared to other models such as Logistic Regression and Random Forest. The average SHAP values for the XGBoost estimator revealed that certain features notably impacted the model's predictions. For instance, Structure Separation Distance (SSD) and flame length had positive average SHAP values of 0.090 and 0.051, respectively, underscoring the importance of building arrangements and fire behavior in risk assessment. Year Built showed an average SHAP value of −0.058, suggesting that newer structures might be associated with lower predicted losses, possibly due to improved building codes and materials.

We also broke down the feature importance results for each of the 5 individual fires assessed (Fig. 5), and found common features

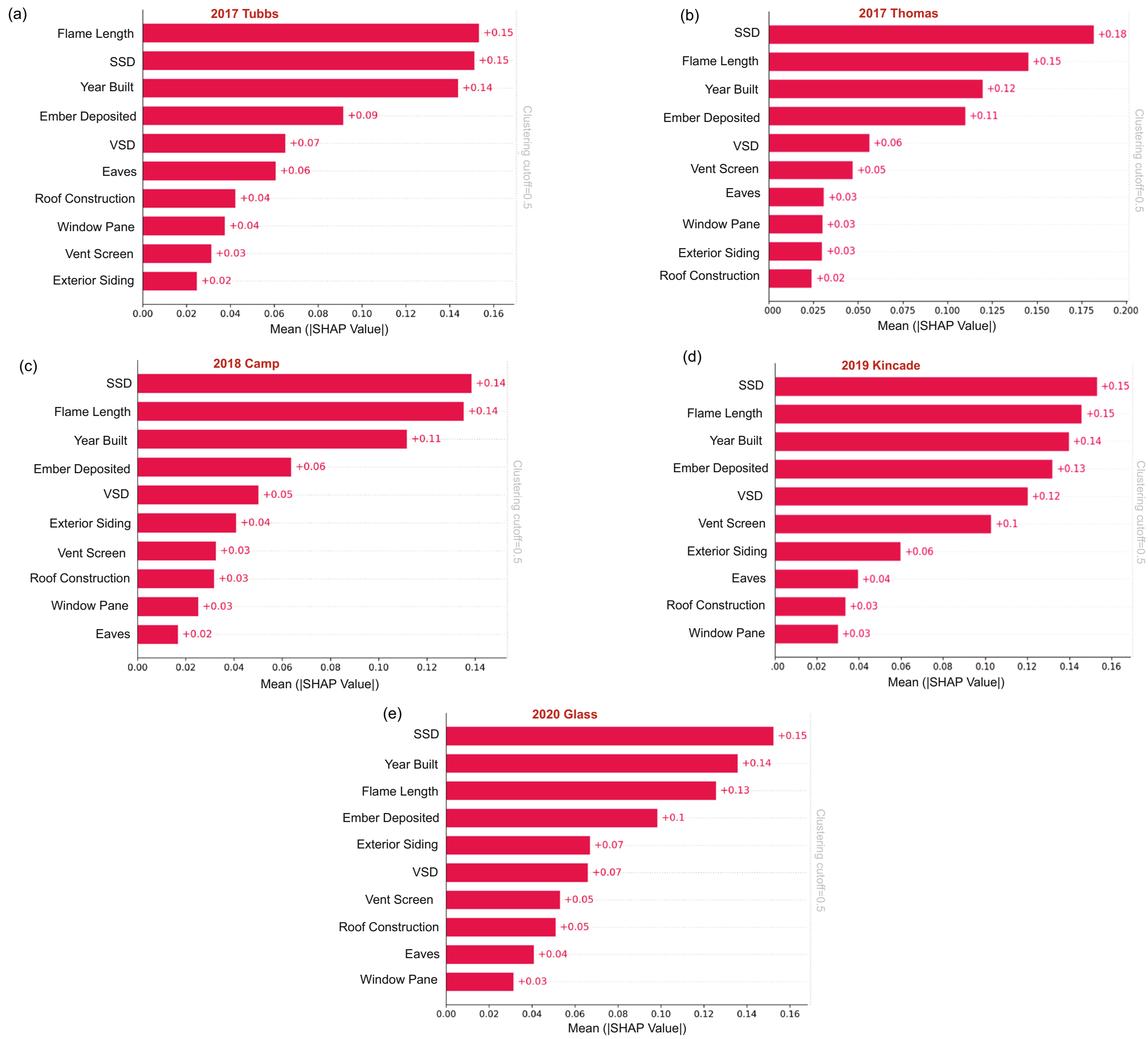

Fig. 5 | SHAP aggregation results for characterizing the contribution of features for five individual fires. Mean absolute SHAP values (mean |SHAP|) for the top ten predictors in each fire-specific XGBoost model. Sample sizes are: **a** 2017 Tubbs, $n = 13{,}027$; **b** 2017 Thomas, $n = 5192$; **c** 2018 Camp, $n = 23{,}204$; **d** 2019 Kincade, $n = 1555$; **e** 2020 Glass, $n = 4768$. Bars are ordered by decreasing mean |SHAP|; annotations show the numeric mean |SHAP| values. The vertical dotted line in each panel marks the hierarchical clustering cutoff (0.5).

of importance: SSD, flame length, and year built, but distinct differences were also revealed between individual fires. Structure separation distance (SSD) was the most important predictive feature in the 2017 Thomas, 2018 Camp, 2019 Kincade and 2020 Glass fires while flame length was the most predictive feature for the 2017 Tubbs fire. In fires that burn through densely populated areas, wildfires can transition into urban conflagrations that become dominated by structure-to-structure spread, which is most strongly influenced by SSD. The high density of structures in the Thomas and Camp fires in the cities of Paradise and Ventura (Butte and Ventura counties) therefore emphasize this mode of spread. In the Kincade and Glass fires, the clustering of structures in Geyserville (Sonoma County) and Deer Park (Napa County) contributed to the rapid urban spread of the fire. Flame Length substantially contributes to structure destruction in the Tubbs fire and is the second most important factor for the Thomas, Camp, and Kincade fires. In the Glass fire, it ranks third in importance, emphasizing the role of nearby buildings and surrounding fuels in spreading flames to structures. Year built, in conjunction with building characteristics (eaves, roof, vent, siding, window), underscores the significance of home hardening in dense WUI areas, limiting fire spread and protecting structures from losses.

Figure 6 shows the distribution of four key features—SSD (structure separation distance), FLAME (flame length), YEAR BUILT (year primary structure on parcel was built), and EMBER (ember load)—across five fires: Tubbs, Camp, Glass, Kincade, and Thomas. Each panel represents one feature, displaying both the distribution of values through a violin plot (in light gray) and the mean values (in blue). The violin plots highlight the density of feature values, with wider sections indicating regions where values are more concentrated, allowing for a comprehensive comparison of how each feature behaves across different fires. For instance, the SSD and YEAR BUILT features show relatively wider distributions in the Glass fire, suggesting a broader range of structure separation distances and building years compared to other fires. Overlaid bar plots show the mean feature values for each fire, providing insight into the central tendencies. For example, the SSD and YEAR BUILT features have relatively higher means in the Camp and Glass fires, indicating greater separation distances and older structures on average in these regions. In contrast, the Kincade and Tubbs fires exhibit lower mean SSD values, suggesting tighter structure spacing. The combination of these two plots makes it possible to assess not only the average feature importance (through the bar plots) but also the variation within each fire (through the violin plots).

Damage prediction results

We applied a range of machine learning models, ultimately selecting an XGBoost Classifier as it was the most accurate to investigate the five large WUI fires in our dataset to predict structure survival during each fire. Linear models (logistic regression) have been used in the past[24,28,40] and achieved an accuracy to predict structure losses for our 5-fire database of 78%, In comparison, the CatBoost and Random Forest classifiers improved performance to 80% and 81% respectively, and the XGBoost classifier further increased accuracy to 82%. Beyond the numerical gains, XGBoost's ability to capture non-linear relationships and interactions among features, along with its robust regularization and efficient hyperparameter tuning, contributed to its superior overall performance. Consequently, after comparing related metrics—including accuracy, precision, AUC, recall and F1-Score—we selected XGBoost as the preferred model for our study.

A comparative analysis between the Logistic Regression, Random Forest, CatBoost, and XGBoost models is included in the "Methods" section and Supplementary Information (Supplementary Materials Figs. 1–3 and Supplementary Materials Tables 1–3) but importantly underscores the need for selecting an appropriate algorithm based on the specific characteristics of the dataset and outcome to be achieved. Additionally, we provide a ranking comparison that summarizes the predictive performance of our models across both the DINS dataset (2017–2022) and the combined dataset for five fires. Table 1 presents key performance metrics including Accuracy and AUC as well as the top three important features identified for each model, offering a comprehensive evaluation of each model's strengths and limitations. This ranking not only highlights the efficacy of our modeling approach but also provides valuable insights into the relative performance across datasets.

A confusion matrix is shown in Table 2 outlining the performance of our XGBoost classification algorithm breaking down predicted outcomes against actual results, delineating true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN). The area under an ROC curve (AUC) is also shown as another measure to evaluate the model's overall performance alongside the accuracy (percentage of correct predictions the model makes). Overall the XGBoost Classifier has a high accuracy in predicting the occurrence of destruction for each of the 5 individual WUI fires, despite severe limitations in data coming from the aftermath of real destructive events. An accuracy threshold of 79% is achieved for each fire except for the Kincade fire (63%) which had a large number of missing values in the DINS inspection dataset and affected the results. The XGB classifier was also applied to the full DINS dataset (2017–2022) which incorporated the same preprocessing as the 5 fires but did not include exposure modeling values and defensible space, although it did incorporate all other analyses including structure spacing, and year built. An accuracy of 77% was achieved which demonstrates the flexibility and applicability of this model even when not all data can be accounted for.

Using our model we were able to examine various scenarios including home hardening and defensible space clearing to compare what changes in predicted structure loss and survivability might occur, in order to propose effective mitigation strategies. This is particularly important because structure density cannot be modified for existing structures (which make up more than 98% of the current housing stock[22,41]. We applied this to the 5-fire database we created. In the first scenario, which involved home hardening, we adjusted all hardening values in our dataset to fire-safe ones (e.g. non-flammable siding, fine mesh over vents, double paned windows, non-flammable roof, etc.) and applied the XGB model. This resulted in a 25% survival rate with

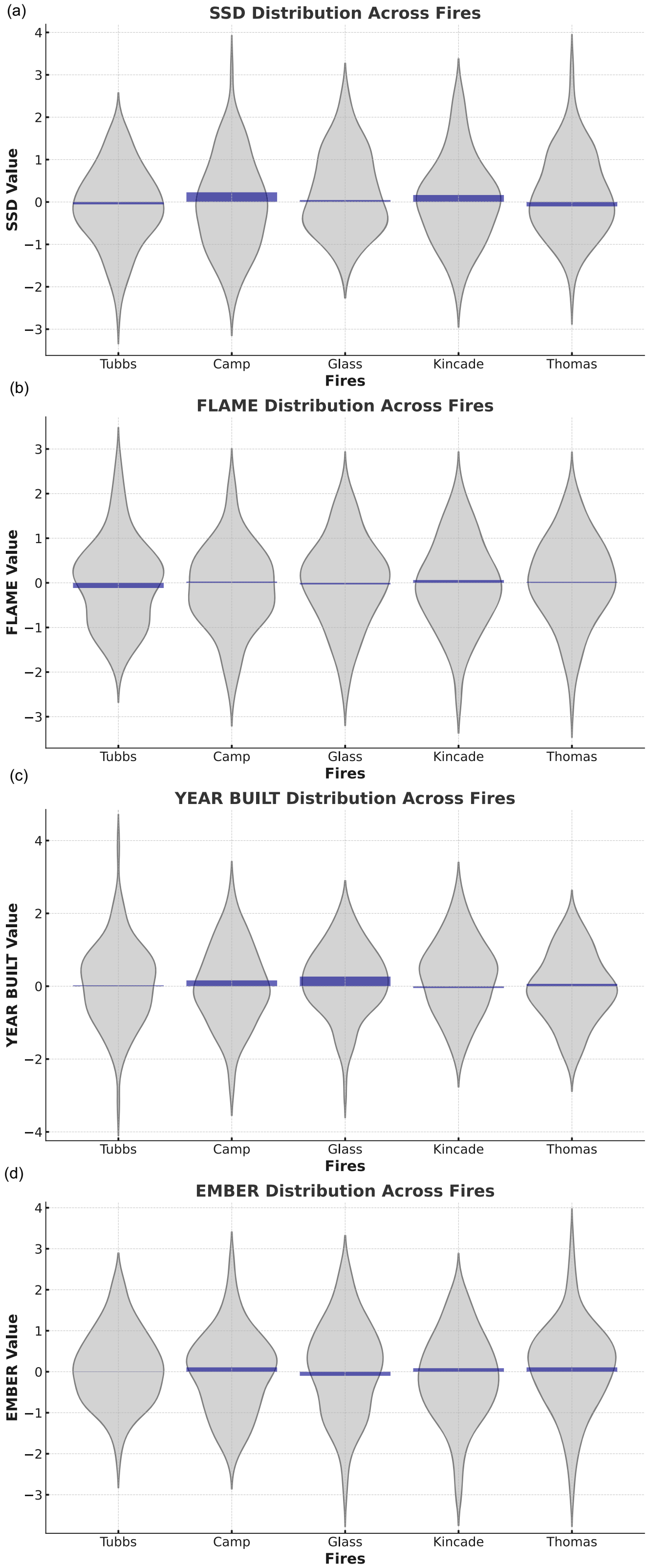

Fig. 6 | The standardized distribution (gray) and mean values (blue) of important features across five fires. Gray violin plots show the standardized distributions of **a** structure separation distance (SSD), **b** flame length, **c** year built and **d** ember deposition for each fire. A bold central line marks the median in each violin. Sample sizes are: Tubbs ($n = 13{,}027$), Camp ($n = 23{,}204$), Glass ($n = 4768$), Kincade ($n = 1555$) and Thomas ($n = 5192$).

Table 1 | Comparative model performance ranking for DINS (2017–2022) and combined five fires datasets

Model	Dataset	Accuracy	AUC	Key features		
Logistic Regression	DINS (2017-22)	0.75	0.81	Exterior Siding	Window Pane	Eaves
Random Forest	DINS (2017-22)	0.75	0.82	Exterior Siding	Year Built	SSD
XGBoost	DINS (2017-22)	0.77	0.84	Exterior Siding	Year Built	SSD
CatBoost	DINS (2017-22)	0.75	0.80	Exterior Siding	Year Built	SSD
Logistic Regression	5 Fires Combined	0.78	0.65	Exterior Siding	Year Built	Vent Screen
Random Forest	5 Fires Combined	0.81	0.83	Exterior Siding	SSD	Vent Screen
XGBoost	5 Fires Combined	0.82	0.83	SSD	Exterior Siding	Year Built
CatBoost	5 Fires Combined	0.80	0.80	SSD	Ember Deposited	Year Built

Table 2 | Results of XGBoost predictions on each test set with a resulting confusion matrix displaying model performance in terms of true positives (TP), true negatives (TN), false positives (FP), false negatives (FN), area under an ROC curve (AUC), and the percentage of correct predictions the model makes (Accuracy), the accuracy of positive predictions (Precision), model's ability to identify all positive instances (Recall), and the harmonic mean of precision and recall (F1 score)

WUI fire	TP	FP	TN	FN	AUC	Accuracy	Precision	Recall	F1-score
Tubbs	1041	58	0	2	0.685	0.94	0.94	0.99	0.97
Thomas	147	25	31	21	0.808	0.79	0.85	0.87	0.86
Camp	3506	686	198	110	0.784	0.82	0.83	0.96	0.89
Kincade	27	58	124	27	0.635	0.63	0.31	0.50	0.38
Glass	151	58	496	106	0.841	0.79	0.72	0.58	0.64
5 Fires Combined	4785	847	885	353	0.833	0.82	0.84	0.93	0.88
All CA DINS (2017-22)	5198	133	2998	1073	0.84	0.77	0.79	0.82	0.81

75% structure loss due to WUI fires (Supplementary Materials Fig. 6). Next, we combined home hardening with clearing defensible space in Zone 0 (0–5 feet; 0–1.5 meters), which effectively doubled the survival rate to 40% and reduced the loss rate to 60% (Supplementary Materials Fig. 7). Finally, we implemented an extreme mitigation scenario that included both home hardening and the clearing of defensible space in Zone 0 (0–5 feet; 0–1.5 meters) and Zone 1 (5–30 feet; 1.5–9 meters). This further increased the survival rate to 48% and reduced the structure loss to 52% (Supplementary Materials Fig. 8). Figure 7 shows the structure loss and survivability across various mitigation scenarios. It is crucial to acknowledge that these hypothetical scenarios did not incorporate the impact of suppression efforts or firefighting strategies, which could substantially influence the outcomes in real-world situations. Therefore, the results from this analysis should be considered as theoretical estimates, and the actual outcomes may differ considerably when these real-world mitigation strategies are applied.

Discussion

Decades of research have shown the importance of ignition-resistant construction, defensible space, and the proximity of structures to one another[16,22,25,32,42]. The ranked importance and interplay between these mitigation measures has now been presented in this study, utilizing simulations to extract exposure conditions during different fires. The application of XGBoost and SHAP methods has illuminated the critical features contributing to structure destruction. Following investigations of the Camp fire by Maranghides et al. and Knapp et al.[22,32] Structure Separation Distance (SSD) arose as a key metric in characterizing the likelihood of loss for any particular structure during these large WUI fires. While smaller fires may occur through sparse housing arrangements, the majority of structure losses in California have occurred in large-loss fires in moderately dense (suburban) communities[28,32]. In these fires, the structures themselves become fuel and contribute to spread. These existing structures pose a unique challenge in hazard management—they are immobile. While these structures can be hardened, they cannot be readily removed or displaced like many other WUI fuels.

The analysis revealed the role of interactions among competing factors (like SSD, flame length, ember load, year built, and exterior siding) in influencing fire dynamics, showcasing that multiple features contribute simultaneously to fire risk to structures. Our results show that the most important factor that cannot be changed is the distance between structures, as conflagrations tend to consume a majority of houses in major fires. Nevertheless, there is still a substantial opportunity to enhance safety through effective mitigation measures such as hardening structures and establishing a defensible space. Mitigation measures on the structure (hardening) combined with removal of surrounding fuels in the area immediately adjacent to the structure (zone 0) has the potential to dramatically reduce losses in future fires. While applying these measures to any particular structure within a dense urban area makes little difference on the survivability of a single home, substantial reductions in losses are achievable when community-wide actions can be applied. This has been proposed in many studies and is a major tenant of community risk-reduction programs, however, it has not been shown to be effective before because previous studies focus more on individual structures. The effect of community risk reduction may have other benefits as well, with amplified effectiveness to responding fire crews[28]. When fewer homes ignite from embers or direct flame contact, less structure-to-structure spread results, and the fire service is freed up to focus on those structures that are most threatened. If arriving early in fire progression, it is possible that embers can be extinguished and the “disaster sequence” posited by Calkin et al.[10] can be disrupted and a smaller number of homes may be lost.

While hardening and defensible space actions may not alter the fundamental risks posed by structure proximity, they can still dramatically improve the survivability of buildings during wildfires. By examining individual fire cases, we can further tailor mitigation approaches to address specific vulnerabilities and enhance resilience against future wildfires. This is apparent when we see that the factors most correlated with structure destruction change for some fires, such as the Tubbs fire where flame length played a greater role than structure spacing overall. During this fire, sparser structures could

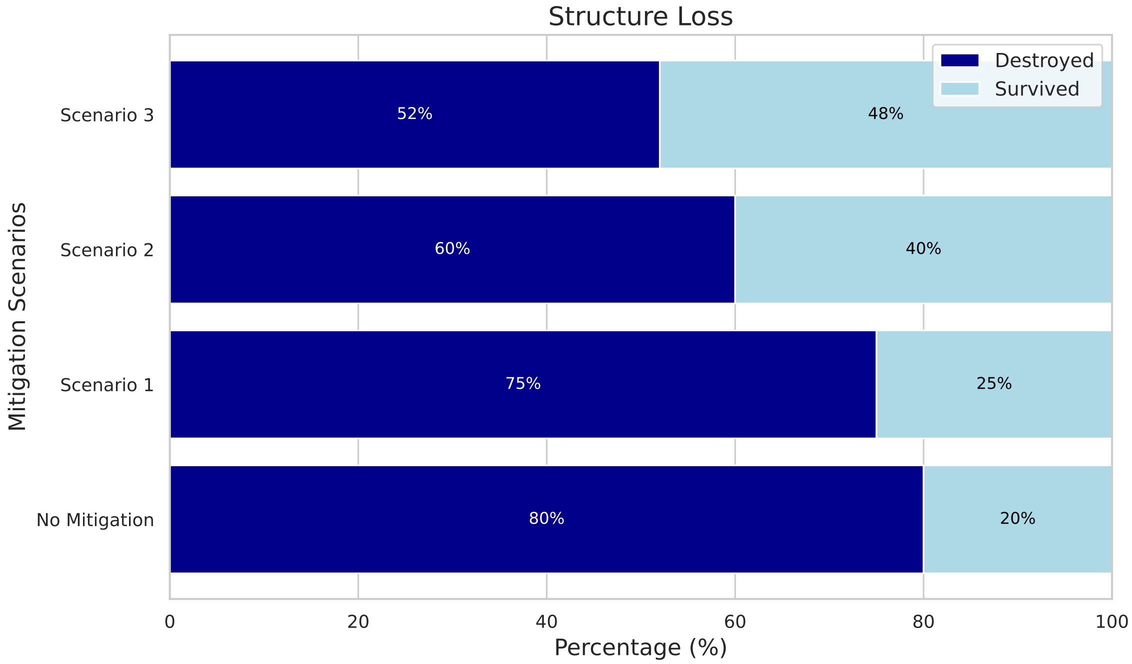

Fig. 7 | Probabilities of predicted structure destruction under various mitigation scenarios. Horizontal stacked bars show percentage of structures Destroyed (navy) versus Survived (pale blue) under various predicted mitigation scenarios: No Mitigation (baseline), Scenario 1 (home hardening only), Scenario 2 (home hardening and clearing Zone 0), and Scenario 3 (home hardening and clearing Zones 0 and 1). Percentage labels inside bars ($n = 47{,}742$).

potentially have benefited from additional fuel management to reduce fire exposure, although some areas, such as the Coffey Park community were dense and still dominated by structure separation. While siding materials were not critical to predict outcomes in any one fire, as an overall predictor they were very important, which speaks to the fact that clustered structures on each fire often had similar construction materials, year built, etc. so that those factors do not appear as important.

Overall, we have shown the potential to combine extensive on-the-ground post-fire data collection, analysis of remotely sensed data, and fire reconstruction modeling to better understand the complicated interactions between different features and structure survivability during wildfires. Despite the improvement of these data and modeling tools, we still have a dramatic lack of information before and during fires that is desperately in need of improvement. Pre-fire inspections are limited and were not available at scale to aid this study, therefore much of the data was collected after the fire and is not at the fine scale to distinguish all potential factors that play a role in destruction. For instance, year built is an inter-related term that also corresponds to materials used, construction type, building codes, etc. It is still useful because it is one of the most easily obtained factors for future analysis, but it makes it harder to distinguish between other factors. During the fires it would also have been useful to observe failure modes more directly, e.g. observation of what part of the exterior ignites by embers, structure-to-structure spread, etc. Still, this study provides a broader understanding useful to the field now and a framework for future data to be applied.

This analysis supports the effectiveness of home hardening and defensible space in reducing structure losses in the WUI, underscoring a need for more application in high-risk areas. Integrating fire risk assessments into land-use planning, including zoning regulations that incorporate risk maps to guide development away from high-exposure areas or require stricter building codes requiring defensible space and home hardening in communities that can be exposed to wildfires may help reduce losses. Similarly, policies that provide financial incentives, subsidies, or insurance benefits for retrofitting homes can also contribute to enhancing community resilience. These results can also be used to inform community outreach and education. Fire risk communication grounded in localized data can empower residents to take action and participate in preparedness efforts.

It is important to highlight potential limitations of the input data and methods used in this study. While reliance on post-fire damage inspection (DINS) assessments provides clear distinctions on the damage state of structures, there is inherent uncertainty on collected features that are difficult to determine in a post-damage state. Additionally, the DINS data may not capture the full range of potential factors that contribute to fire damage, such as local preparedness, fire suppression efforts, construction practices, etc., which could affect the generalizability of the findings to other regions or future fires. Remotely-sensed data, particularly for vegetation separation distance (VSD) is also subject to potential errors as small fuels that can contribute to local fire spread may not be visible at the resolution captured. The moisture content, species, and arrangement of vegetation and other flammable materials may also influence the effectiveness of defensible space but can't be captured through remote sensing modalities. Estimates of fire and ember exposure from fire reconstruction modeling are also subject to potential errors from deviations in fuel or weather input data and the empirical nature of the model itself. Machine Learning models are also limited in their reliance only on provided data. Efforts have been taken to minimize these potential sources of error, including conducting a comprehensive sensitivity analysis with perturbations, an assessment of the trained ML model to systematically assess how variations in key parameters influence our predictions, and use of a validation dataset to assess the performance of the model.

Methods

We primarily relied on a modified database from five selected fires that includes more than 47,000 structures with two broad damage states: "Survived" and "Destroyed", and five detailed damage states: "Destroyed (>50%)", Damaged ("Major (26–50%)", "Minor (10–25%)", "Affected (1–9%)"), "No Damage". The CAL FIRE Damage INSpection Program (DINS) was founded with the goal to collect data on damaged, destroyed, and unburned structures during and immediately after fire events to assist in the recovery process, and to provide local governments and scientists information for analyzing why some structures burned and why some survived[43]. Through a public records request, we acquired DINS data for more than 90,000 structures that survived, were damaged, or were destroyed across all California wildfires from 2013–2022, making this potentially the largest combined dataset of its sort. We then incorporated risk factors associated with structure destruction by wildfires to the DINS data to gain a deeper understanding of WUI destruction. These factors include structure density, building materials, year built, defensible space, and exposures to structures (fire intensity and ember). We employed several Machine Learning (ML) techniques to identify and highlight the important features in our WUI data. These techniques included feature selection, feature engineering, and model interpretation methods to ensure we could pinpoint the most influential variables influencing our results. To enhance the performance of the ML model in this study, we implemented a range of data preprocessing techniques such as data cleaning, normalization, and encoding. These preprocessing steps were crucial for improving model accuracy, reducing noise, and ensuring the robustness of our findings. By meticulously preparing the data, we ensured that the ML model could effectively learn and make accurate predictions from our complex WUI dataset. We opted for the XGBoost (eXtreme Gradient Boosting) algorithm for our ML model due to its superior performance over other methods on our dataset. We also leveraged the SHAP (SHapley Additive exPlanations) model, which provides a nuanced understanding of each column's contribution to the overall predictive outcome. This technique allowed for a comprehensive assessment of the importance of variables within the dataset, enhancing the robustness and reliability of our analysis. The results of Confusion Matrices and Receiver operating characteristics (ROC) Curves, in addition to an advanced computational framework, allowed us to delve into the intricacies of the dataset, capturing complex relationships and patterns that might not be discernible through conventional methods. Our evaluation extended beyond a generalized assessment, as we calculated the accuracy and sensitivity metrics for each individual fire and aggregated the results to encompass all structures within the damage dataset. This meticulous analysis not only provided insights into the predictive performance of our model on a per-fire basis but also yielded a comprehensive understanding of its effectiveness across the entire spectrum of structures in the damage data.

Risk factors to structures from wildfires in the WUI

The methodology for integrating risk factors related to structure destruction builds upon the combination of on-the-ground data with fire modeling reconstructions by Hakes and Theodori et al.[34] for community-level risk assessment for the Tubbs fire, which includes:

Structure spacing which represents "Structure Separation Distance (SSD)". We employed the Microsoft Maps dataset (available at https://github.com/microsoft/USBuildingFootprints), which encompasses open building footprints datasets for entire counties in the United States. This dataset comprises 129,591,852 computer-generated building footprints. Additionally, we utilized QGIS software to access geospatial data concerning urban infrastructure, building locations, and their spatial interconnections.

The *year built* refers to the year in which the primary structure on a parcel of land was constructed. In the context of analyzing the impact of WUI fires, the Year Built variable is important because the age of a structure can influence its susceptibility to fire damage. Furthermore, it acts as a confounding variable that can affect both the building features and the extent of damage.

Concerning fire safety in *building construction materials*, numerous in-depth studies have been carried out through meticulously planned laboratory tests[18,44]. Despite the solid laboratory evidence, few empirical studies have documented building characteristics associated with structure loss in real wildfire situations[28]. In this study building characteristics include eaves, vent screens, exterior siding, roof construction, and window panes.

In terms of *defensible space*, which is representing in this study as "Vegetation Separation Distance (VSD)", the state of California requires fire-exposed homeowners to create a minimum of 30 m (100 ft) of defensible space around structures, and some localities are beginning to require at least 60 m (200 ft) in certain circumstances[26]. We established three categories for the Vegetation Separation Distance (VSD): Zone0, which comprises the initial five feet from the building or "0–5"; Zone1, encompassing the area within 30 feet of the building or "5–30"; and Zone2, extending to within 100 feet of the building or "30–100" (CAL FIRE DSpace: https://www.fire.ca.gov/dspace). Remote sensing techniques were utilized to analyze the density and distribution of vegetation in the WUI regions and urban settings, extracting valuable insights from the aerial and satellite imagery and LiDAR data. The publicly available datasets (including countywide LiDAR data and a fine scale vegetation and habitat map) which were produced by the Sonoma County Agricultural Preservation and Open Space District and the Sonoma County Water Agency, provide an accurate, up-to-date inventory of the county's landscape features, ecological communities and habitats (Sonoma County Vegetation Map: https://sonomavegmap.org/).

Exposures including fire intensity (flame length) and firebrand (ember load). Houses are destroyed during wildfires when exposed to flames in adjacent fuel, radiant heat from nearby fuel (≤40 m)[16], or airborne embers and firebrands originating in nearby and distant fuel (typically < 10 km)[45,46]. In this study, we used the Eulerian Level set Model of FIRE spread, ELMFIRE, an operational fire behavior and spread simulation tool[35] for its additional capability in simulating ember deposition of multiple embers and its implementation of Monte Carlo analysis[36] to capture the stochasticity and uncertainty inherent in wildland fire modeling. We used and modified the semi-physical model of[36,47] to include urban fire spread by using the empirical approach of HAMADA[37].

Data preprocessing

To predict the damage for any of the fire datasets, the dataset was divided into the target variable or y, and all the other features as inputs or X. A stratified split was executed based on "y" values, allocating 80% of the data for training purposes and reserving the remaining 20% for the testing set. This stratified approach ensured that the class proportions in the target variable were similar in both subsets, minimizing the risk of bias due to imbalanced classes. By preserving the target class distribution, this partitioning strategy not only improved the model's ability to generalize but also provided a more accurate and reliable performance evaluation when tested on unseen data. Additionally, the use of a fixed random_state ensured that the split was reproducible, allowing for consistent model training and evaluation across different iterations. As part of the model training process, we utilized GridSearchCV for hyperparameter tuning across several models, including Logistic Regression, Random Forest, and XGBoost. During the grid search, k-fold cross-validation (with cv_k_folds set to 10) was employed to evaluate the models, ensuring robust validation and mitigating overfitting. In the cross-validation process, the data was split into k-folds, where each fold served as the validation set once, while the remaining k-1 folds were used for training. This allowed the grid search to identify the optimal set of hyperparameters based on performance metrics, such as accuracy and F-beta scores. After selecting the best hyperparameters, the model was refitted on the entire training set, ensuring that the final model was well-tuned for testing.

To address the noteworthy variations in the scales of the model inputs, a vital preprocessing step was implemented prior to model training. Using the scikit-learn package[48], we first designed imputation strategies through IterativeImputer to handle missing values. These strategies were trained on the training set and then applied to both the training and test sets. The imputation strategy was tailored for each feature in stacked WUI data and for each wildfire case. For example, Roof Construction (19,318 non-null), Eaves (19,318 non-null), Vent Screen (19,318 non-null), Exterior Siding (19,318 non-null), Window Pane (19,318 non-null), VSD (3504 non-null), and Year Built (22,501 non-null) were imputed using a nearest neighbor approach. For Year Built in individual fire cases, either nearest neighbor imputation or a median-based strategy was adopted, whereas numerical features like Embers (11,549 non-null), and Flame length (14,578 non-null) were aggregated (e.g., using the mean or median, potentially augmented by k-nearest neighbors) to fill in missing values. In our approach, we incorporated a spatial clustering technique that utilizes proximity-based methods for data imputation. Specifically, we leveraged Haversine Distance and Pairwise Distance metrics in UTM coordinates to cluster data points based on their geographic proximity. This spatial clustering approach ensures that similar locations, defined by latitude and longitude, are treated consistently when imputing missing values. By considering spatial proximity, we make the assumption that nearby data points are likely to share similar attributes, enhancing the robustness of the imputation process. Next, we normalized the numerical variables using StandardScaler, ensuring that they were on a similar scale, which helps in the convergence and performance of various models. Additionally, we conducted OneHotEncoding and Label Encoding on categorical variables using OneHotEncoder and LabelEncoder from scikit-learn to convert them into a numerical format that can be understood by the models. Class balance is achieved through the binarization of different labels/classes with damaged and not damaged/survived. This approach is essential, particularly in scenarios where certain damage classes may be underrepresented. This preprocessing pipeline allowed us to use a variety of models on the dataset, ensuring compatibility and enhancing the overall performance of the models.

In essence, this procedure, encompassing data categorization, stratified splitting, imputation, standard scaling, OneHotEncoding/Label Encoding, and resampling, laid the foundation for a robust and unbiased evaluation of the model's predictive capabilities regarding fire damage across diverse datasets.

Machine learning techniques

Machine learning (ML) methods have recently been applied to wildland fire[49] and present an ideal platform for WUI fires as interactions between competing factors can be fit and modeled. In this work, we employed both regression and classification ML techniques to our combined dataset resulting in a predictive model for structure destruction based on home hardening (roof, siding, vents, eaves, window, year built), vegetation separation (defensible space and surrounding), exposure metrics (flames and embers), and structure spacing. The XGBoost (eXtreme Gradient Boosting) machine learning algorithm was chosen as it outperformed other methods on our dataset. The model hyper parameters were tuned using RandomizedSearchCV, which was employed to perform a randomized search over a predefined parameter grid. This approach was used because of the large number of parameters in the XGBoost model. Hyper parameter selection is performed using the best result in terms of the following classification metrics: F-beta[50], F1-Score[50], accuracy[51], balanced accuracy[52] and precision-recall scores[53]. The F-beta score is used to balance precision and recall, with the beta parameter allowing for tuning the model's sensitivity to false positives and false negatives. Finally, feature importance with SHAP aggregation analysis was utilized to quantify the contribution of each feature to the target variable. A higher feature importance score indicates that the feature has a greater influence on the model's prediction[54]. The SHAP model connects optimal credit allocation with local explanations using the classic Shapley values from game theory and their related extensions[55]. This was then applied to a unified framework for interpreting predictions to explain the output of any machine learning model.

Classifiers

We employed several classification models, including Logistic Regression and Random Forest[48], and Gradient Boosting based XGBoost[56] since there is another method called Gradient Boosting Machine other than Extreme Gradient Boosting Machines (XGBoost). Each of these models offers distinct advantages and methodologies for analyzing feature importance.

Logistic Regression is a generalized linear model used for classification problems[57] and we use it as a base model to compare with more complex models. The second model used in this work is the Random Forest. Random Forests are a technique in ensemble learning utilized for tasks such as classification and regression. During the training, several decision trees are built. In classification, the random forest outputs the class chosen by the majority of trees[58]. CatBoost employs an ordered boosting technique to minimize target leakage from categorical features, often leading to robust performance even with limited parameter tuning[56]. While CatBoost can seamlessly integrate categorical data with minimal preprocessing and achieve competitive performance on binary classification tasks, logistic regression, random forest, and XGBoost typically require more elaborate feature engineering and preprocessing, which in turn can influence both model performance and the interpretability of sensitivity analyses such as those based on SHAP values. Finally, Gradient Boosting (GB) is a method in machine learning that employs boosting within a functional framework. The XGBoost (eXtreme Gradient Boosting) is a GB implementation that has been used as it outperformed other methods on our dataset. XGBoost is often preferable for developing predictive models for large datasets due to its accuracy, efficiency, and adaptability[38]. Furthermore, XGBoost is a robust algorithm for both classification and regression problems. Due to its strengths in model prediction, XGBoost can be utilized for damage assessment to create predictive models for structure destruction. The SHAP analysis results for all four models are provided in the Supplementary Materials (Supplementary Figs. 1–3). These figures offer a detailed breakdown of how each feature contributes to the predictions across models, enhancing the interpretability of our findings and complementing the results discussed in the main text.

Feature contribution through SHAP analysis

While machine learning (ML) models are increasingly used due to their high predictive power, their use in understanding the data-generating process (DGP) is limited. Understanding the DGP requires insights into feature-target associations, which many ML models cannot directly provide, due to their lack of understanding causal effects. Feature importance (FI) methods provide useful insights into the DGP under certain conditions[59]. Furthermore, SHAP (SHapley Additive exPlanations) is a unified framework for interpreting machine learning models based on cooperative game theory[55]. It assigns each feature an importance value for a particular prediction by computing the contribution of each feature to the prediction, averaging over all possible combinations of features. This approach ensures consistency and local accuracy, providing insights into how different features influence model predictions. SHAP values can explain individual predictions and provide a global understanding of the model's behavior, making it a valuable tool for model interpretability in research[54]. SHAP can be considered a form of in-sample sensitivity analysis because it assesses how changing a feature or a subset of features affects the model's output. It evaluates the impact of including or excluding a feature and identifies which features contribute most to the predictions[60]. We utilized SHAP interpretation analysis of feature importance to identify and understand the key factors driving structure destruction in WUI

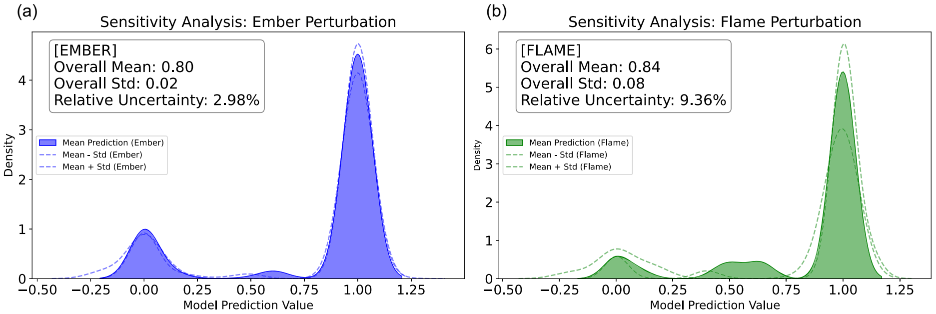

Fig. 8 | Sensitivity analysis with respect to ember and flame exposure with perturbations. A sensitivity analysis is shown, performed by perturbing two key exposure inputs—ember deposition and flame length—using 100 ensemble outputs from the ELMFIRE spread model (HAMADA extension) for each fire, while holding all other predictors constant. For each test sample ($n = 47{,}742$), the model's predicted survival probability was computed across ensembles to yield a mean prediction (solid fill) and its uncertainty (shaded region = ± 1 standard deviation). **a** Ember perturbation: blue fill shows the kernel density of mean predictions under varied ember load; dashed blue lines mark mean ± std. Inset reports overall mean, standard deviation and relative uncertainty (%). **b** Flame perturbation: green fill shows the kernel density of predictions under varied flame length; dashed green lines mark mean ± std. Inset reports overall mean, standard deviation and relative uncertainty (%). This framework quantifies the influence of non-linear interactions and input variability on the binary damage classification (0 = not damaged, 1 = damaged), reveals emergent intermediate prediction modes, and offers both local and global insights into model behavior under uncertainty.

fires. In this study, we opted for SHAP (SHapley Additive exPlanations) as a model-agnostic tool because its values not only quantify the magnitude and direction of each feature's contribution, but also capture complex non-linear interactions between variables[55]. This provides both local and global insights that are critical for understanding the multifaceted nature of fire damage. For example, SHAP allowed us to reveal how features such as SSD, ember exposure, and flame length interact in non-linear ways that traditional importance measures might overlook. Ultimately, the detailed and context-specific information provided by SHAP helped us interpret the predictive factors driving structural vulnerability, reinforcing the robustness of our findings.

Sensitivity analysis for the machine learning model

We developed a comprehensive sensitivity analysis framework to assess how variability in key input features from the exposure model (ember load and flame length) affects our model predictions. For each of the five fires, ensemble outputs from the WUI fire spread model were used to perturb the "ember load" and "flame length" variables while keeping other inputs fixed. By aggregating the model outputs from these multiple ensemble runs, we computed the mean predictions and corresponding uncertainties for each test sample. This approach allowed us to quantify the impact of non-linear interactions and input variability on the final predictions, offering both local and global insights into model performance.

Visualizations, such as kernel density estimation (KDE) plots, clearly illustrate the distribution and variability of the predictions across the test samples (Fig. 8). The shaded regions represent the uncertainty around the mean predictions for both ember and flame perturbations, with the respective overall mean, standard deviation, and relative uncertainty values indicated within the plots. These distributions provide a clear view of the uncertainty and variability in the model's response to perturbations in ember load and flame length. Additionally, SHAP analysis was employed to further interpret the contributions of each feature, enhancing our understanding of the model's behavior under different exposure conditions. This sensitivity analysis not only characterizes the associated uncertainties related to flame and ember in the model but also suggests that the machine learning estimator, XGBoost, has learned an underlying understanding of the problem implying intermediary outcomes other than damaged and survived are possible in the dataset; see the emerged middle class distributions in Fig. 8. Additionally, it helped us gain insights into the physical factors influencing damage, as it highlights the non-binary classifications for the damage classes, offering a more nuanced understanding of the damage severity.

Confusion matrix and ROC curve for predictions

A confusion matrix summarizes the classification performance of a classifier with respect to some test data. It is a two-dimensional matrix, indexed in one dimension by the true class of an object and in the other by the class that the classifier assigns[61]. Receiver operating characteristics (ROC) graphs are useful for organizing classifiers and visualizing their performance. A receiver operating characteristics (ROC) graph is a technique for visualizing, organizing and selecting classifiers based on their performance[62]. We investigated the five large WUI fires in our dataset to predict structure survival during each fire by understanding the model's accuracy, and other key performance metrics. By analyzing the confusion matrices and ROC curves for each fire event, we were able to identify patterns and discrepancies in model performance, leading to a better understanding of the factors influencing structure survival in large WUI fires.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets generated during and/or analyzed during the current study are available in the [DINS_data_analysis] repository, [https://github.com/berkeley-firelab/DINS_data_analysis]; [https://doi.org/10.5281/zenodo.15776778][63].

Code availability

The code used to conduct the analysis in this study is available in the [DINS_data_analysis] repository at [https://github.com/berkeley-firelab/DINS_data_analysis]; [https://doi.org/10.5281/zenodo.15776778][63].

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Acknowledgements

We would like to express our deepest gratitude to Matt Lee, Dave Shew, Dave Sapsis, Steve Hawks, and William Brewer from CAL FIRE for their invaluable contributions, guidance, and expertise throughout this study. Funding for this project was provided by the California Department of Forestry and Fire Protection's Forest Health Program as part of the California Climate Investments Program, grant 8GG21815. Additional funding by the Gordon and Betty Moore Foundation (11999), and the National Science Foundation (NSF) (1854952) also supported this work.

Author contributions

M. Zamanialaei performed the conceptualization, data curation, data analysis, and wrote the original draft. D. San Martin carried out the conceptualization, data analysis, and methodology. M. Theodori performed the data curation, conceptualization, and methodology. D. Purnomo contributed to the conceptualization, and reviewing and editing. A. Tohidi conducted data analysis, visualization, methodology, and reviewing and editing. CH. Lautenberger contributed to the methodology and reviewing and editing. Y. Qin contributed to the methodology and reviewing and editing. A. Trouvé contributed to the methodology and reviewing and editing. M. Gollner supervised the work, contributed to conceptualization, and reviewed and edited the writing.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-025-63386-2.

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Peer review information *Nature Communications* thanks Patricia Alexandre, Taskin Kavzoglu and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.