


Wildfire Risk Indices & the Built Environment:

Part 2 - Gaps and Opportunities

Winter 2025

HEADWATERS ECONOMICS

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About Headwaters Economics
Headwaters Economics is an independent, nonprofit research group whose mission is to improve community development and land management decisions. https://headwaterseconomics.org/

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Executive Summary

The increasing frequency of WUI wildfire disasters has spurred greater attention, funding, and research, bringing new disciplines and deeper expertise to risk modeling in the built environment. While recent advancements have significantly improved risk models for the built environment, there remain critical barriers to making models accurate, scalable, and transparent.

Structured interviews with 30 experts in wildfire risk modeling for the built environment revealed both divergent perspectives and common themes that highlight opportunities for advancing the field. While some experts argue that changing human behavior is the primary barrier to risk reduction, others contend that better risk information is essential to guide mitigation investments. Opinions also vary on the viability of operational models, use cases, and the balance between fine-scale fire physics and simplified, computationally efficient models. Despite these differences, experts broadly agree on key challenges and opportunities.

Five common themes emerged. First, the complexity of wildfire in the built environment requires bridging wildland and built environment models while accounting for human behavior and dynamic conditions. Second, a lack of coordination and collaboration across disciplines and agencies hampers progress, underscoring the need for a central coordinating body. Third, gaps in risk components limit model accuracy and validation. Opportunities to enhance risk components include improved data on the built environment, fire science, social science, engineering, modeling approaches, and technology. Fourth, operational readiness is constrained by challenges in reproducibility, model validation, scalability, and usability for practitioners. Finally, experts emphasize that risk modeling must expand beyond individual structures to address community-wide vulnerabilities, standardize risk communication, and support public education and workforce development.

Addressing these challenges will require a systems approach built on three pillars: (1) formalizing coordination and collaboration across disciplines; (2) clarifying the linkages, dependencies, and bottlenecks among research components; and (3) expanding the view of communities to account for not only physical vulnerabilities but also community capacities and broader social impacts. Five near-term opportunities could accelerate progress:

- Establishing a central coordinating body,
- Prioritizing data collection and characterization,
- Enhancing model transparency and validation,
- Clarifying problem definitions and practitioner needs, and
- Balancing risk modeling with behavioral change.

While improved risk modeling is essential, it must be embedded within a broader risk management approach—including risk communication, community engagement, and practical mitigation efforts—to drive meaningful reductions in wildfire risk.

1. Purpose and Background

Accurate models of wildfire risk are needed to inform disaster preparedness, land use planning, and land management decisions. As wildfire risks increase and as populations expand into wildfire-prone areas, the potential of fires entering and spreading through neighborhoods is also increasing. However, emerging science that captures the physical and probabilistic processes of how fires ignite homes and spread through the built environment has not yet been operationalized in national, publicly available models of wildfire risk.

This report is the second phase of a project in partnership with the U.S. Fire Administration, Headwaters Economics, and Pyrolgoix, a Vibrant Planet Company. Phase 1 inventoried and evaluated existing fire risk indices through literature review.[1] We found that emerging risk models capturing fire ignition and spread in the built environment are not yet operational in national, public wildfire risk models. Current models trade off built environment detail for operational readiness. In other words, scalable models lack precision, while detailed models are not ready for widespread use.

Phase 2 of the project, synthesized here, builds on findings from Phase 1. It addresses the gaps and opportunities in risk modeling indices with additional context, perspective, and insight from interviews with 30 subject matter experts.

2. Methodology

We identified subject matter experts (SME) to include in the interviews by first targeting prominent researchers whose work was reviewed in Phase 1, with a focus on those working on built environment risk modeling. Second, we used snowball sampling by asking each SME to provide additional recommendations in their networks. Third, we iterated with collaborators to validate our list and to provide additional recommendations. Most of the potential SMEs we contacted were responsive and agreed to the interview, but some were unresponsive or had scheduling barriers. One potential SME declined to be interviewed.

In total, 30 SMEs participated. Appendix A provides a complete list of SMEs interviewed and more detail about the expertise represented in the interview pool. Subject matter experts interviewed span the private, nonprofit, government, and academic sectors, and they have expertise in WUI fire spread modeling, risk modeling, civil engineering, fire protection engineering, fire physics, fire ecology, economics, insurance, and data science. While we strived for diversity of opinions and experience in our choice of interviewees, the perspectives expressed are primarily by researchers since the focus was on gaps in risk modeling, not gaps in its application or user experience. We also limited our pool to experts working in the United States. Interviewees may carry biases given their specific area of expertise and work history, and the interviewers from Pyrologix may similarly have domain bias or knowledge gaps.

We conducted structured interviews in remote video calls and recorded transcripts using Tactiq. Each interview followed a standard set of questions (Appendix B) that were generalized to bring out the area of expertise of individual SMEs. Questions were primarily open-ended to allow for open-ended remarks.

Interview notes and transcripts were reviewed and categorized to winnow and identify key themes and sub-themes, noting points of SME agreement or disagreement. Salient quotes from SMEs were selected and tagged (Appendix C). While interviewees rarely discussed specific details or solutions, broad themes and opportunities clearly emerged and are enumerated in the following section.

[1] Headwaters Economics & Pyrologix. 2025. *Wildfire Risk Indices & the Built Environment: An Inventory of Current Models.*

3. Key Findings

The following sections describe key findings and emergent themes. We begin with divergent perspectives. Though generally few, these reflect concerns around high-level issues such as need, purpose, and viability. We believe awareness of these divergences will help with interpretation of the rest of the report. We next review points of commonality, which were many, and which focus on identifying and articulating gaps related to wildfire risk modeling in the built environment. Select quotes pertaining to each finding can be found in Appendix C.

3.1. Divergent Perspectives

Given diverse interviewee expertise and backgrounds, some divergence in priorities and perspectives was expected. However, the more compelling divergences we observed related to the utility, near-term feasibility, and potential use cases of implementing models capable of credibly simulating fire spread and loss in the built environment. Divergences can be grouped into the following themes.

1. **Need.** Some argue that behavior change is the primary barrier, not lack of risk information. Others contend that in the absence of better risk information, investments in mitigation could be misallocated. As one example, wildfire risk was compared to smoking – people won't change their behavior even when they are aware of the risk. Others contended that in the absence of better risk information, investments in mitigation and hardening could be misallocated – for example the individual parcel with the highest localized risk may pose the least risk at the community scale given configuration of built environment fuels or prevailing wildland exposure pathways.

2. **Viability of models**. While some experts see near-term feasibility for operational models, others contend that the science isn't mature enough for credible predictions, especially regarding structure ignition and mitigation strategies. Some went so far as to suggest that attempting to model structure ignition processes is a fool's errand given the sheer number of variables influencing vulnerability. This could relate to different interpretations of prediction and probabilistic forecasting in risk assessments, which was beyond the scope of our interviews.

3. **Use cases.** Not all experts agreed on the spectrum of potential use cases, which included home and community hardening, fuels mitigation, evacuation planning, and firefighting operations. Opinions varied around their relevance in real-time operations. Some contended that risk information could help more precisely prioritize structure protection efforts to avert transition to an urban conflagration, whereas others suggested that in these types of scenarios firefighting resources are often overwhelmed or ineffective and therefore promoted use for prevention and mitigation before a fire. Some researchers suggested the primary near-term use case is scenario analysis to explore assumptions and the efficacy of various mitigation options, with an attenuated chain to eventual on-the-ground action.

4. **Complexity and fire physics.** There is debate on whether to focus on fine-scale fire physics or adopt simplified models that emphasize computational efficiency and uncertainty quantification. Several interviewees lamented limited progress in our basic understanding of fire physics or the combustibility of various structures. We heard the perspective that researchers might be "putting the cart before the horse" by focusing on model efficiency or catalyzing action when the basic science is not sufficiently mature. Others by contrast are less insistent on capturing fine-scale physical processes and believe that simplifying assumptions and improving computational efficiency allow for ensemble modeling that accounts for multiple sources and types of uncertainty to provide useful probabilistic estimates. Similar differences of

> ***"Would better mapping reduce the gap between the science about what we know we want people to do, and what people are actually doing?"***

opinion were expressed regarding the role of artificial intelligence and machine learning, and that absent comprehensive understanding of how events unfolded (e.g., did the tree catch on fire first and ignite the home or the other way around), the model-derived patterns could be misleading.

5. **Timeline to operational readiness.** Optimistic views suggest operational models may be achievable in a few years, while more skeptical perspectives see timelines ranging from 5 to 15 years or longer for sufficient validation and data. Generally, those in the modeling space believed that operational use was attainable in the coming years, at least for pilots with local communities and eventually scaling up. One interviewee suggested that the modeling community is more than one generation from accurately capturing risk.

3.2. Common Themes

Perspectives of interviewees generally converged around five main categories: (1) complexity and change; (2) collaboration and coordination; (3) risk components; (4) operational readiness; and (5) expanded opportunities. Each is synthesized in Table 1 and described in more detail below.

Table 1: Common Themes, Gaps, & Opportunities

Primary Themes	Subthemes
Complexity & Change *Modeling fire in the built environment is inherently complex and rapidly changing.*	**Salient events:** Catastrophic events are changing perspectives, awareness, and creating opportunities for research.
	Awareness: Due to more frequent catastrophic events, awareness is increasing and the focus is shifting toward the WUI and built environment.
	Climate: Changes in extreme weather and climate are contributing to the complexity and uncertainty of modeling.
	Funding: There is more attention from funders, but also more researchers working on these issues, increasing competition.
Collaboration & Coordination *Addressing built environment fire risk requires a formalized, structured, multidisciplinary and interagency approach.*	**Interdisciplinary:** Coordination and collaboration is needed across the research community, including fire scientists, fire ecologists, fire behavior modelers, data scientists, civil engineers, mechanical engineers, fire protection engineers, and social scientists.
	Interagency: Agencies have been siloed and can lack willingness to change direction or share historical ownership of problem areas.
	Researcher-practitioner interaction: Better understanding of practitioner needs and use cases could improve models.
	Mechanisms for coordination: Collaboration is unlikely to happen organically and there is need for a systemic coordination through formal and/or funding channels.
Risk Components *Improved data, science, and technology are needed to better capture built environment and structure-to-structure ignition risk components.*	**Data**: Better data is needed about the characteristics of the built environment, how fire propagates through it, and with what consequences, including data about: • Built environment characteristics • Real-world fire observations • Post-fire damage assessments • Mitigation and response activities
	Fire Science: Improved understanding is needed about how structures ignite and propagate ignitions, including: • Ember generation and transport • Flame spread dynamics • Fire-atmosphere-fuel interactions
	Social Science: Human behavior introduces uncertainty in modeling, requiring deeper understanding of: • Human behavior • Risk communication • Policy & regulation
	Engineering: Standardized experiments are needed to test building materials and evaluate structure performance against different exposure thresholds. • Materials testing • Burning experiments • Exposure and performance thresholds
	Modeling approaches: There is need to integrate modeling approaches to incorporate: • Coupled wildland & built environment models at multiple scales • Physical processes • Scenarios, probabilities, and predictions
	Technology: Advances in technology may facilitate improved data collection, analysis, and scalability, including: • Remote sensing • AI/ML modeling • Computational efficiency

Table 1: Common Themes, Gaps, & Opportunities	
Primary Themes	**Subthemes**
Operational Readiness *Structural risk models need to be validated, public, broadly scaled, and transparent.*	**Reproducibility**: To achieve transparency, robust critique, and public sector use, models will need: • Open science • Data governance • Benchmark datasets
	Model validation: Existing structure-to-structure fire spread models require further validation, which may be facilitated by: • Damage assessments • Fire progression observations • Evaluation criteria
	Scalability: Computational efficiency remains a concern for widespread use, especially for more intensive fire physics models. This can be aided by: • High performance computing • Pilot partnerships • Expanded geographies
	Useability for practitioners: Ensuring models are accessible to practitioners requires expertise beyond fire science and focused efforts on: • Scenario analysis • User focus • Training
Expanded Opportunities *Broader opportunities for development and application of fire risk indices should be considered.*	**Communitywide focus**: Risk modeling should extend beyond structures and parcels to include the full breadth of community values, including: • Critical infrastructure • Public health impacts • Collective action
	Standardization: Consistency and standards can help advance fire risk indices, especially around: • Design • Codes • Language
	Education: Increased public awareness is crucial, and training pipelines could help reduce barriers to entry in risk modeling. These efforts should include: • Public awareness • Translational research • Workforce development

(1) Complexity and Change

Experts agree that modeling fire in the built environment is inherently complex and rapidly evolving. Interviewees largely agreed that more comprehensive, actionable risk assessment hinges on developing models with greater realism, bridging wildland and fine-scale built environment models. However, wildfire's stochastic, dynamic nature—compounded by the complexities of human behavior and extreme weather—poses significant challenges. One interviewee cited human unpredictability, such as parking an RV in a hardened community or abandoned vehicles during evacuation, as a key vulnerability. Generating data to improve models requires detailed instrumentation, burning experiments, and post-fire case studies to understand critical drivers of incident evolution.

> ***"The uncertainties in these models are unbounded."***

Many interviewees noted that recent catastrophic fires like Tubbs, Camp, or Marshall[2] have heightened awareness, reframed WUI fire as an "urban fire problem," and attracted funding, researchers, and innovation. This influx has fostered progress but also intensified competition. Demand for risk models now spans different sectors, including fire protection districts, communities, utilities, and insurance. One interviewee noted that the biggest change in the wake of these events was simply the recognition that fire behavior in the built environment remains poorly understood. Some interviewees focused on the research

[2] Note that interviews were all conducted before the Palisades and Eaton fires in Los Angeles in January 2025.

community's reaction to these events, highlighting development of WUI fire spread models and advances in remote sensing and machine learning.

(2) Collaboration and Coordination

Interviewees almost universally cited the lack of collaboration and coordination as a central challenge, with silos leading to duplication and missed synergies. Key areas for improvement include: (1) interdisciplinary, (2) interagency, and (3) researcher-practitioner collaboration.

Interdisciplinary collaboration requires integrating diverse scientific perspectives (e.g., social science) into risk modeling and educating relative newcomers about the fundamentals of fire physics and structural engineering. Interagency collaboration faces hurdles in aligning missions, sharing historical ownership, and willingness to shift direction. Researcher-practitioner interaction needs better targeting of practitioner informational needs and use cases—though not all model developers interviewed prioritized this.

Many interviewees were skeptical that collaboration would emerge without a forcing function, suggesting the need for a stronger coordinating role. Some proposed creating a new agency. Others recommended shifting practices of funding agencies to support larger teams, longer time horizons, and unconventional, fundamental research to foster sustained development and knowledge generation. Whether through new initiatives, existing efforts like WUI Data Commons, the Wildfire Science and Technology Commons, or the "Fire Environment Center" recommended by the Wildland Fire Mitigation and Management Commission report, interviewees agreed the gap persists. A systems approach could clarify linkages, dependencies, and bottlenecks across research domains, improving coordination and knowledge generation.

> *"... the barrier is that we work in silos."*

(3) Risk Components

Experts identified multiple interrelated gaps in and opportunities for incorporating more information about the built environment and structure-to-structure ignition into risk components and modeling technologies, especially for the WUI Fire Spread model family, which simulate wildfire spread through communities. These models operate in the built environment and are sometimes able to be initiated with outputs of wildland fire spread models. They typically operate at the scale of single communities or structures. For more detail, see the Phase 1 report. (Appendix D includes a discussion of recommendations for the Wildland Fire Spread model family.)

Interviewees identified six interconnected gaps in risk modeling: (1) data, (2) fire science, (3) social science, (4) engineering, (5) modeling, and (6) technology. These categories are interrelated and therefore a systems approach is needed to advance modeling wildfire risk in the built environment. For example, remote sensing can enhance fire progression and damage maps, but without detailed post-fire case studies, root causes of failure may remain unclear. Further, better damage data improves structure vulnerability models but may do little to improve models of structures as a source of hazard or exposure pathway. Experts emphasized the importance of linking better data, science, and technology to specific risk components, including structure-to-structure ignition (Figure 1).

Data

Unsurprisingly, better data was a commonly identified need. WUI fire spread models rely on simplified assumptions that do not sufficiently capture the differences between buildings or the characteristics of defensible space. These differences remain uncharacterized due to the lack of WUI fuel attribute databases and the difficulty obtaining such data. Critical data is needed about built environment characteristics, fire propagation mechanisms, and associated consequences.

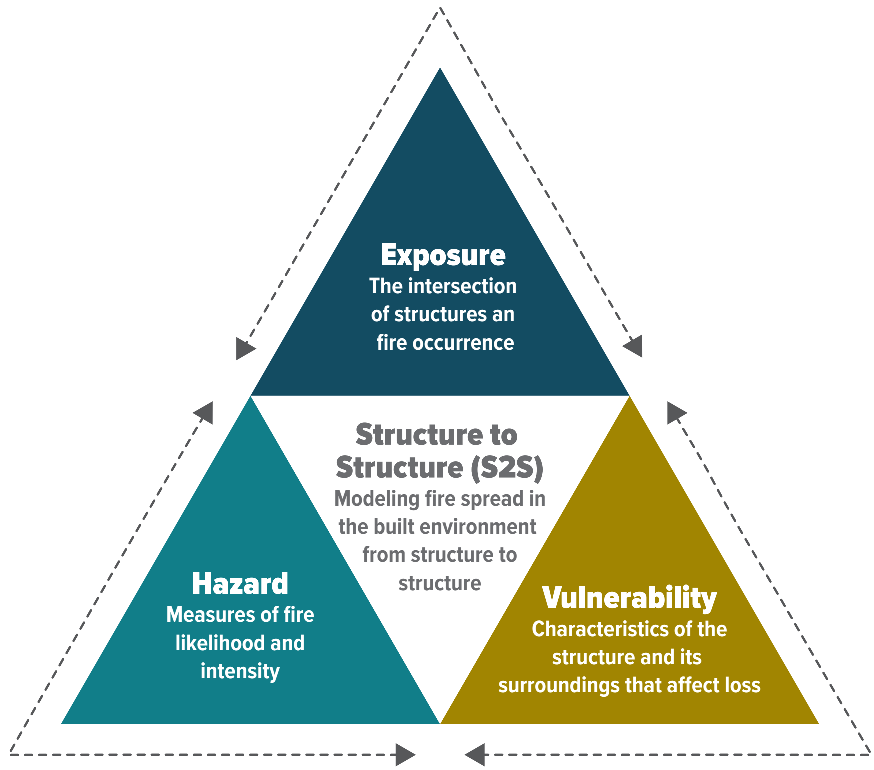
Some interviewees saw crowd-sourced data as a potential "silver bullet," while others raised quality control concerns. The absence of real-world data on fire behavior in the built environment was widely viewed as a key bottleneck. Addressing this gap depends on accelerating experimental and observational data collection—fires like Palisades and Eaton in Los Angeles, CA, will likely serve as test beds for future model validation. Experts suggested measuring heat release rates during urban conflagrations and conducting larger burning experiments. However, large-scale neighborhood burning experiments under varying wind and configuration conditions are unlikely in the near term due to budget and lab constraints.

The timeliness of built environment data was also highlighted. For example, homeowners may alter landscaping, renovate homes, or experience storm damage over time, significantly affecting hazard and vulnerability.

Finally, interviewees identified the lack of data on mitigation and response activities as a key gap hindering both retrospective and prospective evaluation of intervention effectiveness — gaps that persist in wildland fire modeling as well.

Figure 1: Risk components in the Built Environment.

Fire risk indices generally rely on three risk components: hazard, exposure, and vulnerability. Structure-to-structure ignition is logically interrelated to all three as shown in the "risk pyramid" below, but its explicit incorporation into models is nascent.



Fire science

The critical thresholds and parameters that govern how structures ignite and propagate ignitions was generally the key gap identified in fire science, with a focus on physical processes such as heat release, smoldering, and ember generation and transport. While flammability, heat release rates, and ember release characteristics have been determined for specific materials, they have not been determined for entire structures in which these materials interact in unknown ways. Capturing dynamic interactions with the atmosphere and the importance of weather in driving WUI fire propagation was also highlighted. Interviewees differed on the importance of capturing the underlying fire physics in models, identifying tradeoffs between causality and computational efficiency, among others.

> ***"Models are only as good as the data inputs"***

Social science

Although we only spoke with three interviewees who identified as social scientists, most interviewees highlighted a need for social science insight. Capturing human behavior as a source of uncertainty in models was mentioned, for example hasty decisions made during evacuation such as accidentally leaving a window open, although how to model these behaviors was not elaborated. More salient concerns regarded how to effectively communicate risks and catalyze uptake of mitigation recommendations. Interviewees also identified "fragmented policies" and a need to evaluate possible changes in policy or regulation.

Engineering

Interviewees identified a large role for engineering to play regarding testing of alternative construction materials and conducting burning experiments. Some interviewees highlighted a need for more intensive cooperation with numerical modelers to design experiments with their needs in mind, and to standardize experiments so results are more broadly transferable. Many highlighted a need to translate lessons learned from other natural hazards to fire, for instance the idea of a “demand” framework that brings a systematic approach to defining exposure thresholds and evaluating structure performance against those thresholds.

Modeling approaches

The primary issue regarding modeling was coupling wildland and built environment fire spread models, which several researchers are demonstrating, and extending further to couple with atmospheric models. The ability to scale these models from community to landscape and larger was also mentioned. The need for a better representation of built environment fuels, both structure and vegetation, was frequently highlighted, with some divergence on the appropriateness of adjusting fire behavior fuel models typically used in wildland fire spread modeling. Regarding appropriate uses of models, interviewees emphasized the need to clearly define scenarios for testing mitigations, related to the idea of demand and exposure thresholds expressed above. The need for probabilistic models capturing various sources of uncertainty was also common, which can allow for models to proceed absent known built environment characteristics or burning parameters, although interviewees diverged on the feasibility of near-term predictive use in risk assessment.

Technology

Lastly, many interviewees expressed optimism that technology could facilitate improved data collection and analysis as well as scalability of modeling. Remote sensing in particular was often mentioned, sometimes paired with computer vision to detect and differentiate built environment characteristics. Interviewees were generally ambivalent about opportunities for artificial intelligence and machine learning fire spread modeling, again highlighting tradeoffs between computational efficiency and interpretability.

(4) Operational Readiness

Interviewees identified a number of gaps related to the operational readiness of WUI fire spread models. The groupings we highlight here are very similar to the evaluation criteria used in the Phase 1 report, but are organized to identify critical improvement pathways. As with improving representation of risk components, improvement in these areas is predicated on collaborative, coordinated effort across research domains.

Reproducibility

Interviewees generally support the need for open science approaches to facilitate reproducibility, transparency, robust critique, and public sector use. The importance of common datasets was emphasized, along with a corresponding need for data governance structures across research institutions and sectors. As stated above, progress in this area is both based on and constrained by the availability and quality of experimental and real-world fire observation data. Interviewees also stressed the need to create benchmark datasets for model comparison.

Model Validation

Experts uniformly identified improved model validation as a clear need. Existing structure-to-structure fire spread models require further validation. Today their use outside of labs that they were developed in has been limited, though they are starting to be tested in communities for predictive purposes. Benchmark datasets—including continuous WUI fire observations with fire pathways, fuel characteristics, and heat release rates—would support validation. Experts point out that making predictions and observing outcomes is key, but especially difficult for rare events. Whether better performance of retrospective simulations will drive adoption remains uncertain.

> ***“The thing we are missing the most is the validation data.”***

Establishing common evaluation criteria and scenarios is needed to enable model comparisons. This could include observed perimeters, area burned, structure damage, spread rates, and incident heat flux. How to evaluate model performance for conditions outside of observed or experimental conditions is an open challenge. With limited historical datasets to benchmark against, a broader collaborative framework may be necessary for model verification and validation and should involve expert review beyond peer review. Interviewees generally believed in the importance of developing multiple modeling approaches and openly daylighting respective strengths and weaknesses.

Scalability

Improving the scalability of models was not an immediate priority for many of the interviewees, given their focus on improving the underlying knowledge basis for models. One common point of agreement was the need for computational efficiency, which in the near term at least precludes some of the more intensive fire physics-based models. Many interviewees believed the most opportune path was to begin testing these models through pilot engagements with communities, and expanding the geographic footprint to work with a diversity of landscape and community conditions.

Usability for Practitioners

Lastly, interviewees expressed the need to ensure models are accessible to practitioners—including planners and residents—which requires expertise beyond fire science, such as software engineering and product design. Investment in documentation and training is necessary for broader usability. While some experts envisioned eventual use in firefighting operations, the most feasible near-term application is scenario analysis to assess problem conditions and prioritize mitigation strategies.

(5) Expanded Opportunities

Beyond technical improvements to risk modeling, interviewees identified a number of opportunities for broader development and application. We organize these into three key areas: (1) communitywide focus; (2) standardization; and (3) education. Notably, these areas are interrelated with themes presented above, convergent with needs for not only a more systematic but also a more systemic approach.

Communitywide Focus

First, interviewees suggested the need to expand from structure and parcel risk to communitywide impacts. This includes consideration of evacuation routes as well as critical infrastructure that provides life-sustaining services and core community functions such as schools and hospitals. Some thought the models should support evacuation planning and implementation. Many interviewees also highlighted a need to better account for public health impacts from smoke and other pollutants. Lastly, consistent with social science themes above, interviewees articulated a need to study and catalyze collective action so that the onus isn't on individual residents and isn't piecemeal.

> ***"The area that is missing is community-level factors. Not every structure exists in a vacuum. If your community gets affected by WUI fires, what is your critical infrastructure?"***

Standardization

Many interviewees suggested a need for more standardization in this space. This may largely apply in the engineering and design space, for instance building on themes above for establishing demand thresholds and structure exposure definitions to inform design of both building materials as well as burning experiments, and can feed directly into code development. Interviewees also highlighted the need for codes to address community-level factors. Related, many interviewees suggested a need for common language to describe risk and design components across disciplines.

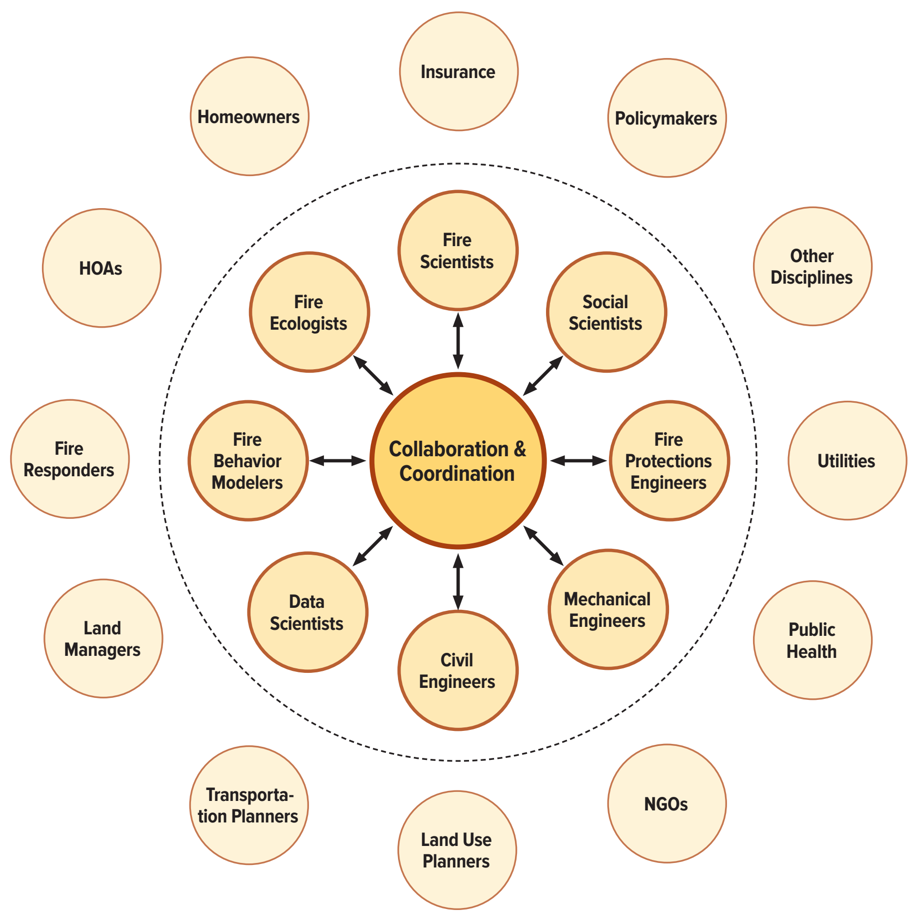
Education

Finally, many interviewees highlighted extensive needs for education. Public awareness was frequently cited, and relates to above social science themes on risk communication. Some interviewees argued that research needed to be more forceful in this space, suggesting that what mitigations might be socially acceptable are often insufficient. This also directly relates to identified needs for research translation and practitioner engagement. Looking ahead to sustained advancement of risk modeling in this space, many interviewees highlighted barriers to entry and the need to formalize workforce pipelines. There are only a handful of fire protection and structure fire engineering programs in the country – meaning most of the workforce comes from backgrounds in wildland fire or engineering in a different discipline, leading to knowledge gaps.

4. Discussion & Recommendations

The increasing frequency of WUI wildfire disasters has spurred greater attention, funding, and research. This influx brings new disciplines and deeper expertise, but it also raises the need for coordination to standardize data collection, minimize redundant efforts, and leverage collective efforts. Most interviewees observed significant advancements in fire science, engineering, and technology over the past five to ten years, which have greatly improved wildfire risk modeling in the built environment. The increasing urgency and demand for WUI fire spread models will likely drive faster development and use, even though some argue that progress should align with the availability of more numerical, experimental, and observational data for analysis—which is markedly slower. Experts agree that gaps in data, fundamental fire physics, and model validation are barriers, but opinions differ on the best ways to resolve these issues and within what timeframes.

Figure 2: Illustrative example of the broad integration needed for collaboration and coordination in a systems approach.



Clearly, for enhanced risk modeling to translate into effective risk management, a much broader set of issues needs to be addressed. We argue that a systems approach is necessary, built on three prongs: (1) improved collaboration and coordination between all the various entities working in this space; (2) improved understanding of the various research components, their linkages, dependencies, and bottlenecks; and (3) expanded view of communities as not only systems with complex interacting hazards and vulnerabilities that can't be addressed at the structure or parcel level, but also an expanded view to consider community capacities and fire impacts beyond structure loss. Risk modeling will only lead to better outcomes insofar as it is embedded within broader processes of risk communication and behavioral change and engagement with community members, funding entities, practitioners, and other sectors (Figure 2).

To move toward a systems approach, we highlight five broad opportunities that may help advance fire risk indices most significantly in the near-term:

1. **Formalize Coordination and Collaboration.** There is a clear need for a central coordinating body to help manage research and model development efforts. This body could conduct needs assessments, direct funding, and ensure collaboration across disciplines, which is currently lacking. A well-organized body can help align efforts and avoid siloed work in the wildfire risk modeling field.

2. **Focus on Data Collection and Characterization**: Better data is widely acknowledged as a bottleneck for both model parameterization and validation. Improved research and data are needed on the characteristics of buildings and defensible space, ember propagation and transport, WUI fire behavior and its relationship with mitigation and suppression, and how materials interact during fire. Developing such data is particularly difficult because there is a small set of real-world events against which to evaluate model performance, and lab capabilities to conduct burning experiments that reflect urban conflagration conditions are virtually nonexistent. Nonetheless, a concerted effort to develop benchmark validation datasets and standardize built environment datasets will be critical for advancing model accuracy.

3. **Enhance Model Transparency and Validation**: Current structure-to-structure fire spread models are not fully validated and have limited real-world applications. There is a need for open comparison and critique of existing models, possibly using publicly available benchmark datasets.

4. **Clarify Problem Definitions and Practitioner Needs**: Models are diverse, with differing assumptions and approaches. Interviewee opinions diverged on the viability and need for real-time use cases, for practical reasons relating to windows of opportunity under urban conflagrations as well as limited understanding of firefighting actions and effectiveness. Clarity is needed in defining problems, scenarios, and practitioners' needs to ensure models are aligned with real-world applications. Interviewees noted that while real-time applications may be impractical, models focused on identifying and prioritizing areas for mitigation are most valuable.

5. **Balance Risk Modeling with Behavioral Change**: While improving models is important, experts also emphasize the need to drive behavioral change, such as home hardening, creating defensible space, and implementing regulations. Investment in risk communication and translating scientific findings into actionable insights can help catalyze this change. Ground-level actions are likely to have a more immediate impact on reducing risk, making it essential to pursue both modeling advancements and practical, on-the-ground efforts simultaneously.

Understanding the distribution of risk is fundamental toward taking action to reduce risk, and the need for improved wildfire risk modeling of the built environment has never been more necessary and urgent. To drive meaningful reductions in wildfire risk, modeling must be embedded within a broader risk management approach, including risk communication, community engagement, and practical mitigation efforts.

Appendix A: Interviewees

The 30 subject matter experts interviewed span the private, nonprofit, government, and academic sectors. They have expertise in fields including WUI fire spread modeling, risk modeling, civil engineering, fire protection engineering, fire physics, fire ecology, economics, insurance, and data science. Of the participants we interviewed, five have been involved in wildfire and WUI issues for 20+ years, 10 for 10-20 years, and 15 participants have been involved for fewer than 10 years. Researchers were equally distributed between basic and applied research with research topics spanning building material heat release rates and ember characteristics to land management and ecological succession. Eight participants had conducted previous research and modeling with earthquakes and other hazards prior to moving into the wildfire space. Of all the participants, five were former firefighters and four worked extensively with practitioners such as fire departments and land managers on direct research applications. Five participants led the development of WUI fire spread models. Four participants worked specifically on the development of codes and standards for WUI risk modeling and wildfire-specific building construction guidelines. Two participants work directly on addressing data gaps in WUI fire risk modeling.

Subject Matter Experts Interviewed

- **Albert Simeoni -** Worcester Polytechnic Institute (WPI)
- **Alexander Maranghides** - National Institute of Standards and Technology (NIST)
- **Alexandra Syphard** - San Diego State University (SDSU)
- **Anna Lang** - Zylient
- **Arnaud Trouve -** University of Maryland (UMD)
- **Casey Zuzak** - FEMA
- **Chris Dunn -** Oregon State University (OSU)
- **Dani Or** - University of Nevada Reno (UNR)
- **Daniel Gorham -** Fire Safety Research Institute (FSRI)
- **Erica Fischer** - OSU
- **Ertugrul Taciroglu** - UCLA
- **Faraz Hedayati -** Insurance Institute for Home and Business (IBHS)
- **Frank Freivalt** - WUI Data Commons
- **Greg Dillon** - United States Forest Service (USFS)
- **Hamed Ebrahimian** - UNR
- **Hussam Mahmoud** - Colorado State University (CSU)
- **Ilkay Altintas -** University of California San Diego (UCSD)
- **James Meldrum** - WiRe, US Geological Survey
- **Jens Stevens** - USFS
- **Jonathan Hodges -** Jensen Hughes
- **Judson Boomhower** - UCSD
- **Leslie Marshall -** Society of Fire Protection Engineers (SFPE)
- **Michael Gollner** - UC Berkeley
- **Negar Elhami** - SUNY Buffalo
- **Nima Masouvaziri -** Berkshire Hathaway Specialty Insurance
- **Patty Champ** - WiRe
- **Sam Manzello -** Reax Engineering
- **Scott Ritter** - USFS
- **Steve Hawks** - IBHS
- **William 'Ruddy' Mell -** USFS

Appendix B: Baseline Interview Questions

The following are baseline interview questions that were generally asked of all interviewees. In order to extract the most salient findings from each interview, we tailored questions to the area of expertise of each interviewee. Therefore, in some cases not every question from the following list was asked to each interviewee, and additional questions were added to illuminate specific subject areas.

1. Briefly describe your background as it relates to WUI risk modeling.
2. What is the most important change that has happened in the last decade in WUI risk?
3. What is the most exciting thing happening currently in WUI risk modeling?
4. What is working that should not be changed?
5. What is not working that should be changed?
6. What are the biggest gaps or weakest links in WUI risk modeling?
7. How do we fill gaps in WUI risk modeling?
8. What are the broader barriers or limitations to advancing WUI risk modeling?
9. What will it take for current WUI models to become operational?
10. What aren't researchers thinking or talking about enough?
11. What aren't practitioners thinking or talking about enough?
12. Given unlimited funding and resources, how would you allocate budgets for the greatest return on investment in reducing WUI risk?
13. What are the barriers to entry for new participants in the WUI risk space?
14. What is the most promising aspect of your corpus of work?

Appendix C: Select Quotes

Select, anonymized quotes are shown here, grouped by themes described in the report body. Some quotes are slightly edited for clarity.

Divergences

Need

"When you are mitigating, it's not so much the science about what needs to be done. Would better mapping reduce the gap between the science about what we know we want people to do, and what people are actually doing? Would a better map with better information change that piece? I don't know, maybe, but I'm skeptical whether or not that's the silver bullet."

" I think that FireWise is overall not very successful, because we're trying to get people to do things that we don't even fully know about."

"Do we even know how well Firewise has worked? Do we know if those were dollars well spent? And on what basis would we even make that evaluation?"

"The state of modeling that's not working is the risk scores provided by FEMA, or even finer scale like those provided by insurance companies. FEMA gives you things at the aggregate level and it doesn't work. Even on a very fine scale, the production doesn't differentiate well between structures in the same neighborhood. The risk scores also haven't been validated."

"NRI is the best thing out there right now but I'm not a fan. NRI is not a measure of risk because they're not taking into account structural vulnerability and exposures, it's just hazard."

Viability

"I am extremely concerned about trying to map risk. Given the level of our understanding, I think there are fundamental issues here that make risk assessment difficult, which is very different from quantifying and mapping hazard. Going from hazard to risk is a tenuous undertaking. The nuances in terms of construction attributes, local exposures, defensive actions, etc., have dramatic impacts on events. When you start introducing homes, it's like counting angels on the head of a pin. I'm very uncomfortable implying that we have the capability to understand these events and how they're going to unfold. The fact that people are collecting data means nothing – it's completely nonsensical."

Use Cases

"We're looking at it from a suppression standpoint of stopping the fire from starting in the first place, putting out as quickly as possible, or preventing them from burning into communities."

"What are the relevant operational decision points that better WUI fire models would enable? Because if I think about Lahaina or Marshall or Camp, what would it look like for a better WUI fire model to have existed at the time that those blazes ignited? What would have been the intervention points that would have allowed for? And I would work backwards from that. Once you get structure-to-structure fire propagation, at what point are you at the mercy of changing weather conditions or changing fuel neighborhood continuity conditions, none of which are the things that you can control in the immediate response phase…. Our models need to be used to support planning decision-making rather than operational response decision-making."

"The thing about our model that has the most promise for advancing WUI fire modeling is the ability to incorporate mitigation. It's not fully in there yet, but it has the ability to do it. We can show the impact and encourage people to do mitigation."

"If there's so much focus on models designed to tell us where the fire is going to go next, rather than models that tell us how to plan, models are less effective in their immediate impact because we can't act as immediately on it."

Complexity Required

"For the types of planning applications that I have seen and have been involved with, I think a lot of the outputs get you most of the way to where you need to be. I think that we're ballparking where risk is relatively higher in one area versus another…. We're painting a reasonable picture of the relative risk landscape. And I think that there's room for refinement but I'm just not sure in all cases. How much is that going to buy you?"

"A house is represented by a piece of wood burning. I'm sorry but no. In terms of building a model we have to burn houses and study spread in the WUI.

Skepticism

"So I don't really see substantial progress…."

"...there's been a lot of energy spent with the use of machine learning and artificial intelligence, massive computers applied using landscape information from GIS and all the remote sensing information, but it's all spinning around very simple models like the Rothamel model. So I feel like it's just a lot more of the same thing."

Short-term vs. Long-term

"People are trying to go very fast and use AI or develop models with the simple understanding we have now, and we're not investing in long-term things."

"There's a time crunch here. We can figure out black holes and astrophysics on a scale of decades, but this is more time sensitive."

Common Themes

(1) Complexity & Change

Complexity

"It's a very complex environment and I don't know how a model spits out a realistic product for how a fire will spread from point A to point B. Considering embers, and how fire can travel along train tracks, etc. Then when it enters the community, there are infinite combinations of building materials."

"The uncertainties in these models are unbounded."

"Wildfire is the only hazard where your neighbor's risk has a huge impact on yours."

Change: Salient Events

"The Camp Fire was the most important thing to happen in terms of civil engineers. It was the first time that civil engineers said, 'We have to be involved.' That all of these heavily engineered buildings could have been completely destroyed in a wildfire was totally mind-boggling."

Change: Awareness

"The level of exposure to the intensity and impacts of these fires, the expansion of the areas that are likely to be impacted by these fires, area coverage of these fires, scale and vulnerability of populations, has shifted people's willingness to talk about this and see it as central to the work they do."

Change: Climate

"We used to characterize the fire problem as increased fuels, climate change, and expanding WUI, but I redefine that these days. It's much more that the changing climate has brought fire into our communities, rather than we've expanded out to it solely. Because everything that's been built in the WUI in the western United States was fine until it wasn't, and that's a real climate shift. And now we see fires in our backyards much more commonly and spreading so much faster that it's really exposing a greater amount of people than ever before."

Change: Funding

"In 2013, people didn't consider that there was a future in WUI fire research. That has completely changed because now there is money."

(2) Lack of Collaboration and Coordination

"... the barrier is that we work in silos."

"I don't see a lot of fire protection engineers in the room."

"The more players that are in the sandbox, the harder it is to coordinate."

"There needs to be people who operate as the connective tissue between depth of expertise - we need breadth and connectors who can see the big picture."

"Within government agencies, there's lack of coordination, but there's also this desire that they want to be the first. Same in academia. Everyone wants to be the first. Some high-level official needs to make a coordinated effort to make an impact on that problem."

"We don't have a needs assessment that prioritizes the most important thing at hand for the science and technology to address."

Interdisciplinary

"People are realizing we need multiple disciplines to solve the wildfire problem, especially with real time fire modeling. We are realizing there's a way to do it, we just have to integrate together."

"If we're looking at what's going to benefit society, we need to get the people to work together so that physics science gets put into these models."

"I've seen a shift in people who were previously not interested, now migrating to that funding. I think that it is a good thing in the sense that we can begin to solve very expensive problems, and it's driving more interest. But it also creates this challenge of understanding who is best suited to address these issues, and are they the right people to do the job."

"But there is this disconnect again between different fields of study. A good portion of this research that's based on using statistical or machine learning methods with remote sensing data is from people who are not in the fire area. So they might be geographers, they might be mathematicians. And so there's been a lack of understanding of fire physics."

Interagency

"There is an institutional inertia in each institution…there's a momentum from how they've done it for the last 20 years. And if that momentum is not allowing you to point in a direction that's going to come together with the other institution, then it's not going to happen."

"I'm seeing USFA show up more in the wildfire space than I was a few years ago. Whether that's pointing us towards better coordination remains to be seen. I don't know as much about their role as a science agency; I don't really know what their mission is."

"I'm pretty convinced there has to be a whole separate institution in the government to address the wildland urban interface problem."

Fostering Collaboration

"Foster is a gentle term, you know? I think you have to force collaboration because it's not gonna happen…. Getting actual real collaboration, even in people with the same background, not even multidisciplinary collaboration, it's very hard."

Funding

"What often is missing is a level of funding that funds two or three people to attack the problem together…. There's no mechanism for getting an interdisciplinary team to be funded."

"The Department of Defense just put out a call for research for WUI fire spread models. I would tell these people – if you want to do that, please work together, build a strong team or network nationally to be able to do that…. They need to be identifying those gaps and seeing who fills the gaps and forcing them to work together."

"Any kind of funding program has to be developed by talking to people on the numerical and experimental sides of the research community."

"The people who have the money need to force these different groups to work together."

"Everyone needs a marching order if we want to have an impact. Otherwise, we are going to spend a lot of money for just incremental gains."

(3) Risk Components

Data

"It's really hard to collect data on the characteristics of the structure. Even if that information was perfect, we don't know enough about how those things burn and what their heat release rates are to credibly parameterize a model that would show how it spreads…. Those construction materials are extremely complex and they're evolving all the time, and not all of those materials have been fire tested."

"When we study more, we need field experiments, lab experiments, and something that nobody is doing is going and measuring the evidence, and fire is the only disaster where we're not doing that. I understand that's a difficult thing, but we can do it in a way that we know is safe and with the technology we have we can measure these phenomena."

"Crowd-sourced data is hard because it changes depending on where you are and data needs to be repeatable."

"People don't talk about that response is the number one mitigation that we take, but we don't study firefighter response and the effects of their actions as much as we need to."

"There is not sufficient data on what protection actions make a meaningful difference in saving a home. We need a lot more data."

Fire Science

"Firebrands – we don't even know the mass distribution in different size classes from a given vegetation type that's burning in a fire of a given intensity due to a given wind field. We don't know any of this stuff. We do know from post-fire and other studies that firebrands are really important to structural ignition. So I would say our understanding of firebrands is the biggest gap."

"I think the dynamics of the fire spread in the communities – we're not really doing that. I understand where the WUI models are coming from, but their houses are represented by pieces of wood. We really need to study the spread in the WUI."

Social Science

"One thing we've observed is that there seems to be broader interest and engagement with the social side of things…. We've seen more interest in what it takes to both understand recommendations and get those recommendations implemented on the ground."

"Some of the biggest challenges we face are not the most technical."

"Communication is needed and can be improved at all levels. Every fire inspector says something different to the question, 'what needs changed about this home?'"

Engineering

"I think we need to do a lot more experiments that are standardized and in coordination…. Then let's do some experiments that would be designed with other modelers in mind, and would be fully replicable by anyone in the world…. What types of experiments can we do to come up with a scientific basis for mitigation?"

"Lab tests have incomplete information for our purposes because they were not conducted with wildfire modeling in mind. You have a simulation with two houses – one hardened and one not – the result of the hardened house not catching fire is not representative of a real wildfire. The amount of radiation of a whole neighborhood on fire is a lot different than just one house on fire. We're looking at the neighborhood because if you harden everything and only two or three houses catch fire, that's manageable."

"That requires laboratory studies that can reproduce exposure conditions that are known to be representative or sufficiently representative of the actual conditions."

"Doing tests such as 50kw exposure on structures and if they can withstand it for 30 minutes they pass. During my time at IBHS I learned about the idea of fragility curves which make sense to apply WUI fire spread models to this problem. But we don't have the knowledge to generate those, and the knowledge we have generated hasn't been in the form that makes it usable for that. Now that we think about it in that way, we can identify gaps and improve on existing research."

Modeling

"A pure physics-based model is the best way to do it, but you cannot run it at a large scale. The computational demand of the model limits the analysis to a specific simulation of a fire path. One single change in the model might completely change the fire boundary, so you need to be able to iterate quickly."

"Structure separation is THE driving force behind the risk. Everything is connected to that. It's fuel connectivity. And also it will be more difficult to evacuate. If I had to choose one element to be the surrogate for other things, it would be structure density in a neighborhood. You could estimate connectivity, evacuation and all those things."

"On the modeling aspect of it, the thing that does not exist is what we would call a scenario definition. What are all the inputs that should be in the model for the model to be considered valid and useful? Does it have to include structural components like building materials? Does it have to include the relative distance between buildings? Are we looking at community scale or just like an individual structure?"

"I think we have the fundamental knowledge to do better. In order to have the integrated wildland-urban platform, we need to rethink the spread process between wildland and WUI. The technology is mature enough that we can come up with semi-empirical models to do this, I believe. It just needs to be developed. And we need to do fire spotting better. And we need to characterize fuel."

"The probabilistic approach to embers works much better than the physics-based approach."

"The models are not working under the same assumptions for how structures burn – one code assumes a certain heat release rate and energy, and another code in terms of fire evolution. It starts with how the structure burns (probability of ignition), and then the fire spotting models. We all claim that this is the big driver of fire spread, and we insert uncertainty into the code…. Somebody needs to focus on fire spotting, somebody needs to focus on ignition. Once we know those details better, I think we can reduce the margin of error."

"Suppression and response time is tough to model and we're not doing that yet."

Technology

"You want to apply AI to satellite images or even detections because that's where we have the most data."

"I would invest in technology: how do we harness observational capabilities with characterization from the past to the present to help responders confidently know what is going to happen? It's not only related to basic science, but to have a platform that tells you 'here are all the components that you need to know' in order to give responders a good idea of what's going to happen."

"Using AI and image recognition, we can get all that information that's required."

"Automating certain components like fencing and decks is trickier. You can see things through Google street view if you want to use AI, but you have a lot of vegetation, and you can expect to have trees covering these things. This makes it harder for AI and the error goes up, so we haven't automated this yet."

(4) Operational Readiness

Reproducible

"And if it's all a black box, a whole lot of fire service folks won't be willing to stake operational decisions on things that they don't feel comfortable with or that they don't understand."

"Having advisory structures over data to say certain types of data need to be handled and shared in a certain way…. The data culture of how fire management or government acquires and owns and serves data is a barrier. They're all different business models. Census data for example is acquired by taxpayer dollars but it's owned by the censors. What happens to private data that insurance and counties collect, and what are the rules for engagement around that data? These are the types of data that can enable risk models, but nobody except those communities can make that data open. The culture is that these things are trade secrets, but it doesn't have to be."

Validation

"In terms of research investments, the first thing that comes to mind is the rigorous confrontation of models with empirical data to at least be able to learn from the bad outcomes that we're going to continue to see."

"The thing we are missing the most is the validation data."

"My main concern is the overuse of simplified methods. I've seen this kind of thing happen, that people will present things that look good, but you can't tell how well they're actually working."

"It's having subject matter experts who are familiar with large fires moving across the landscape assess these things. It's looking at sensitivity analysis within a model itself, but then also comparing models to each other. There's basically none of that, especially comparing models to each other, going on that I can tell."

Scalable

"We may be reliant on private technology for scalability. The WRF-Fire people don't have the people or money to say 'can I create a GPU version of this, or can I run a bazillion simulations simultaneously on any asset?' I see that happening on the private side. On the government side, they're just kind of lounging around."

"Scaling our model requires data collection on fuel in communities regarding defensible space, and the processing and archiving of that data. Getting servers to run the model on. Good ignition probability maps. Developing a GUI that allows people to use this easily without having to worry about thousands of lines of code in the model…. It's going to scale quickly. If it's not taken up at a national scale, communities will reach out to us. Scaling up in the next two years would be possible and really cool."

Usable

"You need a PhD or be a PhD student to start to run that, right? We need the people who are going to build the interface and we need to have a convergence here. We need also to have more trained people in the different places, not the research part, but the operational part; people to operate those models. So there is a component about the delivery."

"Practitioners are no longer just firefighters and foresters. They are city planners, insurance, homeowners, construction workers, etc. We haven't thought about how the models are going to be used by people. Even if we get an output, what do we show them? How do we show them some impact quickly without overstating or understating? You can twist the model to suit your purpose and there are a lot of issues with that."

(5) Expanded Opportunities

Community Focus

"But there are also needs of community members that aren't premised on those models improving, right? We can understand how to provide better warnings and how to provide better identification of egress routes and refuge zones within a community."

"I think there's been a broader acceptance that there's no one building component, it's where those components intersect. The step forward is to take a systems approach and scale that up to the community where it's not just an individual fuel but an amalgamation of fuel. That's where we're catching up in the codes and standards space because they're not historically built in that way."

"The area that is missing is community-level factors. Not every structure exists in a vacuum. If your community gets affected by WUI fires, what is your critical infrastructure, in particular maintaining water systems. Fire suppression in the US is dependent on water-based systems (trucks, hydrants). We've seen instances when there are catastrophic events that affect water pressure (Marshall Fire) and that's a problem."

Standardization

"We're missing descriptors that differentiate the Camp Fire from the Tubbs Fire, and we're missing the vocabulary to describe the relative exposure of different communities."

"We need a language to understand capacity and demand with respect to building materials and wildfire. We don't have a vocabulary for this. What is the magnitude 9 (earthquake) version of wildfire? Once we can talk about the demand, then we can talk about the capacity that structures need to handle that given demand. Right now we're just saying "fire," and there's no quantification of the demand, so we can't model it and we can't build to standards for capacity."

"What I'm trying to build is a standard vocabulary and social technical framework for people to work with open data and open science in a computational sandbox."

“ICC 605 Task Group 2 is coming up with a new code for WUI and there’s a chapter for communities: ‘standard for residential construction in regions with wildfire hazards.’ And they’re using the knowledge we’re generating to develop these.”

“Most of the researchers in the US are completely out to lunch on the standards and codes. We looked at what test methods are available for WUI materials (roofs, decking), then we recognized that there were no test methods for firebrand exposure. We also recognized that there is no globally accepted method for doing a damage assessment after a WUI fire.”

Education

“That science is great. I think the problem has been there’s just a huge gap in proper implementation of that science.”

“There is a big gap between research funding and the benefit of that research to boots on the ground.”

“It seems like there’s good work going on in the space, but as is often the problem, the physicists and the engineers should try to talk to the firefighters a little more – and vice versa.”

Appendix D: Recommendations for Wildland Fire Spread Models

Most of the interviews focused on gaps and opportunities for WUI Fire Spread models. However, as identified in Phase 1 of this research, the Wildland Fire Spread modeling family generally has the greatest operational readiness. Wildland Fire Spread models capture the influence of topography, weather, and flammable vegetation on fire spread potential. They characterize risk impact to the built environment through wildland fire exposure. They typically operate at national, regional, and multiple community scales.

Though Wildland Fire Spread models generally lack granularity of built environment characteristics and have a limited ability to capture complex structure-vegetation fire interactions, incremental improvements could help advance these models to better capture built environment risk.

Some recommendations for improving risk components in Wildland Fire Spread models were offered during the interviews and include:

- **Account for structure density,** which is often included when assessing structure vulnerability but not necessarily for hazard or exposure modeling, and the related metric of structure separation distance.
- **Differentiate vulnerabilities across structures,** which is true for WUI fire spread modeling as well.
- **Refine spatial smoothing** of wildland hazard metrics into developed areas.
- **Refine customized fire behavior fuel models** for developed areas based on observed fire spread into and through communities.