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The NIST Wildland-Urban Interface Fire Case Study Approach and Outlook

Eric D. Link

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Cover Photos
Field data collection of a damage home (left) and a technical discussion meeting (right).

Abstract

Wildland-urban interface (WUI) fires are a threat to thousands of communities in the United States. Thousands of structures are destroyed, and thousands of lives are threatened or upended by fires every year. There are valuable lessons to be learned from these WUI fire events to help communities become more prepared, resilient, and resistant to fires in the future. Since 2007, the National Institute of Standards and Technology (NIST) has conducted four post-fire case studies to do just that. This document summarizes the past case studies, which have served as a technical anchor for NIST's WUI research, as background and motivation for future case studies. The approach and methodology for data collection and analysis is described. A range of different post-fire deployment possibilities is presented along with parameters to consider for future case studies including areas of technical interest, staffing, training requirements, and suggested tools and equipment.

Keywords

case study; field data collection; fire; investigation; wildland-urban interface; WUI

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Acknowledgments

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1. Introduction

The hazards and impacts of wildland-urban interface (WUI) fires significantly affect life safety and property across the U.S. In 2020, 44 million housing units in the U.S. were located in the WUI [1], with more than 60 thousand communities at risk of WUI fires [2]. Thousands of structures are destroyed [3], and dozens of lives are lost in WUI fires each year. The effects of climate change resulting in increased fire activity and severity [4], combined with the expansion of WUI [5] presents increased risk of losses in wildfire events. Numerous states across the nation have experienced their largest or most destructive WUI fires since 2018, including California, Oregon, Washington, Colorado, New Mexico, Hawaii, and Tennessee.

Understanding the mechanisms of these fire events—how fire spreads through communities, how incidents progress, how actions of first responders affect outcomes, and how mitigation efforts perform—are critical research aspects to reduce the burden of WUI fires. Post-fire case studies provide a means to learn from past incidents and experiences [6]. Case studies vary in scope and detail, ranging from data collection to count and identify damaged structures (e.g., [7-9]) to comprehensive incident analyses conducted by government commissions [10, 11]. Topics and themes from a sample of past case studies include identification of home/structure ignitions and vulnerabilities [12-14], spatiotemporal fire progression [15-17], evacuation [18, 19], and effects of vegetative fuel treatments [20]. Other studies highlight multiple aspects of a single fire incident [21, 22], or conduct bulk data analysis across multiple fires [23-25]. The National Institute of Standards and Technology (NIST) Fire Research Division has a long history of post-fire case studies, in both indoor fires and WUI fires. Since 2007, NIST WUI fire researchers have conducted four in-depth case studies. The understanding of WUI fire incidents achieved through these detailed post-fire case studies have provided a foundation for WUI fire research and mitigation efforts within NIST and beyond. However, there is still work to be done to develop and implement proven mitigation approaches to reduce structure losses in WUI fires and enhance life safety of both residents and first responders. Furthermore, a host of recent rapidly spreading and devastating fires have illustrated the need for improved response, notification, evacuation, and recovery plans for communities at risk of WUI fires. Additional in-depth case studies of WUI fires will continue to inform scientific advancement through the lens of real-world incidents, confirm the efficacy of mitigation and response strategies, and identify necessary improvements [26-32].

The primary objective of this report is to outline the technical and logistical requirements for possible paths for future NIST WUI fire case studies. A brief overview of the previous four WUI fire case studies is presented in Sec. 2 to provide background and context for guiding future efforts. Section 3 describes the technical foundation and approach of past NIST case studies. Section 4 presents the range of potential technical responses to future WUI fire incidents and highlights logistical and technical plans for future WUI fire case studies.

2. Previous NIST Case Studies

NIST researchers have conducted ten primary post-fire field deployment activities since beginning dedicated WUI fire research in the mid-2000s. Those activities, listed in Table 1, include four in-depth case studies and other related fieldwork to support or develop such studies. Events include wildfires in interface communities, where wildland vegetation abuts a developed area, and intermix communities, where a community is situated among wildland vegetation. Additional WUI fire incidents beyond those in Table 1 have prompted specific outreach between state/local agencies and NIST researchers, but the number of fires far exceeds the capacity of researchers to study each in detail.

Table 1. Previous NIST post-fire field deployments and case study fires.

Year	Event Name	Location	Event Type	Deployment Type
2007	Witch/Guejito Fire	San Diego, CA	Interface	Reconnaissance and first case study
2009	Station Fire	Los Angeles, CA	Interface	Practiced quick-response deployment and integration into the incident command system (ICS)
2009	Black Saturday fires	Australia	Interface	Consulted on data collection methodology and fire behavior
2010	TFS[A] Training	Bastrop, TX	Training	Trained collaborators in the NIST WUI data collection methods
2011	Tanglewood Complex	Amarillo, TX	Interface	Reconnaissance and case study
2012	Ponderosa Fire	Manton, CA	Intermix	Technical advisor to the incident commander
2012	Waldo Canyon Fire	Colorado Springs, CO	Interface	Reconnaissance and case study
2017	Tubbs Fire	Santa Rosa, CA	Interface/urban	Reconnaissance and follow-up collaborations
2018	Camp Fire	Paradise, CA	Intermix	Reconnaissance and case study
2023	Maui fires	Lahaina, HI	Interface	Reconnaissance

[A] TFS: Texas Forest Service

The four case studies have resulted in a wide range of findings at all scales of WUI fire incidents, from parcel-level fire behavior and firefighting effectiveness to interconnected incident-level dynamics of fire progression and response. This has contributed to a more comprehensive understanding of WUI fire incidents and enabled targeted insights into post-fire data, leading to implementable mitigation and preparedness strategies. Each of these case studies were undertaken with support and partnership from local fire departments and other federal, state, and local agencies and non-governmental organizations. These collaborations enable access to fire incidents for focused data collection and facilitate knowledge transfer directly to the affected communities and practitioners.

Distinct benefits of WUI case studies include:

1. enabling researchers to understand what occurs during complex WUI fire incidents, including fire progression, emergency response, defensive actions, and structure performance;
2. providing a focal point for the research activities of NIST and other collaborators, including the implementation of mitigation strategies via input to codes, standards, and best practices; and
3. establishing a platform for direct knowledge transfer with stakeholders around the U.S.

The technical focus areas of the four case studies are summarized below in Table 2. While many similarities can be drawn between the four incidents, each fire presents unique circumstances and data availability, leading to differences in the scope and findings of each study. A brief review of each case study is provided in the following sections.

Table 2. General technical focus areas of previous NIST case studies.

Witch and Guejito Fires **2007** **San Diego, CA**	**Tanglewood Complex** **2011** **Amarillo, TX**	**Waldo Canyon Fire** **2012** **Colorado Springs, CO**	**Camp Fire** **2018** **Paradise, CA**
• Timeline reconstruction • Structure ignition pathways • Defensive actions • Exposure quantification • Effectiveness of mitigation • Methodology for future deployments	• Detailed reconstruction of fire behavior and timeline • Advanced field data collection methods • Damage assessments • Neighborhood case studies • Parcel-level attributes	• Timeline reconstruction • Fire behavior and spread in WUI interface • Detailed assessment of defensive actions	• Timeline reconstruction • Fire spread in WUI intermix • Burnovers • Damage assessments • Notification, evacuation, traffic, temporary refuge areas, rescues • Link between timelines of evacuation and fire

2.1. Witch/Guejito Fires (San Diego, CA 2007)

The first NIST WUI case study was conducted in collaboration with the California Department of Forestry and Fire Protection (CAL FIRE) and the San Diego Fire-Rescue Department (SDFD) after the October 2007 Southern California Fire Siege. More than 3000 structures were destroyed by 17 major fires that ignited within a three day period across southern California [33]. The Witch Fire was the most destructive, accounting for more than half of the destroyed structures. The NIST case study focused on The Trails, a small interface neighborhood of 274 homes that was affected by the Witch and Guejito Fires in the Rancho Bernardo area of San Diego, CA on October 22, 2007.

The case study was published in two reports; the first [34] documented the fire progression and defensive actions, and the second [35] assessed the effectiveness of mitigation actions that were taken before the fire. The NIST WUI data collection methodology was developed during this case study.

Overall, 34 findings were listed between the two reports. Three overarching findings identified include:

1. A systematic data collection methodology was necessary to document the WUI fire scene.
2. The post-fire scene (i.e., structure performance) cannot be reliably interpreted without accounting for exposure and defensive actions.
3. A scale should be formulated to quantify fire and ember exposures.

2.2. Tanglewood Complex Fire (Amarillo, TX 2011)

After field data collection at The Trails, the NIST data collection methodology was formalized into *WUI 1* and *WUI 2* levels of complexity [36] (discussed in Sec. 3) and refined based on the experiences from the Witch Fire. Additional data collection partners were identified, including the Texas Forest Service (TFS) who had recently conducted several post-fire data collection efforts and case studies [37-40]. In 2010, NIST researchers trained TFS post-fire data collectors in Bastrop, TX on the NIST *WUI 1* and *WUI 2* data collection methodology. NIST WUI field data collection kits containing personal protective equipment (PPE) and basic field survey equipment, including Global Positioning System (GPS) units, cameras, tape measures, and electronic data tablets, were then pre-positioned in Bastrop in preparation for a rapid response to a future WUI fire in Texas. A full list of equipment is included in Appendix A.

On February 27, 2011, several fires destroyed homes in the WUI near Amarillo, TX. TFS and NIST dispatched a joint WUI data collection task force to Amarillo and were integrated into the Incident Command System (ICS), logistics, and standard operating procedures within 44 h after ignition. Detailed data collection of fire spread using the *WUI 2* method focused primarily on the Tanglewood Complex fire, which destroyed 35 residences. Field data, including structure attributes, building construction materials, type of combustibles and proximity of combustibles to the structure, and damage to wildland and ornamental vegetation, was collected from more than 150 residences over a 21-day period. The rapid data collection was enabled by the partnership with TFS and the timely gathering of multiple geographic information system (GIS) layers that were used to drive the electronic data collection.

Two reports were published detailing this case study. The first [36] described the initial reconnaissance and data collection efforts by the NIST/TFS team. The second [30] included in-depth analysis of the fire spread mechanisms, damage assessments, and defensive actions, as well as an assessment of the data collection and analysis methods.

The Tanglewood Complex case study identified 34 technical findings and presented eight recommendations. Generalized technical findings include:

1. Data should be collected on all structures within the fire perimeter, including structures with no reported damage.
2. Data collection should be conducted in a standardized fashion.
3. A nationwide, incident-centric data repository is needed to document WUI losses and effectiveness of hazard mitigation.
4. Fire and ember exposures can differ significantly over small length scales (<5 m).

2.3. Waldo Canyon Fire (Colorado Springs, CO 2012)

The Waldo Canyon Fire ignited on June 23, 2012, and spread into Colorado Springs, CO on June 26, 2012, affecting the communities of Cedar Heights, Mountain Shadows, and Peregrine. The fire resulted in two fatalities and the destruction of 344 residences, all in the Mountain Shadows community, and was the most destructive fire in Colorado history at that time.

At the invitation of the Colorado Springs Fire Department, NIST collected post-fire data and initiated an in-depth case study. The primary objective was to reconstruct the fire spread timeline, quantify structural losses and vulnerabilities, and specifically document the extent and type of defensive actions that were taken in Mountain Shadows.

The Waldo Canyon Fire case study [41] identified 37 technical findings and presented 13 recommendations. Technical findings can be generalized into the following areas:

1. Defensive actions were effective in suppressing burning structures and containing the Waldo Canyon Fire.
2. Pre-fire planning is essential to enabling safe, effective, and quick deployment of firefighting resources in WUI fire incidents due to rapid fire spread during WUI fires.
3. Current concepts of defensible space do not account for hazards of burning primary structures, hazards presented by embers, and hazards outside of the home ignition zone.
4. Collecting structure damage data during and shortly after an incident will enable the identification of structure ignition vulnerabilities.

2.4. Camp Fire (Paradise, CA 2018)

The most recent case study details the Camp Fire, which ignited on November 8, 2018, in Butte County in northern California. The first 24 h were characterized by a fast-moving fire with initial spread driven by high winds up to 22 m/s (50 mi/h) and long-range spotting up to 6.3 km (3.9 mi) into the wildland-urban intermix communities of Concow, Paradise, and Magalia. The Camp Fire was the most destructive and deadly fire in California history with more than 18 000 destroyed structures, 700 damaged structures, and 85 fatalities.

After a reconnaissance in collaboration with CAL FIRE, it was determined that abundant data were available [42, 43] to support a comprehensive case study. As with the previous case studies, the first step was to develop a detailed timeline of the fire progression, focused on the first day across the entire incident (24 h to 30 h after ignition).

The available data also supported additional in-depth analysis of the significant threats to life safety experienced during the large-scale evacuation. Details of the emergency notifications, evacuation, traffic, temporary refuge areas, and rescues (collectively abbreviated as NETTRA) were explored. The fire progression timeline [44] served as the foundation to provide important context to the various NETTRA components [45]. Further analysis on defensive actions is underway.

The ongoing study has resulted in four reports [42-45], with a fifth currently in progress. So far, the case study has yielded 64 technical findings and 26 recommendations that address fire behavior and life safety. Select generalized findings include:

1. The location of wildland fire ignition relative to the community can dramatically influence the spatial extent of the fire and its impact on the community.
2. Multiple parcel-level fire spread pathways caused structure ignitions.
3. 23 burnover events were identified, with many involving evacuating civilians.
4. Fast-spreading fires can outpace the time necessary for evacuation, leading to dangerous conditions and high exposures to civilians.

2.5. Outputs and Impacts of Previous Case Studies

Each previous reconstruction has been anchored by its respective fire progression timeline. Beyond that, each case study is different, as seen by the comparisons in Table 3. Differences are driven by data availability, incident specifics, and the goals of each case study.

Table 3. Summarized technical findings of previous case studies.

Case Study	Technical Findings
Witch/Guejito	• Exposure intensity is non-uniform within a community • Exposure source (fire and embers) impacts structure ignition pathways • Defensive actions have significant influence on structure survival and the post-fire scene • There is a need for adaptable post-fire case study methodology • There is a need for an exposure scale and framework for characterizing WUI disasters
Tanglewood Complex	• Parcel-level vulnerabilities enhance fire spread among parcels • Multiple structure ignition vulnerabilities were identified in the existing building stock • Fire spread pathways exist within and across parcels
Waldo Canyon	• Impact of response time on incident development and structure losses • Timeline of structural losses identified a small fraction of structure ignitions were from wildland exposures • Community destruction was driven by structure-to-structure fire spread • Impact of defensive actions and relationship between structure losses and density of first responders • Defensive actions became more effective in stopping the fire when the wind abated within the community
Camp Fire	• Incident-level fire progression timeline illustrates the fire spread and effect of spot fires • Quantified the temporal relationship between evacuation notifications and fire progression • Evacuation and life safety issues were widespread • Burnovers impacted a large number of civilians • Impacts of fire on evacuation were life-threatening

Outputs from the case studies can be divided into two categories: direct outputs that are used to document the studies, and indirect outputs that bridge the gap between the incident-specific detailed reports and practitioners, such as the fire service and local governments.

Direct outputs from the case studies have been documented in NIST Technical Notes (TN). These comprehensive documents and associated data are the primary repository of the case studies and are listed in Table 4. A number of additional indirect outputs include methodologies and guidance for how to apply the knowledge collected from the studies to facilitate learning and application to future mitigation and preparedness [46, 47]. Descriptions of these outputs are provided in Appendix B.

Table 4. Direct outputs of previous case studies.

Case Study	NIST TN	Title	Ref.
Witch/Guejito	1635	A Case Study of a Community Affected by the Witch and Guejito Fires	[34]
	1796	A Case Study of a Community Affected by the Witch and Guejito Fires: Report #2 — Evaluating the Effects of Hazard Mitigation Actions on Structure Ignitions	[35]
Amarillo	1708	Initial Reconnaissance of the 2011 Wildland-Urban Interface Fires in Amarillo, Texas	[36]
	1909	2011 Wildland Urban Interface Amarillo Fires Report #2 — Assessment of Fire Behavior and WUI Measurement Science	[30]
Waldo Canyon	1910	A Case Study of a Community Affected by the Waldo Fire — Event Timeline and Defensive Actions	[41]
Camp	2105	Camp Fire Preliminary Reconnaissance	[42]
	2128	Preliminary Data Collected from the Camp Fire Reconnaissance	[43]
	2135	A Case Study of the Camp Fire — Fire Progression Timeline	[44]
	2252	A Case Study of the Camp Fire — Notification, Evacuation, Traffic, and Temporary Refuge Areas	[45]

3. Case Study Overview

A case study goes through several phases from preparation and planning, through data collection, data analysis, and technology transfer. Individual tasks within each phase are listed in the work breakdown structure illustrated in Fig. 1. Aspects within the different phases are discussed through the remainder of this report.

WUI Fire Case Study Overview

Preparation & Planning	Pre-fire Reconnaissance	Post-fire Data Collection	Data Analysis	Technology Transfer
1. Identify requirements	1. Coordinate with local departments/collaborators	1. Identify fire incident of technical interest	1. Data entry/digitization	1. NIST Technical Note(s)
2. Identify project team	2. Conduct pre-fire reconnaissance visit	2. Coordinate with local department and Incident Command	2. Identify scope of possible outcomes given the available data	2. Direct presentation to local departments/organizations
3. Training	3. Assess local pre-fire datasets	3. Conduct reconnaissance	3. Integration and quality control	3. Dissemination to appropriate stakeholders
4. Determine potential locations and state/local departments	4. Collect pre-fire data	4. Collect field data	4. Establish fire progression and incident timeline	4. Recorded presentation(s) / WUI Fire Days / seminars
5. Identify potential technical questions or incident type/scale/scope		5. Collect incident data	5. Evaluate life safety components	5. Scientific journals conferences
6. Prepare deployment kits and data collection systems		6. Collect local pre-fire plans and data	6. Evaluate defensive actions	6. Website(s)
		7. Conduct technical discussions	7. Evaluate structure performance	

Fig. 1. Phase-based work breakdown structure of a post-fire case study.

A structured yet flexible data collection and analysis methodology that addresses the unique attributes of WUI events has been developed and refined through the previous case study experiences. Independent of the size of the incident, reconstruction of a robust spatiotemporal timeline of the fire progression and incident development is the foundation of NIST WUI case study. This is accomplished through extensive technical discussions with first responders and other relevant officials to document thousands of firsthand observations of fire progression and response actions during the incident [44]. This information is then integrated with field data and incident data for specific analyses.

A rapid deployment to the fire location is necessary to conduct a reconnaissance of the particular incident. This provides an opportunity to interface with the incident command team and receive a briefing from the local agencies to gain firsthand information. The incident dynamics and characteristics (i.e., fire behavior, structure damages, evacuations, communications) and the range of available data is reviewed during the reconnaissance to determine if a case study is feasible and warranted. If so, the reconnaissance transitions into more detailed case study data collection. Perishable field data is then collected immediately to avoid data loss and contamination from weather and recovery efforts. Longer term data collection, such as the technical discussions, should follow as soon as possible.

The following aspects have been key to a successful NIST WUI case study.

1. The case study team is trained, available, and ready to conduct a case study.
2. The WUI fire exhibits incident characteristics in one or more technical areas of interest.

3. Necessary data exists and is accessible to the research team.
4. Data are collected before the data perishes or is contaminated.
5. There is support from local jurisdictions to allow access to pre- and post-fire field data, incident data, and first responders and other personnel involved in the incident.
6. The technical questions of interest are compatible with the spatiotemporal density of data.

3.1. Case Study and Data Scope

The potential scope of post-fire data collection and studies spans a wide range, from basic data collection to quantify losses, to in-depth analysis of structure ignitions and fire spread behavior or specific details relating to the progression or development of the incident, such as response or evacuation [6]. NIST has used a tiered classification to describe the depth or level of complexity of data collection and incident study; *WUI 0*, *WUI 1*, and *WUI 2* [36, 41]. Figure 2 shows the continuum of data collection and related potential case study findings in the context of damaged structures, which is a common post-fire metric.

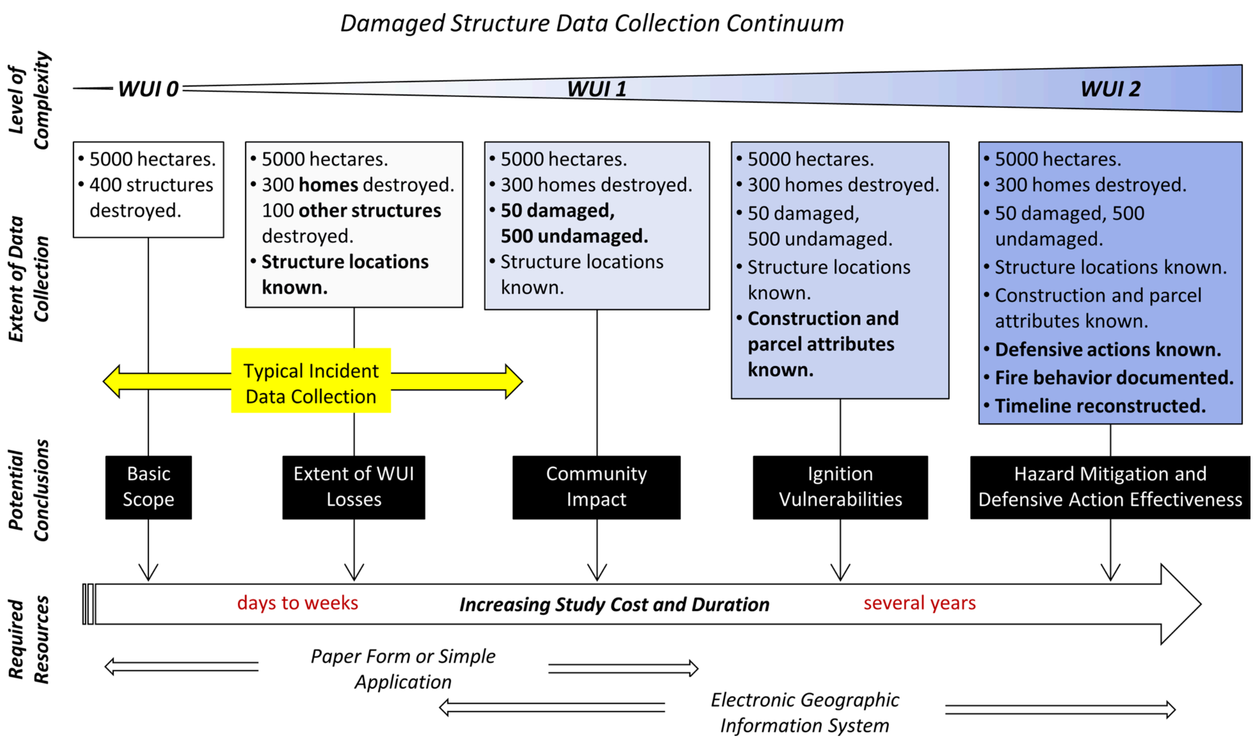

Fig. 2. The range in scopes of data collection and case studies pertaining to damaged structures. Increasing complexity toward the right of the figure describes the added level of detail in data collection, analysis, and potential conclusions. Modified from [6].

Typical basic incident-level data includes the number and location of structures damaged (*WUI 0/1*). Such data are important for public information and insurance purposes, to quantify losses and impacts, and begin recovery. Additional basic information may include the number of casualties or the number of evacuated people. This information is typically collected by the incident management team, although the extent and standardization of data vary depending on the size of the incident and the locality and agencies involved.

Standardized post-fire field data collection can define the scope of the WUI fire problem and identify hazards and potential vulnerabilities to structure ignitions. However, bulk post-fire data have limitations that can impact how an event is interpreted. This can be demonstrated when considering surviving (damaged/undamaged) structures without the context of exposures and defensive actions (intensity and timing). Bulk post-fire data collection shows that structure damage status is often a binary outcome between being undamaged or destroyed. Few structures remain standing with partial damage, especially in large incidents; the ratio of destroyed to damaged single-family residential structures from post-fire damage inspection data in California between 2013 and 2022 is approximately 10 to 1 [9]. This is largely a function of the limited number of firefighters relative to the number of exposed structures. Once structures ignite there are often insufficient resources to suppress them, and structures burn completely while resources are dedicated to life safety tasks or preventing ignition of other structures. In the absence of detailed pre-fire data and fire exposure information, the ignition pathways and characteristics of destroyed houses are unknown. They may have been comparable to structures that were defended or otherwise experienced lower exposures and thus survived with limited damage. Without timeline information, it is also difficult or impossible to determine the sequence of ignitions.

Therefore, more in-depth analysis is required to understand the context and interpret the post-fire conditions (*WUI 2*). NIST's previous case studies are built upon detailed spatiotemporal reconstructions of WUI fire incidents that are established through integration of multiple datasets, including thousands of firsthand observations from first responders and other personnel. This spatiotemporal foundation allows for findings that expand on the typical post-fire data collection conducted at an incident level or department level. Through integration of multiple datasets, observations, and perspectives, detailed case studies provide a more complete level of understanding of WUI incidents than individual incident commanders and first responders can provide. The fundamental difference is the depth of understanding of the event and the subsequent implications of the technical findings.

3.2. Data Collection Methodology

The NIST data collection methodology has been refined over the past four case studies and adapted to the technical scope and available data types for each incident. In general, case study data have three primary categories entailing different data collection methods and sources [6, 32]: field data, observation data, and recorded/documented data.

Field data includes data that are collected from direct observation and measurement of the post-fire scene, with focus on the conditions and circumstances of the post-fire scene. Many post-fire case studies incorporate some type of field data collection related to structure damage. Data collection involves methodical documentation of structure construction and material details, ignition locations, and damage level; vegetative and WUI fuels; fire spread indicators; and exposure sources. Simple paper forms are a minimum requirement to collect the basic information [6]. Examples of structure damage assessment forms used to collect field data can be found in Refs. [13, 36, 42, 48, 49]. However, a mobile GIS application is preferred, and may be necessary depending on the desired spatial resolution and subsequent analyses. A majority of this data collection requires ground-level physical surveys, although high resolution aerial imagery often provides valuable information and advanced analyses to support ground surveys [50]. Ground and aerial data can help alleviate limitations of the other. Post-fire field data are perishable in the sense that weather and recovery can change the appearance of the post-fire scene, so timely data collection is required.

Observation data consists of firsthand observations of first responders related to what they saw and did. This information is critical to develop an incident timeline and to contextualize much of the other data. In the assessment of structure performance and damage, observation data is often the only way to identify and confirm fire suppression actions. These data are collected through technical discussions (TDs) with a range of incident officials to generate narrative accounts of firsthand observations during the fire. The methods are described in Ref. [44], but the general approach is to start from the incident commander and work down the command structure to individual fire engines and firefighters, building individual timelines of their involvement in the incident. A similar approach can be taken with local emergency management and law enforcement agencies. By following leads to other contacts along the way, a critical mass of information can be obtained. Generally, TDs are conducted until no new information is identified. Approximately 220 TDs were conducted during the Waldo Canyon Fire case study; the last 10 % of discussions did not add any new information about the incident. While these data are not perishable in the same sense as field data, there are time limitations related to memory recall and access to/availability of individuals.

Other recorded and documented data can span a wide range of media and encapsulate other data sources that are recorded as numerical data, videos/images, audio, and written documents or reports [6, 32]. These data are generally not directly measured, recorded, or created by the case study team like the field data and observation data, but rather are collected and integrated from other various sources. Some of the data may be time sensitive (i.e., systematically overwritten) if not automatically archived, such as dashboard/body-worn cameras, fire engine apparatus GPS tracking records (automatic vehicle location [AVL] logs), and audio files from radios and dispatch. Other data may be saved routinely, such as weather observations, or archived in publications, documents, or databases such as community wildfire protection plans (CWPP), evacuation plans, or pre-fire mitigation assessments. Crowdsourced information is becoming increasingly accessible through technology, and may be beneficial if time, location, and content can be verified. Home or business security cameras are increasingly common and may be an additional source of information in future studies. Additional data from surveys may be collected by the research team if necessary for the desired study, for example, on evacuee behavior or decision-making [51].

Data within these three categories and from the numerous data sources can be associated among five technical themes [32]:

- spatiotemporal fire progression,
- weather, topography, and wildland environment,
- response of structures, land parcels, and community to the fire,
- human and community response to the fire, and
- emergency response.

The extent to which data are collected related to each theme is driven by two important attributes of the NIST WUI data collection and subsequent analyses:

1. Coupling the desired technical outcomes of the case study to the spatiotemporal density of available data.
2. Adaptability of the method to meet the needs of different incident sizes and study scopes.

Data availability, data accessibility, and spatiotemporal density are driving factors that determine the limits of what can be studied. To generate a reliable fire progression timeline, data are needed from first responders including, but not limited to, radio logs, AVL records, and TDs.

The NIST WUI data collection methodology can leverage the data density of smaller events while being flexible and applicable to very large events. This is demonstrated by comparing the case studies of the Amarillo fires and Camp Fire, where structure losses ranged from 35 to more than 18 000. Additionally, the incident characteristics and scale of the Camp Fire and availability of the relevant data led to significant findings related to evacuations and life safety which were not present to the same extent during the Amarillo fires.

3.3. Deployment and Data Collection Timeline

Figure 3 illustrates a general timeline of a WUI fire event and how the different aspects of the event relate to each other and data collection. Reading upward from the bottom of the figure, the timeline shows fire activity, defensive actions and response, evacuation, and data collection activities. Across from left to right is advancing time.

The active period of the fire incident is shown between the ignition and when the fire is controlled. Emergency response and defensive actions occur immediately after ignition, ramping up as resources are dispatched and arrive. Evacuations may follow a wide range of timescales. In this illustration, evacuation occurs soon after ignition, and a majority of the population leaves quickly, indicated by the steep drop in the line representing the number of residents in the affected area.

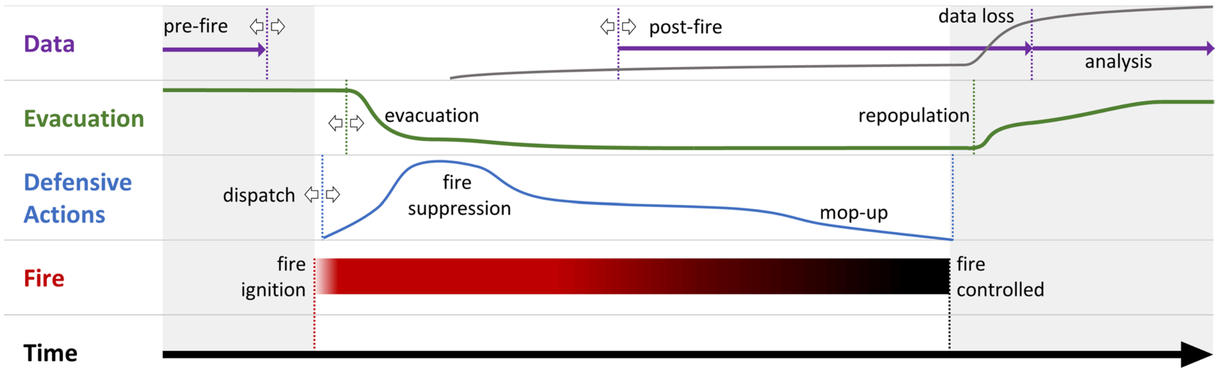

Fig. 3. Generalized WUI fire event timeline showing components of data collection, evacuation, response, and fire.

Post-fire data collection should begin as soon as safely feasible, synchronized with the operations and recovery of the incident. Coordination with the local authorities having jurisdiction (AHJ) and the incident command team is essential. Access to affected areas may be restricted due to fire operations, safety hazards, or recovery work, and may influence the data that are available. Structure and parcel-level data, together with incident fire behavior indicators, must be captured before the data are contaminated or lost. Quick access to the fire scene allows for timely collection of the structure and parcel-level data of interest. Once repopulation begins and residents return to clean up and to recover, access to data is hindered and data loss accelerates, as illustrated at the top right of Fig. 3. Non-perishable and recorded/archived community-level and incident-level data can be collected when time allows.

While not to scale, the illustration in Fig. 3 represents a duration of several days to weeks. Table 5 summarizes the approximate WUI deployment timeline in the context of key field deployment events. The timeline of an entire case study can span several years. As an example, the chart in Fig. 4 lists the different stages of the Camp Fire case study from ignition of the fire in November 2018; data collection, integration, and analysis; and reporting and publication of the first report just over two years later.

Table 5. Approximate timeline of key case study field activities/events.

Activity	Time From Ignition	Notes
Identify collaborating states/departments and geographic areas of interest	−24 months (minimum)	Discuss technical needs with local AHJs during pre-fire reconnaissance deployments
Engage state and local AHJs and discuss possible WUI case study parameters	−18 months to −3 months (minimum)	Done in conjunction with pre-fire reconnaissance deployments
Coordinate data and access needs	−18 months to −3 months (minimum)	Done in conjunction with pre-fire reconnaissance deployments
Monitor local conditions in locations of interest		During time window of interest and availability
Ignition and fire in location of interest	t = 0	During time window of interest and availability
Deploy team for reconnaissance	+2 d to +5 d	For large incidents this activity can occur up to 3 d later
Confirm availability and accessibility of technical data	+7 d to +9 d	While on reconnaissance
Evaluate merits of case study or other paths forward	+9 d to +11 d	While on reconnaissance
Initiate field data collection of incident/parcel/structure data	+10 d to +12 d	Capture perishable field and other recorded and documented data. Field data must be collected ahead of recovery activities. Electronic data may be overwritten or deleted.
Collect field data and conduct TDs in 2- or 3-week increments	+12 d to +6 months	Field data collection is followed by TDs
Collect other recorded and documented data as it becomes available	+12 d through duration	Perishable data should continue to be collected as soon as it becomes available. Other data sources may be archived or published at a later date.

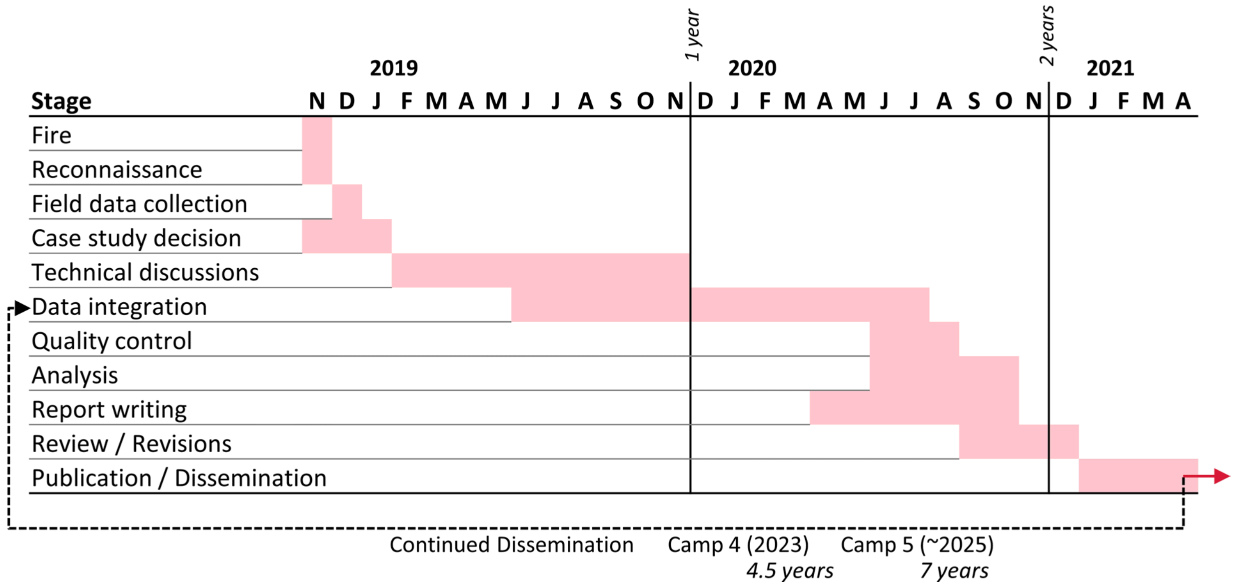

Fig. 4. Activity timeline of the Camp Fire case study from ignition in November 2018 through publication and initial dissemination of the fire progression timeline report in early Q1 2021.

3.4. Data Analysis

Given the wide-ranging nature of the relevant data and technical questions, analysis employs a mix of quantitative and qualitative methods. There are often three scales of interest to obtain a complete perspective of the event: community, incident, and parcel/structure scales.

Data integration, quality control, and documentation contribute to multiple interrelated databases [44]. Spatiotemporal data are integrated with the aid of GIS to reconstruct a timeline of the event. Different data types and technical questions will require different specialized analyses and may include more detailed sub-incident-level timelines. For example, detailed parcel-level fire spread and behavior or analysis of burnover events will require specific minute-by-minute timelines at higher local resolution than the general summary of fire progression for the whole incident.

The goal of the analysis has two aspects. First, to understand the details as they relate to the specific incident being studied, and second, in generalizable ways so that the technical findings and lessons learned can be applied to future fires and in different communities.

3.5. Technology Transfer

Dissemination of the technical findings is an integral part of the overall case study effort. Communication of the lessons learned influences and guides AHJs, codes, standards, and future research, as demonstrated in Appendix A. Stakeholders and end-users include other fire science researchers, the fire service, emergency managers, federal agencies, state and local governments, policymakers, non-governmental organizations (NGOs), building designers and engineers, and the public.

Technology dissemination starts with the documentation of the case study in comprehensive NIST Technical Notes. Using these publications as a foundation, there are several other approaches to deliver relevant information and lessons learned to diverse audiences, including archival journal publications, technical presentations directly to stakeholders or through conferences, workshops, seminars, websites, and factsheets.

4. Future Case Studies

The knowledge base and incident-level understanding established by previous WUI fire case studies are a driving force in WUI fire science and resilience efforts. There are valuable learnings to be obtained from conducting additional detailed case studies of WUI fires. NIST is uniquely positioned with the combination of experience, impartiality, and alignment of mission focus to conduct post-fire case studies of this type spanning multiple years and engaging several subject matter experts (SMEs). Collaboration with state and local governments and fire services will make the work possible.

Based on the learnings from previous case studies, the approach for future NIST case studies is divided into five activities including:

1. pre-fire deployment planning and identification of general WUI fire incident characteristics and locations of interest, and preparation of the data collection team, methodology, and equipment,
2. pre-fire reconnaissance to establish partnerships with potential state/local agencies and departments to facilitate data collection and case studies,
3. post-fire collection of field, incident, community, and other recorded and documented data,
4. data integration, quality control, analysis, and documentation,
5. technology transfer through dissemination of technical findings and recommendations to enhance life safety and reduce WUI fire losses.

Section 4.1 describes four different types of deployments that can be implemented to advance post-fire case studies and continue to apply previous lessons learned in relation to future incidents. Incident parameters and characteristics related to desired technical findings are outlined in Sec. 4.2. Sections 4.3 through 4.5 discuss equipment, staffing, and training requirements to conduct a case study.

4.1. Deployment Types

Four types of deployments can be utilized depending on the technical goals of the response, the phase of the fire incident (e.g., before, during, or after the fire), incident characteristics, and the interests, needs, and capacity of the local jurisdiction(s). The types include pre-fire recon, recon, case study, and collaborative/knowledge transfer deployments.

4.1.1. Pre-fire Reconnaissance

A pre-fire reconnaissance is a proactive effort that can be conducted in preparation for a future case study and to build relationships with state and local fire departments and AHJs. Pre-fire reconnaissance deployments can provide several direct benefits to facilitate a potential case study through the following objectives:

- confirm that identified locations of interest meet technical and logistical needs of a future case study;
- communicate to the local AHJs the level of effort needed from both NIST and the AHJs to conduct/support a case study;
- evaluate the receptivity of a location to participate in a case study;
- establish a timeline for communication and procedures after ignition, including logistics for access to the fire scene/incident command, and damage inspector data; and
- coordinate data availability and accessibility, including pre-, during-, and post-fire data from state/local agencies.

These actions allow NIST to build a working relationship with the local community to facilitate future deployments and provide training opportunities for the research team. Pre-fire recons can also support WUI research beyond the immediate case study by expanding the reach and dissemination of current WUI fire science and contributing to a wider understanding of current hazards, practices and standards of community preparedness, response capacity, construction and building material types, and mitigation efforts in different locations. This type of deployment may take place over a one- or two-week period or consist of multiple trips to specific communities.

Ideally, a pre-fire reconnaissance will also independently provide benefits to local AHJs. For example, discussions related to data needs and research areas of interest may support local pre- and post-fire data collection efforts. In turn, this could establish a pre-fire database of local structure and fuel conditions to support local mitigation programs or grant applications.

It should be acknowledged that a case study may not take place in the locations where pre-fire recons have been conducted. While the selected locations will likely have a relatively high probability of WUI fires, a suitable fire may not occur during a case study response window (i.e., a time period in which staff and resources are available to initiate a study), a reconnaissance may determine that a fire incident lacks desired technical attributes, or a significant fire that warrants a case study may occur first in a different location.[1]

4.1.2. Reconnaissance

A reconnaissance deployment occurs during or immediately after a WUI fire to gain a firsthand perspective on the specific incident beyond available news reporting or other public information, facilitate direct contact with the local AHJs and incident command, and to collect preliminary data and information about the incident. The goal of the reconnaissance is to assess the incident characteristics and evaluate the extent and availability of data with respect to the potential for significant findings from an in-depth case study. It can be considered the initial response phase preceding the initiation of a case study; however, a reconnaissance does not necessarily mean a case study will be undertaken. Should a case study be deemed infeasible

[1] Due to the limited availability of SMEs, historically at NIST only one case study has been conducted at a time.

after recon, a collaborative/knowledge transfer deployment may be appropriate (see Sec. 4.1.4).

A reconnaissance deployment can be especially beneficial if responding to a fire in a location where the research team has limited or no pre-fire coordination or technical relationship (whether through pre-fire reconnaissance or other pre-existing collaborations). A primary limitation in this scenario is the potential time delay induced between the fire ignition and a decision to commit to a case study in order to establish collaboration between agencies and identify data sources. This can have significant implications on the viability of perishable data. Another factor that may hinder a case study is if the local departments and AHJs have a limited understanding about the necessary contributions and involvement they will have in a potential case study. While this can be overcome, the loss of time and access to perishable data is typically unrecoverable. This points to the benefit of pre-fire reconnaissance deployments and established relationships with AHJs in regions/states of interest prior to the occurrence of a WUI fire event.

Depending on the scale of the incident, a reconnaissance deployment can be accomplished with approximately one week of time on scene interfacing with the incident command team, learning about the incident dynamics, and getting oriented to the location. If the reconnaissance assessment indicates that a case study is warranted, the reconnaissance should transition immediately into formal data collection.

4.1.3. Case Study

A full case study deployment can begin immediately after a reconnaissance verifies that the fire incident has aspects aligned with the technical interests and needs of the research team, data are available and accessible, and the AHJs are supportive of a case study. The decision to initiate a case study should be made the NIST Fire Risk Reduction in Communities Program leader in consultation with the research team shortly after arrival for a reconnaissance to avoid data loss due to time delays. As described in this document, the range and scope of a case study can vary depending on the incident specifics and the available data. However, the standard approach for data collection and timeline reconstruction guides the process.

While it is advantageous for a case study to be undertaken in a location where a pre-fire reconnaissance has taken place, it is not necessarily a requirement. Given the expansive geographic area at risk of WUI fire, the range of impactful research topics, and the variability in fire event scenarios, a case study may be appropriate for technically significant incidents if other requirements to conduct a case study are otherwise met.

As described in Sec. 3.3, a case study can take several years, including data collection, analysis, and reporting. Given the focus and resources required to conduct a case study, only one incident can be reconstructed at a time.

4.1.4. Collaborative/Knowledge Transfer

The fourth deployment type focuses more on knowledge transfer from WUI fire research to local AHJs rather than analysis or evaluation of a specific recent fire in that locality. This type of deployment can occur after a WUI fire event of national interest or a significant local event when a full case study cannot be initiated at that time for logistical, technical, or other reasons.

The purpose of the collaborative deployment is not to assess the local conditions in the context of a new case study, but rather to connect with the incident command and local AHJs and get an overview of the event to help guide the collaboration and focus the technology transfer material to the specific needs of the community. While every WUI fire has unique attributes, many catastrophic events have similarities that can be related to and viewed within the context of past fires. This type of response provides the incident command and impacted communities with direct access to relevant WUI fire science knowledge and community tools to introduce or improve preparedness and mitigation approaches during the recovery phase to increase resilience. For example, recent research efforts like HMM [46] and ESCAPE [47] may provide relevant information to the affected community as they rebuild and reassess their emergency response plans.

A collaborative deployment can be accomplished within a three- to five-day visit. The timing of such a deployment can be determined after discussion with the incident command and local AHJs and is not necessarily appropriate during the active fire incident or in the immediate time after.

4.2. Case Study Parameters

Several aspects guide the planning and goals for future case studies including areas of technical interest, the scale of an incident, and general locations of interest. With thousands of wildland fires in the U.S. each year, having criteria clearly defined in advance will help to focus future case study research efforts on fire incidents with the desired attributes.

4.2.1. Areas of Technical Interest

Bénichou et al. [52] list a wide range of key factors that affect the outcome of a WUI fire event, including incident location, timeline, losses, community type and demographics, structure/parcel characteristics, weather, and response details. Each of these aspects can provide important insight into WUI fires. While there are often commonalities between WUI fire incidents, each event presents a unique combination of circumstances with opportunities to learn. However, not all areas of technical interest will be present in every incident, nor will every incident have adequate data to support an in-depth case study of a desired topic. Therefore, a range of pre-identified areas of technical interest can facilitate screening for the appropriate case study fire.

Potential areas of technical interest to the NIST Fire Research Division and the WUI Fire Group are outlined in Table 6, along with desired findings topics, and associated pre- and post-fire data requirements. The general themes include impact and response of the built environment, effectiveness and influence of defensive actions, and civilian life safety. Beyond the items listed in Table 6, additional studies related to incident communication, evacuation decision-making, emergency notifications, fatalities, or other significant characteristics of the incident may also occur, and may require additional staffing and expertise beyond what is outlined in this report. As discussed in Sec. 3, reconstruction of the fire progression timeline is the technical anchor of any detailed case study. Any additional analyses will be a function of incident specifics.

Table 6. List of areas of technical interest and the types of required incident and other data.

Area of Technical Interest	Desired Technical Findings	Data Needs
Structure ignition vulnerabilities	Identify vulnerabilities and assess effectiveness of defensive action/structure hardening/ building code performance	Post-fire damage data, exposure source data, defensive actions
Parcel-level fire spread	Effects of defensible space and structure separation distance (SSD) on fire spread at the parcel level [46]	High-resolution parcel data collection (NIST *WUI 2*) coupled with defensive actions and post-fire imagery
Vegetative fuel reduction treatments surrounding communities	Characterize effectiveness of fuel treatments in reducing exposures to WUI parcels/community	Fuel treatment attributes, fire behavior information, defensive actions
Notification and evacuation timeline	Assess notification response time and evacuation performance (see ignition to activation [ITA] and ignition to safety [ITS] in Ref. [47])	Fire progression timeline, notification records, traffic data or observations
Life safety	Effects of fire on civilian life safety and evacuation; use and performance of temporary fire refuge areas (TFRA)	Fire progression timeline, evacuation timeline, burnover, and TFRA data

4.2.2. Incident Scale

The spatiotemporal extent of the case study can range from a focused study of a particular community to the study of the entire fire depending on the size of the incident, extent of destruction, availability of data, and the technical goal of the study. The progression of the past four NIST case studies has covered a range of incident scales in increasing order:

1. A single community within a larger incident;
2. A complete small-scale incident, from ignition through destruction;
3. A medium to large incident, through the complete WUI exposure;
4. The largest incident, complete from ignition through the first 24 h.

The scope of NIST’s first case study was focused on the community of The Trails in Rancho Bernardo, CA within the larger perimeter of the Witch Fire. The community was selected because almost the entire community (275 residences) had been impacted by the fire, with a mix of destroyed, damaged, and non-damaged structures. The case study covered each individual structure within an approximate study area of 180 ha (450 ac). Similar scale studies were conducted for the Amarillo and Waldo Canyon Fires, with detailed studies possible on parcel and structure-level fire behavior. In contrast, the scope of the Camp Fire case study covered a larger geographic range to highlight the first 24 h of the incident, roughly 35 000 ha (86 500 ac). Due to the size and scope, the data density is different than the previous studies, resulting in more incident- and community-scale findings rather than individual parcel findings.

For the purposes of NIST WUI reconstructions, events of interest can be generalized as either small or large. Small events are defined by a limited number of impacted structures where an in-depth NIST *WUI 2* field data collection is possible. Due to the extensive time needed for NIST *WUI 2* data collection, this type of deployment can only occur in smaller incidents, or be restricted to subsections of larger incidents, limited to approximately 50 destroyed structures. The limiting factor is directly related to the need to collect field data before the fire scene is compromised by weather, repopulation, and recovery activities.

To that end, there are two different types of small incidents. The first is a scenario where a small, isolated community is completely impacted. The second is when first responders are able to contain the fire within a small total area, limiting the number of structures involved. Since a detailed study also requires that first responders were present to make observations that help to reconstruct the event, the second type of incident is more desirable since the ratio of first responders to exposed structures is higher, and therefore increases the spatiotemporal density of observation data.

Studies of smaller fire incidents can contribute detailed findings, especially when they are contained near the ignition or when emergency resources outnumber impacted parcels. The high data density can result in lower uncertainties and fine-scale observations about fire spread, structure ignitions, mitigation effectiveness, and response tactics [53]. However, issues and complications that occur in larger incidents may not manifest in smaller incidents. One significant challenge with smaller incidents is that repopulation can occur quickly, limiting the time available to collect uncontaminated post-fire field data.

In the context of case studies, large incidents span a wide range of scales, from 50 structures to tens of thousands of structures affected. These larger incidents can offer multiple potential case study themes. Their large scale may introduce or compound complications in areas including communications, emergency response, and evacuation. Large numbers of structures may be affected, presenting the opportunity for large sample sizes. However, the volume of data or the potential low spatiotemporal density of available data may restrict the scope of a potential case study. This may preclude the ability to reconstruct detailed *WUI 2* parcel-level fire spread across the entire incident. While these aspects must be considered in all case studies, these challenges may be exacerbated by the scale of large incidents.

Table 7 summarizes the benefits and limitations of case studies of both incident sizes.

Table 7. Benefits and limitations of case studies related to incident size.

Small Incident	Large Incident
+ High resolution spatiotemporal data allows for detailed understanding of parcel-level fire spread	– Lower resolution spatiotemporal data limits findings related to parcel-level fire spread
+ Small incidents can offer disproportionate defensive actions, and by extension, reduced losses – Technical findings from small incidents do not necessarily apply to larger incidents with respect to incident response and evacuation	+ Large incidents are responsible for the majority of total structural losses; response, tactics, and mitigation knowledge from these types of events can have broad impact on the national problem progression
– Complications that manifest at larger scale may not be evident in smaller incidents	+ Allows for an understanding of the overall incident rather than parcel-to-parcel fire spread
+ Knowledge from inter- and intra-parcel fire spread and exposures can guide laboratory research and codes and standards development	+ Knowledge from these incidents can be used to develop community-level methodologies and guides like ESCAPE [47]

4.2.3. Locations of Interest

WUI fires occur throughout the nation where differences in fuels, weather, construction practices, response capacity, and pre-fire preparedness lead to a wide range of potential case study scenarios. To prepare for case studies in diverse areas, connections with several different states should be maintained to establish a range of possible case study locations. Connections with state/local agencies should be established prior to deployments, if possible. Geographically, at least one state should be selected on the west coast, one in the mountain west and one in the mid-Atlantic or southeastern states. The selection of these regions will add diversity in the fuels/topographies/construction that can be studied and continue facilitating the NIST WUI technology transfer to different regions of the country.

Pre-fire reconnaissance deployments to locations of interest allow for the development of collaborative partnerships that facilitate a future case study. The value of pre-existing connections with state and local agencies has been demonstrated during previous case studies conducted by NIST. For example, pre-fire discussions and statements of needs with CAL FIRE enabled the successful partnership, data sweep, and subsequent multiyear collaborations for both the Witch and Camp Fire case studies. The collaboration and training with TFS contributed to the success of the rapid deployment and *WUI 2* data collection after the Amarillo fires. Deployments to the identified areas should start at least 12 months to 18 months prior to the potential initiation of the next case study. This time is necessary to inform local jurisdictions of the desired future collaboration and enable them to identify/implement processes to secure the relevant data in the event of a case study.

The first three NIST case studies involved WUI interface locations, while the communities affected by the Camp Fire are categorized as WUI intermix, with more vegetation within the built environment. Additional case studies in the WUI intermix would provide context for the findings of the Camp Fire and provide additional insights for fire behavior, structure survivability, life safety/notification and evacuations, and defensive actions in the intermix environment.

4.3. Equipment and Data Collection Development

Field data collection has modest equipment requirements, including measurement tools, electronics, and personal protective equipment. Deployment kit contents are listed in Appendix A. Measurement devices include at least a tape measure, GPS unit, and digital cameras. A consumer-grade digital camera with a wide zoom range is sufficient.

Advancing technology in data storage and camera function make the use of high-resolution 360-degree cameras a great future addition to the field data collection kit. The capture of still images or videos while driving through case study areas and during structure assessments would provide valuable documentation of the post-fire conditions in a format comparable to Google Street View or Bing Maps Streetside imagery products. Aerial or drone imagery is also valuable but is not as readily implemented. Aerial imagery may be collected by the incident management team or local community and should be pursued, if available.

The full electronic *WUI 2* field data collection was not conducted during the most recent NIST case study at the Camp Fire. Updates to hardware, software, and equipment are necessary to advance the data collection methodology to utilize the latest technology. Several recommendations and improvements were previously listed after the Amarillo case study [36], which is the most recent NIST study to use the electronic field data collection program. New software has been developed in the time since, and emergency management agencies such as CAL FIRE have implemented electronic checklist versions of *WUI 1* damage assessment surveys. Re-development of the data collection applications, equipment, and procedures before the next case study will be necessary to capture detailed parcel-level fire behavior and spread data.

4.4. Staffing Requirements

Case study project staff consists of at least five different positions, summarized in Table 8. Positions include two primary researchers, with assistance from field data collectors, technical discussion data collectors (scribes), and an information technology (IT) expert. Depending on the expertise of the base team members and the desired research goals, additional subject matter expertise may be needed.

Table 8. Case study staffing responsibilities and technical and other prerequisites.

Position	Primary responsibility	Technical prerequisites	Other prerequisites
Principal Investigator (PI)	Oversee case study	Have been a co-lead in at least one NIST WUI case study	Red Card training Ability to be on extended travel (totaling ~6 months in 3-week intervals)
Co-Investigator (Co-I)	Support field deployments, data collection, quality control, analysis, and report writing	Two years pre-deployment training on the NIST WUI Data Collection and Analysis Methodology Proficient in NIST WUI TD Methodology	Red Card training Ability to be on extended travel (totaling ~6 months in 3-week intervals)
Field Data Collector 1	Support field data collection and manage field data	Trained in NIST WUI Data Collection Methodology and NIST IT data-handing requirements	Red Card training Ability to be on extended travel (totaling ~1.5 months to 2 months in 3-week intervals)
Field Data Collector 2	Support field data collection	Trained in NIST WUI Data Collection Methodology	Red Card training Ability to be on extended travel (totaling ~1.5 months to 2 months in 3-week intervals)
TD Scribe 1	Document TDs	Proficient in NIST WUI TD methodology	Red Card training recommended Ability to be on extended travel (totaling 4 months in 2-week intervals)
TD Scribe 2	Document TDs	Proficient in NIST WUI TD methodology	Red Card training recommended Ability to be on extended travel (totaling 4 months in 2-week intervals)
IT Specialist	Collect data from different data sources	Proficient in GIS and NIST data storage and access requirements during reconnaissance and field data collection of damaged structures	Red Card training recommended Ability to be on extended travel (totaling 2 months in 3-week intervals)

The principal investigator (PI) leads the overall case study and is assisted by another researcher dedicated to the case study, the co-investigator (Co-I). The PI and Co-I should be well-versed in the previous four NIST WUI case studies and have in-depth knowledge of the NIST WUI data collection and TD methodologies, goals, and analyses. They should have experience and relevant knowledge of WUI incident dynamics.

Field data collectors should be knowledgeable in the data collection methodology and practice collecting data with the entire team before a case study, as described in the next section on training. The minimum field data collection team size is five, consisting of the PI, Co-I, two data collectors, and the IT specialist.

Scribes support the PI and/or Co-I during TDs and are responsible for documenting the discussion as presented. TDs can be conducted with a minimum of two individuals; the PI/Co-I and one scribe. However, two or three scribes are preferred.

IT and data support is necessary both in the field and for TDs, with tasks including electronic data collection (data files, reports, documents, images, videos) and data management. The IT specialist may also double as a field data collector or scribe if training requirements are met and the data collection situation permits. However, the IT specialist may need to remain at the incident command post to collect relevant electronic data during the reconnaissance or may need to spend time dedicated to data management that would preclude them from active field data collection.

Fieldwork and TDs are generally sequential phases of the data collection. Therefore, the field data collection and scribe positions can be performed by two people if all the necessary proficiency and training requirements are met. Note that it is beneficial for the same team to conduct all activities of the same type (field data or TD data collection) to maintain a consistent and complete mental picture of the case study.

Finally, additional support from staff who are not on travel may be beneficial to help with specific research, data, or administrative tasks that members in the field do not have access to or time to conduct while deployed.

Staff from other agencies may wish to participate in the NIST-led case study to learn about the specifics of a WUI event, support the case study, and provide access to specific data and collaborators. In past case studies, staff from other federal agencies, including the US Forest Service (USFS), US Fire Administration (USFA), and Federal Emergency Management Agency (FEMA), have participated.

Table 9 describes the full-time equivalent (FTE) requirements to complete a case study. The study is divided into six phases, starting with the pre-fire recon, and ending with the development of first-generation technology transfer tools. Staffing requirements vary throughout the phases of a case study as outlined in the table. Depending on the size and events of the incident and extent of the analysis beyond reconstructing the fire progression timeline, previous NIST WUI fire case studies have taken three to six years to complete.

Table 9. Duration of NIST WUI case studies and minimum FTE staff requirements.

Phase	Duration	Staff Positions	Min. Staff Count	Total FTE Staff Years
1. Pre-fire recon	2 weeks per location, 6 weeks to 8 weeks total (3 or 4 sites)	PI, Co-I, 2 × Field Data Collector [A]	4	0.5 year to 1 year
2. Recon/field data collection (including TDs)	6 months	PI, Co-I, 2 × Field Data Collector, 2 × Scribe, [A] IT Specialist	5	2.5 years
3. Data integration and quality control	6 months to 12 months	PI, Co-I, IT Specialist [A]	2	1 year to 3 years
4. Analysis	6 months to 18 months	PI, Co-I	2	1 year to 3 years
5. Report writing	12 months to 24 months	PI, Co-I	2	2 years to 4 years
6. Technology transfer including first-generation tools (e.g., websites)	6 months to 12 months	PI, Co-I	2	1 year to 2 years
Total	3 years to 6 years		5	8 years to 16 years

[A] Optional, but desirable depending on scope of activities.

4.5. Training and Personal Protective Equipment (PPE)

Safety and technical training requirements must be completed by all field staff before any deployments take place, and appropriate PPE must be utilized in the field. Training and usage of proper equipment and PPE contributes to safe operations in the field and helps to ensure the quality of data collected by the team. Training topics can be grouped into three categories described in the following sections:

1. general NIST safety training and PPE requirements,
2. wildland firefighter training, and
3. case study technical training.

Each team member must satisfy these training requirements in addition to any fundamental skills training or knowledge for their specific technical role, such as GIS or IT background.

General safety training requirements are set by NIST and the Engineering Laboratory. Additional trainings related to field deployments are also required, including topics such as first aid, heat stress, and specific PPE training for respirators and chemical hazards. The PPE for WUI field deployments is a combination of NIST and National Wildfire Coordinating Group (NWCG) requirements. Specific PPE is listed in Appendix A. Specifications of fire-specific PPE are listed in NFPA 1977 (Standard on Protective Clothing and Equipment for Wildland Fire Fighting and Urban Interface Fire Fighting).

4.5.1. Wildland Fire Incident Qualification and Certification, "Red Card"

Training specific to wildland firefighting, the fire environment, and the Incident Command System (ICS) is necessary to maintain safe operations and enhances the understanding and contributions of team members. The NWCG Standards for Wildland Fire Position Qualifications [54] establishes baseline training requirements for fire personnel. An Incident Qualification Card, commonly referred to as a "red card," is issued after successful completion of the training requirements.

While team members will not encounter the fireline, the team will integrate with the local incident command for data collection and access within the fire perimeter and will frequently interact with firefighters and other first responder personnel. Basic wildland firefighter training provides several benefits to NST field team members, including:

1. understanding safety hazards of the fire and post-fire environment,
2. learning basic wildland fire behavior,
3. understanding how the ICS functions, and
4. introduction to wildland fire response and the roles of different fire personnel.

The NWCG course requirements for basic firefighter training to obtain a red card (entry-level Firefighter Type 2, FFT2 [55]) include:

- ICS-100 – Introduction to the Incident Command System (ICS)
- IS-700 –An Introduction to the National Incident Management System (NIMS)
- L-180 – Human Factors in the Wildland Fire Service
- S-130 – Firefighter Training
- S-190 – Introduction to Wildland Fire Behavior
- RT-130 – Wildland Fire Safety Training Annual Refresher

Relevant, but not required, advanced NWCG courses include:

- S-131 – Firefighter Type 1
- FI-210 – Wildland Fire Origin and Cause Determination
- S-215 – Fire Operations in Wildland/Urban Interface
- S-290 – Intermediate Wildland Fire Behavior
- IS-200 – Basic ICS for Initial Response

In addition to the coursework, red card certification requires a minimum level of physical fitness assessed through a work capacity test. The work capacity test consists of a hike over level terrain while carrying a weighted pack. The distance, pack weight, and completion time requirements vary depending on the intensity level (Arduous, Moderate, or Light) required by the job position. WUI field data collection is a physical activity that requires walking and carrying equipment several miles each day while being alert to the post-fire surroundings. Field data collection equipment and hardware weighs a considerable amount, and days in the field can be long. Additional physical fitness is necessary to safely perform field operations for the duration of a deployment. Therefore, team members must meet at least the Moderate pack test fitness standard.[2]

4.5.2. Case Study Technical Training

Technical training is focused on the specific roles and needs of the case study including the field data collection and technical discussion methods.

Technical proficiency requires knowledge of the NIST WUI data collection methodologies as well as regular practice using them before an actual case study. Pre-deployment technical training serves to maintain competence and ensure data quality. It is recommended that the team conducts at least three data collection proficiency exercises (simulated field data collection) before initiation of a case study. This familiarizes team members with the process, roles, communication, and equipment.

The benefits of a well-prepared data collection team were clearly demonstrated by TFS during the Amarillo case study. Regular pre-fire training exercises every six weeks for the three to six months prior to the fire enabled the team to master the NIST WUI 2 data collection system and efficiently use the application when they deployed in Amarillo.

Field exercises should also be augmented by at least two technical discussion exercises. These practice exercises can be conducted in a conference room setting using maps and data from previous case studies to simulate a technical discussion.

[2] The Moderate Field Test requires a 2-mile walk completed in less than 30 min while carrying a 25-pound pack. The Arduous Pack Test requires a 3-mile walk completed in less than 45 min while carrying a 45-pound pack.

5. Conclusion

The valuable insights and lessons learned from WUI fire events provide the context needed to interpret various post-fire datasets and support development or improvement in community preparedness and resilience efforts. However, the level of effort to understand the incident dynamics and context for the post-fire scene and anecdotal information is extensive. The NIST WUI research post-fire study portfolio has led to impactful findings with applications to reduce structure ignitions, quantify the value and influence of first responders on incident outcomes, and enhance the life safety of civilians. Continued fire losses show that there is much more to learn from these disasters that can improve outcomes in the future.

The scope of routine post-fire data collection is to quantify losses and impacts. Deeper understanding of the data and the interconnected dynamics of WUI fire events can be learned through detailed post-fire case studies. As an impartial science research agency, NIST is uniquely positioned to continue conducting detailed post-fire studies. This document presented the robust approach and methodology that are a foundation for this research. Each fire incident has unique circumstances, dynamics, and community characteristics that require a well-structured yet flexible case study approach. A range of different post-fire deployment possibilities were presented, from relationship-building pre-fire recons to full case studies, to collaborative post-fire technology transfer workshops. Case study parameters including areas of technical interest, staffing, and training requirements were presented to support planning for future efforts. Pre-deployment preparations, including pre-fire recons and case study team training, identify times when the team is ready and able to initiate a study, focus the research goals, and facilitate a rapid deployment. Findings from future post-fire case studies will allow us to learn from these disastrous events by identifying challenges and gaps exposed by real-world incidents to ultimately improve mitigation efforts and community resilience.

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Appendix A. Field PPE and Data Collection Kit Equipment List

The following equipment is included in the field data collection kits that have been previously used to conduct post-fire damaged structure surveys.

PPE

- Helmet with chin strap meeting NFPA 1977
- Flame-resistant (e.g., Nomex) pants and long-sleeved shirt to be worn over cotton or wool underlayers meeting NFPA 1977
- Wildland fire boots (8-inch high, laced, leather work boots with melt-resistant lug soles)
- Safety glasses with side shields meeting ANSI Z87.1
- Safety goggles
- Earplugs
- High-visibility safety vest meeting Class 2 ANSI/ISEA 107-2015
- Leather gloves
- Emergency fire shelter M-2002 meeting U.S. Forest Service Specification 5100-606
- First aid kit
- Sunscreen and insect repellent

Equipment

- GPS unit
- Weatherproof notebook and pens
- Tape measure (25 ft)
- Range finder
- Clinometer
- Compass
- Multitool
- Communication radios
- Flashlight Flagging tape; custom "NIST" tape recommended
- Digital camera(s); wide zoom range required; at least 20 MP recommended; capability of AA/AAA battery backup recommended
- 360-degree camera (*not previously used, but future use recommended)
- Electronic tablet and related field survey GPS equipment (*historically used, with updates required and new technology available)
- Spare batteries, charging cords, power inverter for charging from vehicle

Miscellaneous

- Large backpack
- Small backpack
- Magnetic car signs to identify vehicles while in the fire area

Appendix B. Indirect Outputs and Knowledge Transfer Resulting from Previous NIST WUI Fire Case Studies

Dedicated effort is required to transition knowledge from research to practitioners and end-users. To enhance and enable effective and efficient communication of the technical findings, outputs from previous NIST case studies have been shared with federal, state, and local agencies and non-governmental organizations (NGOs) through several means.

Direct technical meetings and presentations have provided opportunities for targeted discussion about specific findings or challenges identified through the case study research. Audiences have included the fire service and local and state agencies and NGOs in the community or region affected by the incident that was studied. Federal partners have included the Federal Emergency Management Agency (FEMA) and the U.S. Fire Administration (USFA), who have extended dissemination to emergency managers and the fire service.

Since 2011, NIST has hosted "NIST WUI Fire Days," which have been a core knowledge dissemination tool of the NIST WUI Fire Group. The seminars began primarily as a research-sharing opportunity among the science community; however, after transitioning to a virtual meeting in 2022, the presentations [56, 57] have been broadcast to a much wider audience including the fire service, government, researchers, and codes and standards organizations. Interested international stakeholders have also participated.

Several additional frameworks and methodologies have been developed from case study findings to facilitate knowledge transfer and provide more direct interpretation and implementation of the lessons learned. These methodologies have impacts on research by directing future case studies and experiments, and in practice by providing guidance for community pre-fire planning and incident response.

B.1. NIST WUI Data Collection Methodology

The NIST WUI data collection methodology described in this document was initially developed to address the field data collection needs identified during the first NIST case study. The methodology has been refined and adapted in subsequent case studies and has proven to be an effective and adaptable tool for field data collection; it has been used in incidents ranging from 35 to over 18 000 destroyed structures. Section 3.2 discusses components of the methodology including incident data collection, post-fire field data collection, and direct observations identified through technical discussions with first responders.

B.2. WUI Fire Exposure Scale

A finding during the analysis in the first NIST case studies was that there is no scale with which to rate or quantify WUI fires in a manner that other natural disasters use to categorize severity and inform engineered building requirements or judge building performance [30]. Specifically, tornadoes and hurricanes are often categorized by wind speeds, and earthquakes by seismic moment or peak ground acceleration.

An analogous concept was developed to categorize the severity of a WUI fire exposure from flames and firebrands (embers) [58]. The WUI Fire Exposure Scale introduced the concepts of variable fire and ember exposures within WUI incidents and started framing the relationship of structure performance to the balance between exposure severity and structure hardening.

B.3. WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology (HMM)

The accumulated knowledge of post-fire case studies and laboratory experiments to identify ignition vulnerabilities has highlighted the shortcomings of current WUI building codes. Of the ember ignition vulnerabilities identified, only 26 % are included in at least one of the three current codes reviewed,[3] and at most one half of the fire (direct flame) exposure vulnerabilities are addressed in the codes [46]. Critically, these codes rarely apply to the retrofit of the millions of existing structures in the WUI.

Therefore, the Hazard Mitigation Methodology (HMM) was developed in conjunction with CAL FIRE and the Insurance Institute for Business & Home Safety (IBHS) to help communities identify and implement cost-effective ways to reduce structural losses from WUI fires. HMM represents a paradigm shift in WUI hazard mitigation through the approach of an exposure-centric, performance-based retrofit system for entire communities. HMM is uncoupled from the traditional parcel-centric mitigation systems that do not account for fire behavior and exposures between parcels. HMM considers home hardening and exposures together, giving AHJs different options to reach enhanced ignition resistance.

The Office of the State Fire Marshal of California and standards bodies such as the International Code Council (ICC) are working to implement the concepts of HMM into current WUI codes.

B.4. Community WUI Fire Hazard Evaluation Framework

Various community information sources exist that support advance planning for response to WUI fire incidents. Currently there is no system or framework in place to standardize this information. A Community WUI Fire Hazard Evaluation Framework [59] was presented in Appendix C of NIST Technical Note 2135 [44] and is intended to help WUI communities identify their unique hazards and to provide a framework of common metrics between communities. It can be used to identify gaps in pre-fire planning, link different aspects of community preparedness and resilience, and facilitate information sharing to mutual aid agencies before and during an incident. The methodology is intended to be used across the entire community and not at an individual structure level. The state of California adopted the framework into Appendix P of the 2022 California Fire Code [60].

B.5. ESCAPE Methodology

The Camp Fire case study yielded influential findings related to the safety of evacuating civilians. The fast rate of fire spread and the ignition of long-range spot fires within the town of

[3] California Building Code Chapter 7A, NFPA 1140, and the ICC International WUI Code

Paradise [44] led to 17 burnover events involving civilians during evacuation [61]. These types of fire events, where the fire spreads into communities faster than they are able to evacuate, are referred to as dire scenarios [62].

ESCAPE, short for Evacuation and Sheltering Considerations—Assessment, Planning, and Execution [47], adapts the lessons learned from the Camp Fire into a more accessible format for communities and distills the overall themes from the Camp Fire-specific data. Several examples from events during the Camp Fire are included in the methodology along with other generalized considerations about WUI fire incidents to help small and intermediate-sized WUI communities develop notification and evacuation plans in preparation for future potential events.

The ESCAPE report proposes a methodology that considers the spatial and temporal aspects of WUI fire spread and the potential impacts of fire impinging on evacuation routes to provide perspective on evacuations and pre-planning that can be used by emergency managers as the foundation for notification and evacuation decisions. The report provides communities a path forward for assessing, planning, and implementing a notification/evacuation plan that leverages pre-fire conditions, local knowledge, and during-event information to enhance the life safety of civilians and first responders.

B.6. Impacts

NIST WUI case studies have provided a significant increase in the fundamental understanding of WUI fires, from fire spread, exposures, and structure ignitions in the WUI, to life safety issues and aspects of emergency response including the outcome of defensive actions and tactics.

These findings have influenced research, community preparedness, and WUI incident response operations in five categories:

- WUI fire incident-level — including how the fire spreads, the relationships between fire and civilian evacuation and how defensive actions impact and ultimately contain the event.
- Laboratory research — including research of smaller parcel-level combustibles like fences and retaining walls, and inter- and intra-parcel exposures from auxiliary structures, as well as research on sealants and gaskets.
- Modeling — field observations provide guidance for modeling at the parcel-level. Modeling impacts and connection to field work can be further categorized as field scale or as identifying specific modeling improvements and use of models to design and simulate specific laboratory activities [63].
- Case studies — directly impact future case studies by improving the WUI data collection and analysis methodology and providing additional direction for future field work.
- Methodologies and tools for existing and new communities — leveraging the lessons learned from all the above work to create implementable solutions to the WUI fire problem, accomplished in collaboration with federal, state, and NGO partners.