The Costs of Wildfire in California

An Independent Review of Scientific and Technical Information

FULL REPORT

A Commissioned Report prepared by the
California Council on Science and Technology

STRONGER WITH SCIENCE FOR 30 YEARS

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

A nonpartisan, nonprofit organization established via the California State Legislature
— making California's policies stronger with science and technology since 1988

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Full Report

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About CCST

The California Council on Science and Technology is a nonpartisan, nonprofit organization established via the California State Legislature in 1988. CCST responds to the Governor, the Legislature, and other State entities who request independent assessment of public policy issues affecting the State of California relating to science and technology. CCST engages leading experts in science and technology to advise state policymakers—ensuring that California policy is strengthened and informed by scientific knowledge, research, and innovation.

Note

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Acronyms and Abbreviations

AB	(California State) Assembly Bill
BAER	(USFS) Burned Area Emergency Response
BLM	Bureau of Land Management
CAA	Clean Air Act
CAL FIRE	California Department of Forestry and Fire Protection
CalRecycle	California Department of Resources Recycling and Recovery
CalTrans	California Department of Transportation
CARB	California Air Resources Board
CCST	California Council on Science and Technology
CBC	California Building Code
CDC	(U.S.) Centers for Disease Control and Prevention
CDOI	California Department of Insurance
CDPH	California Department of Public Health
CEMA	Catastrophic Event Memorandum Account
CFC	California Fire Code
CGE	Computable General Equilibrium
COPD	Chronic Obstructive Pulmonary Disease
COVID-19	Coronavirus Disease 2019
CPUC	California Public Utilities Commission
DHCS	(California) Department of Health Care Services

DINS	(CAL FIRE) Damage INSpection Program
DIRS	Disaster Information Reporting System
DOC	California) Department of Conservation
DOI	(U.S.) Department of the Interior
DTSC	(California) Department of Toxic Substances
ED	Emergency Department
EDD	(California) Employment Development Department
EPA	(U.S.) Environmental Protection Agency
ER	Emergency Room
ES	Executive Summary
FAMWEB	National Fire and Aviation Management Web
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FHSZ	Fire Hazard Severity Zones
FRA	Federal Responsibility Area
FRAP	(CAL FIRE) Fire and Resource Assessment Program
FRID	Fire Return Interval Departure
GDP	Gross Domestic Product
GGRF	Greenhouse Gas Reduction Fund
HEPA	High Efficiency Particulate Air (filter)
HMS	(NOAA) Hazard Mapping System
HMS Smoke	(NOAA) Office of Satellite and Product Operations HMS Fire and Smoke Product

HVAC	Heating, Ventilation, and Air Conditioning
ICE	(Berkeley Lab) Interruption Cost Estimate (calculator)
III	Insurance Information Institute
IQ	Intelligence Quotient
LADWP	Los Angeles Department of Water and Power
LRA	Local Responsibility Area
MCL	Maximum Contaminant Levels
MERV	Minimum Efficiency Reporting Value
MIS/DSS	DHCS Management Information System/Decision Support System
MMTCO2	Million Metric Tons of CO2
MTBS	Monitoring Trends in Burn Severity
NAS	National Academy of Sciences
NC RWQCB	North Coast Regional Water Quality Control Boards
NFIRS	National Fire Incident Reporting System
NOAA	National Oceanic and Atmospheric Administration
OES	(California Governor) Office of Emergency Services
OSHPD	(California) Office of Statewide Health Planning and Development
PE	Pulmonary Embolism
PFIRS	(California) Prescribed Fire Information Reporting System
PG&E	Pacific Gas and Electric Company
PM	Particulate Matter
PM2.5	Particulate matter with a diameter of less than 2.5 micrometers

PM10	Particulate matter with a diameter of less than 10 micrometers
PRC	(California) Public Resources Code
PSPS	Public Safety Power Shutoff
PTSD	Post-Traumatic Stress Disorder
RAVG	Rapid Assessment of Vegetation Condition
SARS-CoV-2	Severe Acute Respiratory Syndrome CoronaVirus 2
SB	(California State) Senate Bill
SCC	Social Cost of Carbon
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SES	SocioEconomic Status
SF RWQCB	San Francisco Regional Water Quality Control Boards
SHELDUS	Spatial Hazard Events and Losses Database for the United States
SMUD	Sacramento Municipal Utility District
SRA	State Responsibility Area
SRAFPF	State Responsibility Area Fire Prevention Fee
SWAMP	Surface Water Ambient Monitoring Program
T&D	Transmission and Distribution
ug/m^3	Micrograms per cubic meter of air
USFS	U.S. Department of Agriculture Forest Service
USGS	U.S. Geological Survey
VLL	Value of Lost Load

VOC Volatile Organic Compound

WERT (California) Watershed Emergency Rehabilitation Teams

WMP (CPUC) Wildfire Mitigation Plan

WUI Wildland-Urban Interface

Chapter 1

Introduction and Conceptual Framework

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Wildfires are a common and natural occurrence in many ecosystems around the world and can provide numerous ecological and societal benefits. However, wildfires can also cause significant loss of lives, infrastructure, and critical ecosystem services. The losses associated with wildfires are predicted to worsen with climate change and an expanding wildland urban interface. The most recent California wildfire seasons have been the most destructive and deadliest on record, raising a number of complex policy issues for the state. There is an urgent need for a broad network of stakeholders, researchers, decision makers, and philanthropists to work together to mitigate, prepare for, and respond to catastrophic wildfires.

In April 2019, the Gordon and Betty Moore Foundation held a "Fire Immediate Response System Workshop" that was attended by a broad representation of experts in wildfire detection, emergency response, natural resource management, and other wildfire-related fields. The resulting report from that workshop identified a number of critical needs, including developing a cost-benefit analysis weighing the investment in solutions against the costs of reactive management of wildfires in California. This report on wildfire costs was proposed as a step toward understanding the current feasibility of performing such a cost-benefit analysis.

1.1 CCST's Role and Charge

The California Council on Science and Technology (CCST) is called upon to provide credible, relevant, and independent information and analysis to inform policy decisions related to science and technology issues. This report is the deliverable of the request by the Gordon and Betty Moore Foundation to examine what considerations should be made to characterize the costs and losses of wildfires in the state of California. This document has been researched and written by principal researchers and select CCST staff under the guidance of a steering committee with an appropriate range of expertise, a balance of perspectives, and no conflicts of interest (see Appendices A and B).

CCST strives to produce documents through a transparent process that ensures the final product is responsive to the questions of the sponsor, while maintaining full scientific independence. Transparency is achieved by engaging the sponsor in dialogue about the nature of their needed information and informing the sponsoring entity of the study progress.

1.2 A Conceptual Framework for Wildfires

We first present a general conceptual framework for understanding the full societal impacts of wildfires in this section before describing the specific scope of the report in the following sections.

Wildfires are complex events that can result in numerous outcomes that impact humans, other living organisms, the built environment, working lands, ecosystems, and even physical processes such as weather events. Reported outcomes of wildfire typically include only those that are attributable to the physical fire itself; these outcomes largely occur during the fire event and within or near the wildfire perimeter. However, wildfires can also generate smoke plumes or increase the risk of post-wildfire landscape events such as erosion, debris flows, and flooding. These related events can also cause significant outcomes even though they occur far from or long after the actual wildfire. A truly comprehensive accounting of the impact of wildfire in California must include all associated wildfire events, namely the physical wildfire, wildfire smoke, and post-wildfire landscape events.

Wildfire outcomes are not inherently beneficial or detrimental. Depending on the context in which a wildfire occurs, some outcomes may be recognized as appreciable benefits to society and others as appreciable losses. The classification of a wildfire outcome as a benefit or a loss depends entirely on our own subjective goals as a society, which can and do change over time or from one fire to the next. For example, we may consider smoke from one wildfire to be a benefit when it settles over a stream and reduces water temperatures to levels favorable for salmon, but consider smoke from another wildfire to be a loss when it settles over a city and reduces the air quality to levels unfavorable for public health. Additionally, it is important to consider the distribution and social context of losses. The same amount of property losses may have different implications for high vs. low income households, and the same amount of pollution exposure may cause different health impacts for particularly vulnerable populations.

In response to wildfire, society engages in a variety of prevention, mitigation, and management actions in an effort to reduce the losses and increase the benefits of wildfire. These actions can affect ignition sources of wildfires, affect conditions that influence wildfire behavior (e.g., weather, fuels, or terrain), or impact specific outcomes when a wildfire does occur. Examples of actions with potential to impact wildfire behavior include: public education campaigns to reduce the incidence of accidental fire starts; mitigation of anthropogenic climate change to avoid projected average temperature increases; vegetation management to promote ecologically beneficial wildfire behavior; and home hardening to reduce the risk of homes burning down when exposed to wildfire embers.

We refer to wildfire benefits that are monetized as estimated gains, and to losses that are monetized as costs. Wildfire costs also include the monetized estimates of prevention, mitigation, and management actions undertaken to increase benefits and/or reduce losses from wildfires. Whether or not wildfires represent a net benefit or a net loss to society depends on the relative balance of the many individual benefits and losses that occur and the actions taken to affect wildfire outcomes. To the extent that there are effective actions available for influencing the outcomes of wildfires, this balance can be intentionally adjusted with various combinations of prevention, mitigation, and management actions to modify the net impact to society.

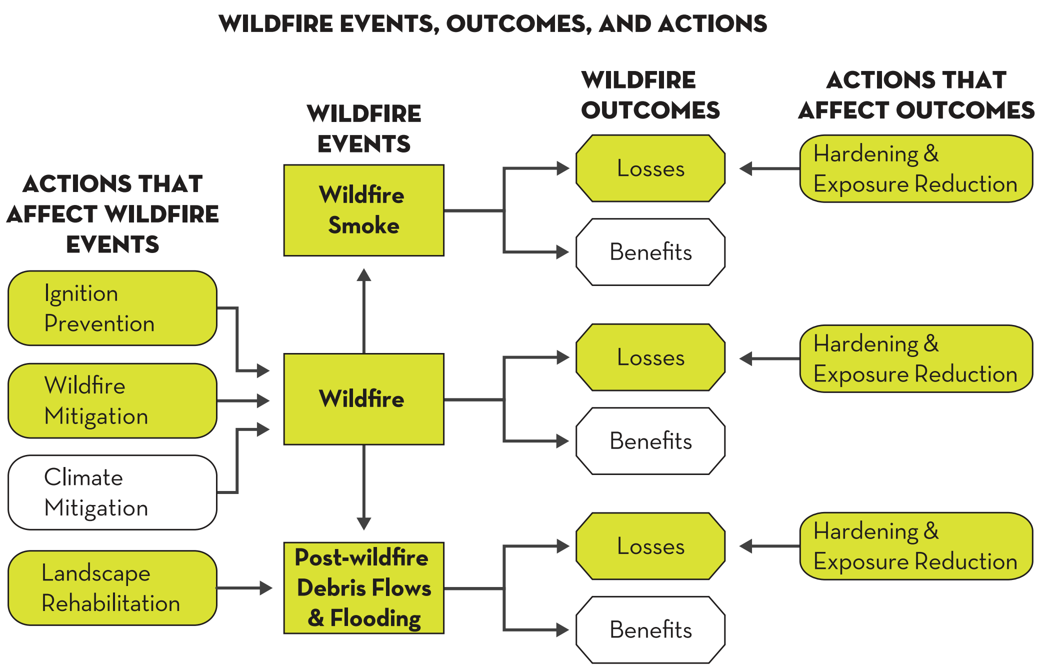

Figure 1.1: A conceptual framework of wildfires. *Wildfire events (second column, rectangles) drive outcomes (third column, polygons), which are categorized as either benefits or losses. Some mitigation and prevention actions (ovals, first column) are intended to directly affect wildfire events, while others (ovals, fourth column) are intended to affect outcomes when wildfire events do occur. The lines connecting the categories indicate cause and effect pathways between wildfire events, outcomes, and prevention and mitigation actions. Green shading indicates topics covered in the scope of this report, including losses caused by wildfire events, and prevention and mitigation actions specifically intended to reduce those losses.*

1.3 Report Goal and Approach

The objective of this report is to provide a framework for understanding the full costs associated with wildfire losses in California and the costs of prevention and mitigation actions undertaken to specifically reduce losses. The scope of this report does not include a review of wildfire benefits to California or of management activities primarily intended to increase wildfire benefits. The report also does not include a review of actions to mitigate anthropogenic climate change, which are generally intended to address a broader suite of outcomes beyond only those caused by wildfires.

We review publicly available resources and the academic literature for wildfire costs relevant to California and the effectiveness of prevention and mitigation to reduce wildfire costs, identifying where the research community's collective knowledge is strong and what gaps remain. We also review the literature for California-specific data on wildfires, identifying where additional data collection would facilitate efforts to address knowledge gaps for California. Understanding the broader landscape of wildfire losses discussed in this report will help better inform decisions about effective fire management, development in the wildland-urban interface, adaptation to smoke in populated areas far away from wildfires, and other prevention and mitigation actions intended to specifically reduce wildfire losses. However, a comprehensive accounting of all activities that can impact wildfire outcomes, in addition to benefits, would be necessary to evaluate the net societal impact of wildfires to California.

Our approach to understanding wildfire losses and their associated costs in this report is broad. We consider both the direct and indirect losses attributable to wildfires themselves, as well as related wildfire events, including wildfire smoke plumes and post-wildfire landslides. Effective policy must rely on this expanded understanding of the costs associated with wildfires and the cost-effectiveness of prevention and mitigation actions when considering public policy tradeoffs. The objective of this report is not to propose what this balance of tradeoffs should ultimately be, but rather to provide a review of the available information on the societal losses and associated costs of wildfires so policymakers and public stakeholders may make informed decisions about the tradeoffs presented by the changing wildfire regimes in the state.

1.4 What is a Catastrophic Wildfire?

There is no common technical or scientific definition for what constitutes a "catastrophic" wildfire, despite the fact that this term is widely used in public discourse. Wildfires are categorized by fire scientists according to traits such as fire size, frequency, intensity, severity, and flame length. However, because losses and benefits depend strongly on the broader context in which a wildfire occurs, these traits alone do not reflect the impact a wildfire will have on society or the environment. Instead, we suggest the term "catastrophic wildfire" refers not to wildfires with specific traits, but to wildfires that cause substantial undesired losses on society and the environment.

Under our proposed conceptualization, not all high-acreage, high-severity, or high-intensity wildfires are “catastrophic.” Wildfires are a natural disturbance for many of California’s ecosystems and in some instances, such wildfires can be ecologically beneficial while simultaneously incurring few losses. Moreover, because there are many dimensions to wildfire losses, not all catastrophic wildfires are catastrophic in the same way. A wildfire that destroys hundreds of homes, a wildfire that produces a smoke plume that sickens hundreds of people, or a wildfire that triggers post-fire erosion that leads to contamination of water sources can all impose substantial losses.

The complexity of wildfire losses means that a single, universal definition for catastrophic wildfire based on a specific set of loss metrics is unlikely to adequately capture all wildfires deemed catastrophic in all situations. Instead, researchers and policymakers should endeavor to explicitly state the working definition (i.e., a specific set of loss metrics) being used to diagnose catastrophic wildfire for their particular situations of interest, similar to the use of species concepts in biology.

> ***Finding:*** *Though the term “catastrophic” wildfire is used widely in public discourse, there is no commonly-accepted technical definition of “catastrophic” wildfire.*

> ***Conclusion:*** *Policy discussions about wildfires would benefit from a consistent focus on the losses or benefits caused by wildfire rather than the traits that characterize wildfire.*

> ***Recommendation:*** *We recommend that the term “catastrophic” wildfire refer not to the characteristics of a specific wildfire, but to the substantial undesired losses that these events impose on society and the environment. Further, any set of loss metrics used to designate a fire as “catastrophic” should be designed for its particular social and environmental contexts.*

1.5 Losses and Costs from Catastrophic Wildfire

If catastrophic wildfires are to be defined according to the losses that they impose on society and the environment, it is important to understand these losses using as comprehensive a framework as possible. In this report, we suggest a framework for categorizing losses into four categories:

1. Losses associated with **damage to or destruction of physical assets**. Physical asset losses can include damage or destruction of homes, structures, and physical infrastructure. Associated costs include costs to repair or replace the physical assets and any personal property or inventory that was also lost, costs to clean up debris and hazardous waste, and costs to provide temporary accommodations or services.

2. Losses associated with **harm to health**. Human health impacts include injury and death to the general public, firefighters, and other emergency response personnel within or nearby the fire perimeter; adverse health impacts, including death, from smoke inhalation both near and far from the wildfire itself; and the mental health impacts associated with the trauma of a wildfire.

3. Losses associated with **changes in ecosystem processes** that affect non-market ecosystem services. For example, net losses of stored carbon would increase greenhouse gas emissions that cause climate change.

4. Losses due to **changes in economic activity**.

These losses can broadly be measured in either the physical units of the losses (e.g. number of homes destroyed by wildfire, number of people displaced by a wildfire event, or number of cases of illness caused by wildfire smoke) or using a monetized estimate of the losses (dollar value of homes, dollar value of disaster recovery assistance, or dollar value of health care). A distinction is made, when possible, to differentiate these different metrics of losses. When losses are monetized, we refer to this as the cost associated with these losses.

In response to catastrophic wildfire, society engages in a variety of prevention and mitigation actions to reduce losses and decrease the associated costs. We categorize prevention and mitigation actions into two main categories:

1. **Actions intended to directly affect the wildfire event itself in ways that result in fewer losses.** Prevention and mitigation of wildfire events include fire suppression to prevent a fire from burning into a populated area, or watershed rehabilitation to prevent increased erosion upstream of a reservoir.

2. **Actions intended to reduce losses when a catastrophic wildfire event does occur**. Mitigation of wildfire losses include home hardening to prevent homes from igniting when they are exposed to embers from a wildfire, and establishing clear air spaces to prevent people from getting sick from exposure to wildfire smoke.

Similar to losses, prevention and mitigation actions can be measured in either physical units (number of homes with fire resistant roofs or HEPA air filters) or as the monetized estimate of the actions (dollar value of replacing a roof or operating an air filter). In a sense, the costs of effective prevention and mitigation actions are an estimate of society's current willingness to pay to avoid a certain degree of the losses from wildfire. When prevention and mitigation actions are cost-effective, spending an additional dollar on prevention and mitigation saves more than a dollar in avoided losses, bringing down the total cost to society.

Together, the monetized costs of wildfire losses and the costs of mitigation and prevention efforts to reduce losses constitute the full suite of societal costs associated with wildfire losses.[1] However, care should be taken whenever adding together costs to reach a total value as there may be substantial overlap in reported cost estimates of different categories. To the

1. As noted earlier in this chapter, calculating the net impact of wildfires on society requires estimating both the gains associated with benefits and the costs associated with losses.

extent that there are effective prevention and mitigation actions available for California, the balance of costs and losses can be adjusted with various combinations of prevention and mitigation actions. Our goal in this report is to catalogue the current knowledge with respect to wildfire losses, the monetized costs associated with those losses, and the costs and effectiveness of prevention and mitigation actions in California to help inform current and future policy discussions on an optimal combination for our society.

1.6 Organization of the Report

The conceptual framework of wildfire events, wildfire losses, and prevention and mitigation actions covered within the scope of this report is shown in Figure 1.2. The report outlines the current peer-reviewed and publicly available literature for each of the following categories:

1. The physical wildfire events driving losses.

2. The four categories of wildfire losses described in section 1.5.

3. Mitigation and prevention actions intended to directly affect wildfire events.

4. Mitigation actions intended to reduce losses when wildfires do occur.

5. The effectiveness of prevention and mitigation actions.

This report is not intended as a comprehensive review of all wildfire impacts in California because it specifically excludes the benefits of wildfire events, actions specifically intended to increase benefits, and actions intended to impact more than just wildfires (e.g., mitigation of anthropomorphic climate change).

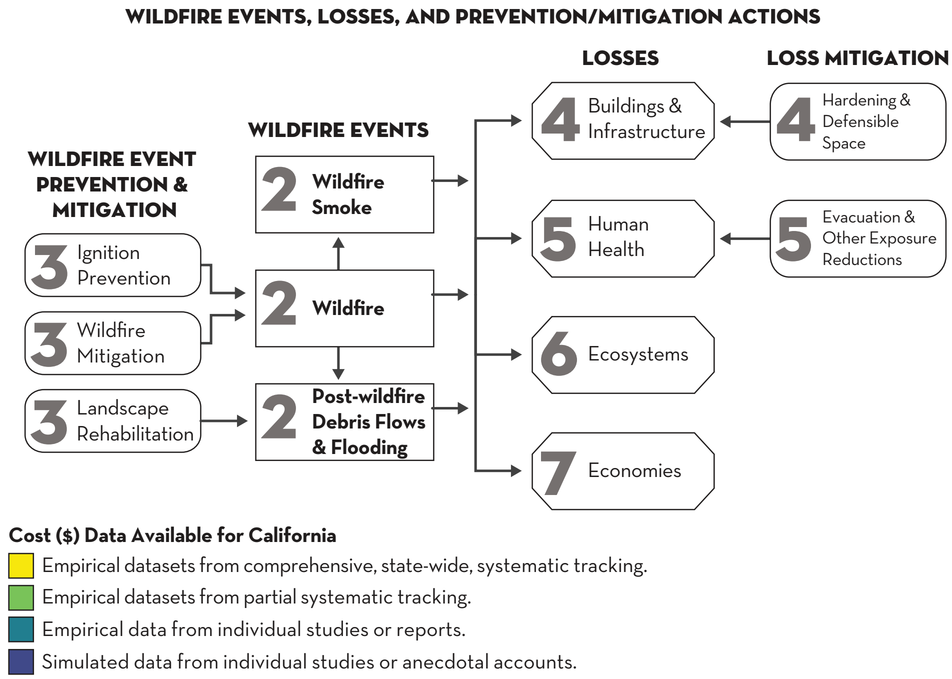

Figure 1.2: A conceptual framework of catastrophic wildfire costs. *Physical wildfire events (second column, rectangles) drive losses, which are categorized here into four groups (third column, polygons). Some mitigation and prevention actions (ovals, first column) are intended to directly affect wildfire events, while others (ovals, fourth column) are intended to reduce losses when wildfire events do occur. The lines connecting the categories indicate cause and effect pathways between wildfire events, losses, and prevention and mitigation actions. Large font numbers within each shape indicate the chapter in which each item is discussed. Not included in the report scope are the benefits of wildfires or climate mitigation actions.*

As shown in Figure 1.2, there are multiple cause and effect pathways between wildfire events, losses, and prevention and mitigation actions. For each category of loss illustrated in Figure 1.2, we review the current literature for the availability of California-specific data that can be used to address the following questions:

1. **What is the exposure to wildfire events?** This question requires data that can help characterize the extent to which something or someone has been exposed to wildfire events in California. Examples include the number of homes that occurred within the perimeter of a wildfire or the number of people who were living within the perimeter of a wildfire smoke plume. Datasets on exposure provide an upper bound for potential losses if all exposed assets or people suffered a loss. These datasets, when paired with vulnerability analyses to estimate expected losses from wildfire, are essential for identifying and evaluating the effectiveness of prevention and mitigation actions.

2. **What are the losses and associated costs of wildfire events?** Relevant data provide either a numeric measure of loss (e.g. number of structures destroyed by wildfire, or number of excess hospitalizations attributed to wildfire smoke) or a dollar value estimate of the costs associated with the loss (e.g. dollar value of the property, cost of health care to treat illnesses). Datasets on losses are essential for calculating the full costs of wildfires in California.

3. **To what extent are prevention and mitigation actions used in California and what are the associated costs?** Relevant data provide either a numeric measure of an action (e.g. number of acres treated with prescribed fires, number of fire engine crews deployed to suppress a fire, or number of homes with fire-resistant roofs) or a dollar value estimate of the costs associated with the action (e.g. cost to conduct the prescribed burn, cost of fire suppression efforts, cost of retrofitting roofs). Datasets on prevention and mitigation actions are essential for calculating the full costs of wildfires in California.

4. **To what extent are prevention and mitigation actions effective at reducing losses, and are the actions also cost-effective?** Relevant data provide either a numeric measure of effectiveness (e.g. for every *x* acres of forest treated with prescribed fire, the risk of home losses decreased by *y* amount) or a dollar value estimate of the cost-effectiveness (e.g. for every $*x* spent on prescribed fire, the State avoids an estimated $*y* in home losses). Datasets on effectiveness of prevention and mitigation actions are essential for identifying strategies to reduce the total costs of wildfire in California.

Our primary focus is on peer-reviewed academic literature and publicly available government datasets. We also consider grey literature reports and select news articles to help frame a topic, particularly when peer-reviewed literature is not robust, but do not attempt an exhaustive review of these sources. In addition to the literature review discussed in the text for each chapter, we provide visual summaries of the conceptual framework (as in Figure 1.2 above) and of the types of datasets used to address each of the four questions listed above. The type of data in a study or dataset is assigned to one of five categories, which are designated by color in summary figures and tables throughout the report (e.g. Figure ES-1):

1. No California-specific information is available, but data may exist for regions outside of the state or aggregated at the national level—white.

2. Information available from anecdotal accounts or simulated data from models based on conditions in California—purple.

3. Empirical data is available from one or more independently conducted real world case studies in California—turquoise.

4. Empirical data is systematically collected as part of an ongoing tracking effort that is known to include some but not all events, losses, or actions in California (e.g. dataset includes fuels mitigation work on public lands but does not include work on privately owned lands)—green.

5. Empirical data is systematically collected as part of an ongoing tracking effort that is intended to be comprehensive of all events, losses, or actions for the entire state—yellow.

Note that the colors in each table or diagram indicate only the type of data available to characterize a specific category of interest, and are not meant to score the quality of the data, nor the results of the data. For example, a case study that finds a fuel treatment was effective at reducing losses of subsequent wildfire would have the same color indicator as a second case study that finds a separate fuel treatment was not effective at reducing losses—turquoise, indicating case studies were available to describe the effectiveness of various treatments.

The remainder of this report is organized as follows:

- Chapter 2 provides a brief background on wildfires in California, including a detailed description of the various wildfire impacts.

- Chapter 3 discusses costs associated with wildfire prevention and mitigation actions.

- Chapter 4 summarizes the literature on the physical losses from wildfire events.

- Chapter 5 reviews the literature on the public health losses associated with wildfires.

- Chapter 6 reviews the literature on impacts to ecosystems and non-market ecosystem services.

- Chapter 7 reviews the literature on the impacts to individual markets and the broader economy.

- Chapter 8 concludes with a summary of key lessons and recommendations.

Chapter 2

Background—California Wildfires

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2.1 Chapter Scope

Chapter 2 provides a brief background on wildfire in California. This background history is meant to provide a brief overview of significant historical trends in order to help contextualize the path to current challenges facing California. The primary focus is to review the literature on recent trends and future projections of wildfire regimes—the prevailing patterns of wildfire—in the state. This background chapter is not meant to be exhaustive, nor to provide a detailed understanding of the complexities of wildfire science and the impacts of wildfires on various ecosystems. The intent is to provide a minimal background for placing into context the report's discussion of wildfire-related costs.

2.2 Brief History of Wildfire in California

Many of California's largely Mediterranean-climate ecosystems are resilient to wildfire, and a number of species and vegetation communities rely on fire as a critical component of healthy ecosystem functioning (Sugihara et al., 2018). These fire-prone landscapes include a wide array of ecosystems, ranging from expansive grasslands to chaparral, coastal woodlands, and mixed conifer forests.

However, wildfire regimes in California have also been shaped by human activity for thousands of years. Prior to European settlement, indigenous communities across the state used prescribed fire to actively manage the landscape for multiple objectives. Research suggests that during this era, wildfire was much more widespread across the landscape (Anderson, 2019). It is likely that prior to European settlement (pre-1800), 4.4–11.2 million acres burned each year in California due to both human and natural ignitions (Stephens et al., 2007). This historic annual burn area is much higher than the current total burned area in California, which rarely exceeds one million acres annually. Wildfire as an ecosystem management tool was not used by European settlers and post-settlement fire activity decreased significantly in the dry mixed-conifer forests in the state as indigenous communities were removed or prohibited from burning. The post-settlement era also saw the introduction of numerous invasive plant species and extensive grazing, which had dramatic effects on the natural and managed wildfire regimes of the Native American era (Brooks et al., 2004; Bartolome et al., 2007; Bossard & Randall, 2007; Balch et al., 2013).

Our contemporary wildfire era arguably began in the mid/late 1800s and early 1900s as forestry and grazing activity on the West's natural lands increased (Stephens and Sugihara, 2018). Fire was seen as a threat to the economic value of these natural resources. In Northern California, fire suppression evolved primarily to protect the state's vast timber resources. In Southern California, suppression evolved to protect the growing rangeland acreage that was being converted from native chaparral ecosystems, often through the use of intentional rangeland burning.

Following the Great Fire of 1910, which burned approximately three million acres across Idaho and Montana, strict fire suppression policies were instituted and implemented by the newly-formed U.S. Forest Service (Egan, 2009). Suppression efforts in dry mixed-conifer forests increased in effectiveness following World War II as mechanized wildfire suppression tools were developed. The suppression efforts of this era were largely effective in reducing the incidence of wildfire in California's dry, mixed-conifer, ponderosa pine-dominated forests, which historically experienced frequent, low severity fires. In these forest types, there were major unintended consequences that have subsequently shaped the nature of contemporary wildfire activity. That is, by effectively reducing wildfire, fuel loads in these forest types increased dramatically over the twentieth century.[1] This issue does not apply to other forest types in the state that naturally experience lower frequency, higher severity fires (Schoennagel et al., 2004).

> ***Finding:*** *Fuel management strategies in the West's dry, mixed-conifer, ponderosa pine-dominated forests changed significantly over the twentieth century to protect economic interests including timber and grazing land, among other commodities and services, with a stated goal of fewer wildfires.*

> ***Conclusion:*** *This management strategy has led to far higher fuel loads in many of the West's mixed-conifer forests compared to pre-European settlement.*

In contrast to forest ecosystems, in most of California's coastal shrubland and woodland areas, fire frequency has not been effectively suppressed. Instead, fire frequency now far exceeds its pre-settlement historical range of variability (Keeley & Syphard, 2018a). Much of this increased fire frequency is due to human population increase and urban expansion, which have increased ignitions in wildlands (Keeley & Syphard, 2018b). Many shrubland communities have a natural fire regime of infrequent, periodic fire. The increasing frequency and distribution of ignitions now threatens species that require long fire-free intervals for post-fire regeneration. Consequently, many native California shrublands are

1. Fuel load is used to express the available vegetative biomass available for burning in a given area.

converting to more flammable grasslands in areas that experience more fires with short intervals between fires (Safford & Van de Water, 2014; Syphard et al., 2019a).

> ***Finding:*** *Human population growth and urban expansion have increased ignitions in California shrubland ecosystems.*

> ***Finding:*** *These increased ignitions have resulted in uncharacteristically high wildfire frequency that is detrimental to the native shrublands in those areas.*

> ***Conclusion:*** *Increased fire frequency contributes to expansion of invasive flammable grasslands that further increase fire frequency and pose additional threats to human assets and reduction of ecological services that the native shrubland provide.*

The earlier objectives of protecting timber and grazing resources evolved over the twentieth century toward protecting life and property. Modern suppression policy is driven largely by these latter two objectives. However, suppression policy and the culture of fire suppression among firefighting agencies in the state also plays a critical role in fire regimes, and the associated costs and losses of wildfire. Across the state, there are multiple approaches to fire suppression, and a number of federal, state, local, and tribal fire protection agencies in California respond to wildland fires.

Federal agencies are responsible for fires on Federal Responsibility Areas (FRA). The state fire agency, the California Department of Forestry and Fire Protection (CAL FIRE), is responsible for the approximately 31 million acres designated as State Responsibility Areas (SRA). Local fire departments are responsible for fires on Local Responsibility Areas (LRA). The distinction between SRA and LRA is largely determined by whether a community is an incorporated city (LRA) or based on housing density within unincorporated lands (see California Public Resource Code, Sections 4125-4137). Figure 2.1 shows federal, state, and local responsibility areas across the state.

There are also six counties in California where CAL FIRE contracts out fire protection on SRAs to county fire authorities. These counties, referred to as “contract counties,” include Marin, Los Angeles, Kern, Orange, Santa Barbara, and Ventura Counties. Several federal agencies, including the USFS and the Department of the Interior (including the National Park Service, Bureau of Land Management, Fish and Wildlife Service, and Bureau of Indian Affairs), have their own firefighting agencies, which are legally responsible for responding to fires on Federal Responsibility Areas (FRA). The USFS, BLM, and National Park Service, which account for the majority of FRA land, are responsible for approximately 21 million acres, 14 million acres, and 7.5 million acres, respectively (Artley, 2009).

Fire suppression for federally recognized tribes in California is largely the official responsibility of the Bureau of Indian Affairs, although several tribes provide their own fire protection services and other tribes contract with CAL FIRE for fire protection services. California tribes that are not federally recognized often contract with CAL FIRE or local fire protection agencies. In general, there are a wide variety of fire protection arrangements and governance structures among the indigenous communities in the state.

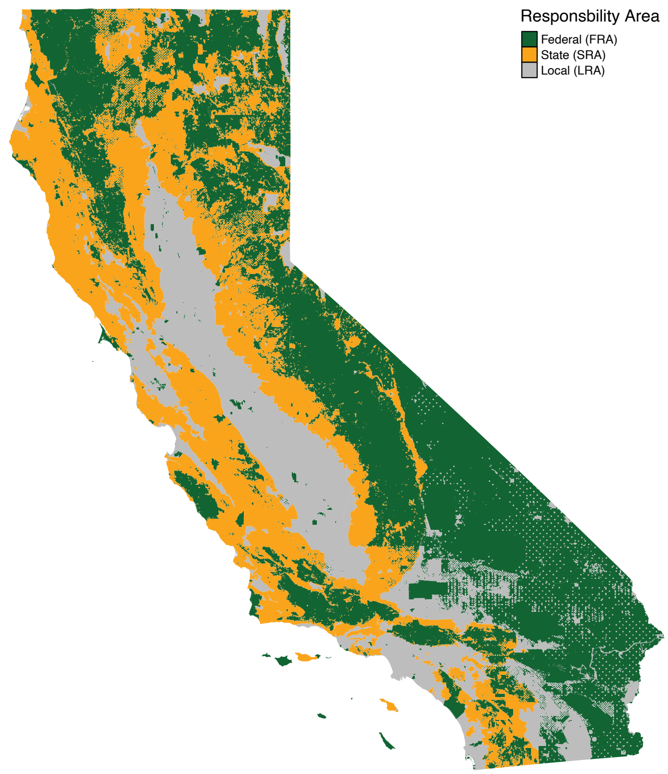

Figure 2.1: *Federal, State, and Local Responsibility Areas. Source: CAL FIRE Fire and Resource Protection Program.*

The policies and culture differ widely across these various agencies, which results in different fire-related outcomes across the state (McCaffrey et al., 2018). Jurisdictional pressures, driven largely by development patterns and regional politics, influence how fire codes and policies are implemented and enforced. For example, contract counties generally spend more money per acre for fire mitigation and suppression than areas managed directly by CAL FIRE. Fire management in LRAs, which have much higher structure densities, are also driven by local constituencies and development pressures. At the federal level, as discussed above, the USFS has a multi-decade history of fire suppression in the state's forest ecosystems, which has been supported by nearly unlimited federal funding (Berry, 2007; Schultz et al., 2019). Although the USFS officially acknowledges the ecological importance of fire, a suppression-focused mindset persists. While a full discussion of these complex interactions is beyond the scope of this report, they are very important in shaping the history and future of wildfire management across the state.

> ***Finding:*** *Wildfire suppression policy in California is determined by multiple agencies and driven by a complex set of jurisdictional stakeholder factors, such as local development patterns and politics.*

> ***Conclusion:*** *The evolution of this multi-stakeholder system has led to varied philosophies on suppression needs, which has in turn made coordinating a statewide approach to wildfire management challenging.*

> ***Conclusion:*** *The varied strategies, policies, and cultures of the many fire suppression organizations often translates to no clear leadership on a comprehensive strategy for maximizing the benefits from fire and mitigating its losses.*

> ***Recommendation:*** *The state should consider how the multiple agencies currently responsible for or affected by wildfire could better coordinate to manage fire to maximize benefits and minimize costs and losses for California.*

2.2.1 Characterizing Wildfire Regimes

Wildfire behavior is driven by both natural and human-caused conditions. Natural factors are topography, fuel, and climatic conditions, in addition to weather events such as high winds. Anthropogenic factors include: fire suppression policy; intentional or accidental human-caused ignitions; forest management; land use change that alters the type, volume, and continuity of fuels; and greenhouse gas emissions. These human-caused factors can alter climate regimes and fuel loads, which in turn affect wildfire behavior. The type of fire regime strongly affects the success of fire management.

Wildfire is a complex natural phenomenon that can be classified using a number of different approaches. For example, fire regimes in California have been classified based on the characteristics of the fire itself, the different ecoregions where fires typically occur, and the nature of the events that drive fire behavior. Classifying fire regimes based on fire characteristics involves understanding several important factors such as wildfire occurrence and frequency, extent (or size), intensity and severity, and timing of wildfire events. Occurrence indicates whether a fire event has taken place, while fire frequency refers to the number of wildfires in a region over a specific period of time. A fire return interval measures the average amount of time between wildfire events in a given location (Collins et al., 2019). Wildfire size specifies the physical extent of an individual wildfire. Wildfire intensity refers to a number of metrics that measure the energy output of a fire during its various phases. Wildfire severity attempts to connect the concept of wildfire intensity to a measure of damage to the ecosystem. Severity often refers to the fraction of vegetation that is lost in a fire. “Severity” or “intensity” can also indicate the fire’s impact on regrowth. For example, a fire that burns down to mineral soil can affect the rate of tree and vegetation regrowth, which then affects runoff and erosion (van Wagtendonk, 2019).

An alternative methodology for characterizing wildfire regimes in California is to classify by ecoregion instead of fire characteristics (Stephens et al., 2018; Syphard & Keeley, 2020). This approach clusters fire by biophysical factors, such as climate, terrain, and vegetation, and anthropogenic factors, such as housing density and road networks. Figure 2.2 shows eight possible fire regime ecoregions for California (Syphard & Keeley, 2020). Using this fire classification approach, fire size and frequency are highest in two ecoregions: the chaparral and woodland ecoregions that occur primarily in coastal regions and the Sierra Nevada foothills (ecoregion 5 in Figure 2.2) and conifer-dominated, with hardwood forest and shrub, land cover (ecoregion 8 in Figure 2.2).

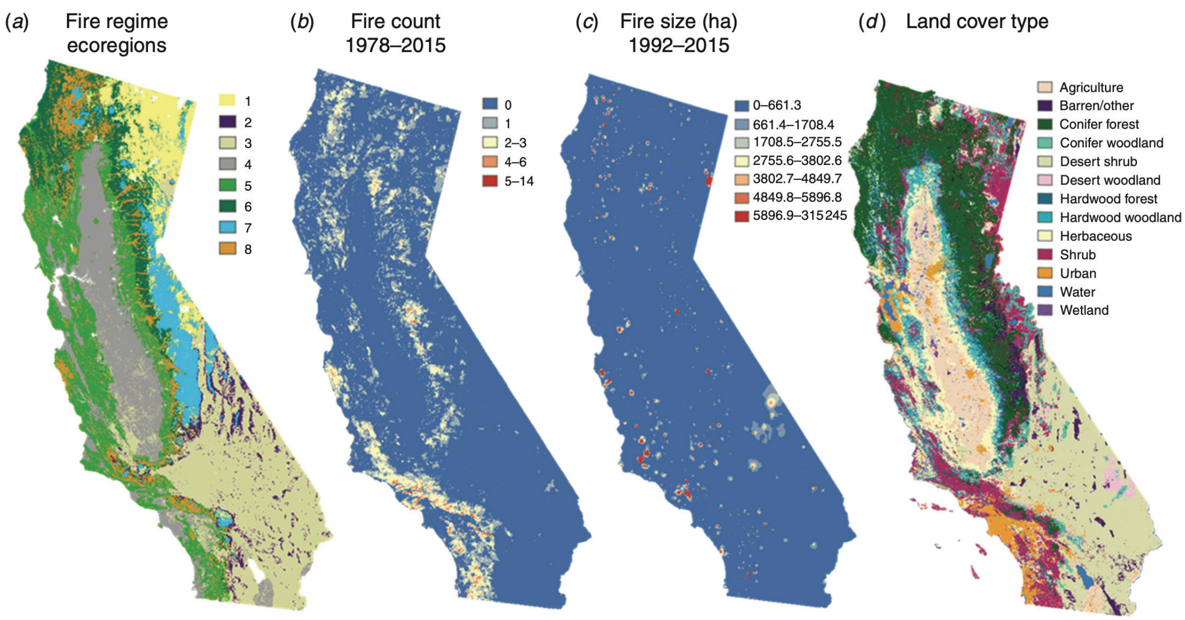

Figure 2.2. Possible fire regime ecoregions for California. *Ecoregion 5 (chaparral and woodlands) and ecoregion 8 (conifer-dominated forest and shrub) are the primary fire-prone ecoregions noted in the study. Source: Syphard and Keeley (2020).*

Keeley & Syphard (2019) propose a third classification approach for California wildfires, with fire regimes categorized as "fuel-dominated" or "wind-dominated." This classification approach is more geographically dispersed, but is useful in understanding the nature of typical wildfire events and thus strategies for planning and management.

In the absence of severe wind conditions, fuel-dominated fires tend to spread because of high fuel loads or low fuel moisture content, and in response to terrain. Examples of fuel-dominated fires include the 2009 Station Fire in Los Angeles County, the 2012 Rush Fire in Lassen County, and the 2013 Rim Fire in Stanislaus County. Wind-dominated wildfires tend to spread because of the high Foehn winds that occur across much of California in autumn (September–November), although severe wind events may occur at any time of year (Keeley & Syphard, 2019).[2] The 2017 Tubbs and Thomas fires, and the 2018 Woolsey and Camp fires, are examples of wind-dominated wildfire events.

There is no single correct approach to classifying wildfire regimes in the state. The various classification approaches are useful in understanding the primary drivers of wildfire behavior across different parts of the state and how policy and management decisions can be determined appropriately relative to a region's natural fire regime. Distinguishing fire regimes is also useful in understanding that wildfire trends, and the factors driving these trends, vary widely across the state.

It is also important to differentiate wildland fires from fires that occur in the wildland-urban interface (WUI). The WUI refers to "the area where houses meet or intermingle with undeveloped wildland vegetation" (USDA & USDI, 2001; Radeloff et al., 2005). The impacts and strategies for fire prevention and mitigation differ significantly between wildland fires and fires in the wildland-urban interface. For example, fuel loads for wildland fires consist primarily of vegetation, whereas WUI fires have fuel loads consisting of vegetation and houses. WUI fires have become a defining challenge for California as development continues to expand into less densely populated regions of the state, putting more homes and people at risk.

2.3 Recent Trends in Wildfire Regime

There is broad consensus in the scientific community that wildfire behavior is changing across the American West in general, and in California in particular. Figure 2.3 highlights trends in wildfire activity in California since 1990. All indicators shown—wildfire occurrence, total area burned, and average fire size—display an upward trend in the last several decades across the state. There is research supporting these statewide trends, such as the large increase in burned area since 1970. Williams et al. (2019) estimate that California experienced a five-fold increase in annual burned area from 1972–2018. This number is consistent with several recent studies formally documenting these trends across the West (Westerling et al., 2006; Dennison et al., 2014; Abatzoglou & Williams, 2016). Note that, with the exception of Williams et al. (2019), these trend studies exclude the 2017-2020 fire seasons, which included seven of California's ten largest fires (as of the writing of this report).

2. The National Wildfire Coordinating Group defines Foehn winds as "a warm, dry, and strong general wind that flows down into the valleys when stable, high pressure air is forced across and then down the lee slopes of a mountain range." https://www.nwcg.gov/term/glossary/foehn-wind

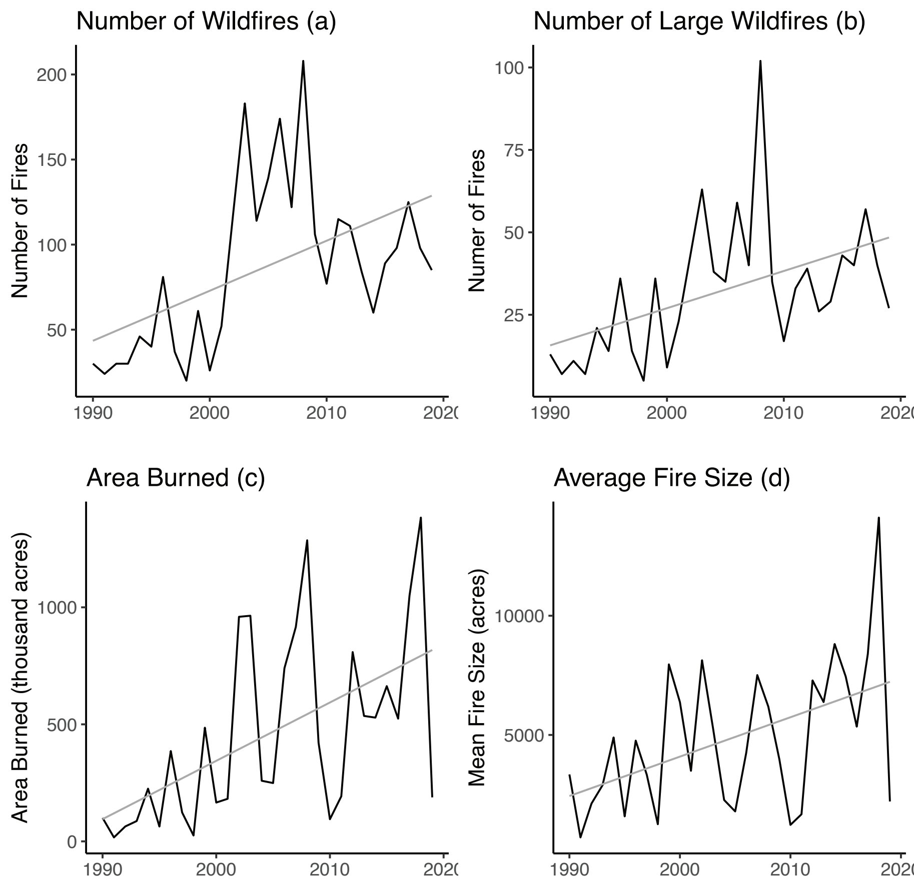

__Figure 2.3__: Trends in California wildfires since 1990. Fires less than 100 acres are excluded. Large wildfires are defined as wildfires with perimeters greater than 1,000 acres. Unadjusted linear trend shown for reference. Source: CAL FIRE Fire and Resource Assessment Program (FRAP).

However, the trends in Figure 2.3 obscure important differences in wildfire regime trends across the state. In such a diverse state, trends often differ considerably at smaller geographic scales because wildfire behavior is driven by numerous local factors (Doerr & Santín, 2016; Mann et al., 2016; Keeley & Syphard, 2017). A robust peer-reviewed literature has analyzed these changing wildfire regimes, the findings of which are summarized below.

2.3.1 Wildfire Trends Across Regions of the State

Most studies of California wildfires have documented an increase in the total burned area, frequency of large fires, and maximum fire size, especially since the mid/late twentieth century. Researchers found an increase in all three indicators from 1910–2008 for the four national forests in northwest California, with pronounced increases since the 1970s (Miller et al., 2012a). A similarly increasing trend was documented in the Sierra Nevada and

Southern Cascades (Miller et al., 2009). A more recent analysis found that burn severity is increasing in forest ecoregions across the state, but at different rates (Steel et al., 2018). This is consistent with studies reporting relatively little change in burn severity in northwest California, but large increases in fire severity in the Sierra Nevada (Miller et al., 2009; Miller et al., 2012b).

Large, forestland wildfires are increasing in size and severity across much of Northern and Central California's forest ecosystems. The overall trend of a five-fold increase in burn area is driven by an even larger (eight-fold) increase in summer forest-area burned (Williams et al., 2019).

In shrubland ecoregions through the state, the natural fire regime is one of infrequent, high-severity crown fires. As the extent of invasive annual grasses has increased, the fire severity has generally decreased but the annual burned area has greatly increased (Park et al., 2019; Westerling, 2016). However, these findings are not universally true—they vary across the state and can also vary based on land ownership (Keeley & Syphard, 2017).

While less of an emphasis in the peer-reviewed literature, it is important to note that the size and severity of fires are intertwined with the offensive and defensive tactics that firefighters choose to employ. Those tactics are in turn dependent on experience, adjacent land use patterns, legal issues, and funding. These factors are likely to account for some of the ecoregion variation described in the academic literature.

> ***Finding:*** *Wildfire trends vary across regions of the state. While some areas of the state have been experiencing changes in fire regime over time, not all have. Where fire regime has changed, the trends are variable.*

> ***Finding:*** *Climate-driven increases in wildfire occurrence, area burned, size, and severity are most pronounced in the Sierra Nevada and southern Cascades. The number of large wildfires and burned areas have also increased since the 1970s in some of the state's chaparral and woodland ecosystems.*

> ***Finding:*** *Wildfire trends vary between forested and non-forested ecosystems.*

> ***Conclusion:*** *Policy and planning should focus on variations in wildfire regimes across the state rather than the state-wide trends. Management and policy is most effective when specific to the local wildfire context.*

2.3.2 Wildfire Season Length

The traditional fire season in California extends from June until October. However, research has shown California's fire season is increasing at both ends, starting earlier in the spring (Westerling, 2016), and ending later into the fall (Williams et al., 2019; Goss et al., 2020). The earlier start to the fire season is likely the result of earlier spring snowmelt and higher temperature. The latter is driven by the delayed onset of winter precipitation, which has historically extinguished large, late-summer wildfires. While this change in climate and snowmelt may explain the lengthening of the fire season in the state's northern forests, patterns in human-caused ignitions may also be an important factor in understanding the length of the wildfire season in the state's shrublands (Keeley & Syphard, 2018b). Human-caused ignitions are the predominant source of ignitions through the state, especially in the southern region of the state (Keeley & Syphard, 2018b), and the longer fire season in southern California shrublands may be related to the expansion of invasive annual grasses that are flammable for much longer periods of the year, and thus more susceptible to the increase in human-caused ignitions.

> ***Finding:*** *The length of wildfire season is increasing.*

> ***Finding:*** *Wildfire regimes in California are the outcome of multiple processes, including both natural and anthropogenic drivers, that operate differently in different parts of the state.*

> ***Conclusion:*** *Successful strategy to reduce the costs of wildfire requires addressing this regional context.*

> ***Recommendation:*** *While state-wide goals are important, management and planning strategies should be tailored to address local and regional fire regimes for greatest success.*

> ***Recommendation:*** *Statewide wildfire trends are usually averaged across a very simple set of metrics (acres burned, number of fires, structures destroyed) but need to be bench-marked against relevant factors such as per capita values, population or housing densities, fire policies, staffing and other influential drivers of fire occurrence and consequences.*

2.3.3 Drivers of Past Wildfire Activity

Three explanations are often proposed for the observed twentieth century trends in wildfire intensity, severity, and increased number of large wildland fires—higher fuel loads, drier fuel loads, and more widely dispersed human-caused ignitions. The relative importance of these various factors vary by wildfire regime across the state (Mann et al., 2016; Syphard et al., 2019b). Wildfire intensity, severity, and size are partially driven by the amount of fuel available to burn, which includes the increased housing development in the WUI. Due to decades of fire suppression and increased tree mortality from drought and bark beetle infestation, tree density and fuel loads have increased dramatically in some forest ecoregions (Minnich et al., 1996: McIntyre et al., 2015; Safford et al., 2017). In addition, a growing body of literature also cites increasing aridity from warmer temperatures associated with climate change as a major factor in drying out these fuel loads, making them more susceptible to combustion (Abatzoglou & Williams, 2016; Fried et al., 2004; Westerling, 2016; Williams et al., 2019). However, the relationship between aridity and fire is complex and likely non-linear, which may be one explanation for why the magnitude of the wildfire-climate relationship varies regionally across the state. There are also likely to be wildfire-climate relationships that are not yet fully understood by the research community. Climate change is most likely to have direct effects on higher-elevation forested ecosystems, while indirectly it can affect coastal shrublands via vegetation change or drought (Mann et al., 2016). In coastal ecosystems, current research suggests land use is a far stronger influence on fire activity than climate (Keeley & Syphard, 2017; Syphard et al., 2019b).

More human-caused wildfire ignitions are also likely to account for the change in wildfire activity across some parts of the state as a result of more people living in the WUI and recreating in California's natural lands (Radeloff et al., 2018; Keeley & Syphard, 2018a). Development patterns in and near the WUI have and will continue to influence wildfire occurrence and area burned (Syphard et al., 2007; Mann et al., 2016). These development patterns are complex and driven by many local factors, but occur against a fast-growing California population (Figure 2.4) in search of affordable housing in areas of high amenity value.

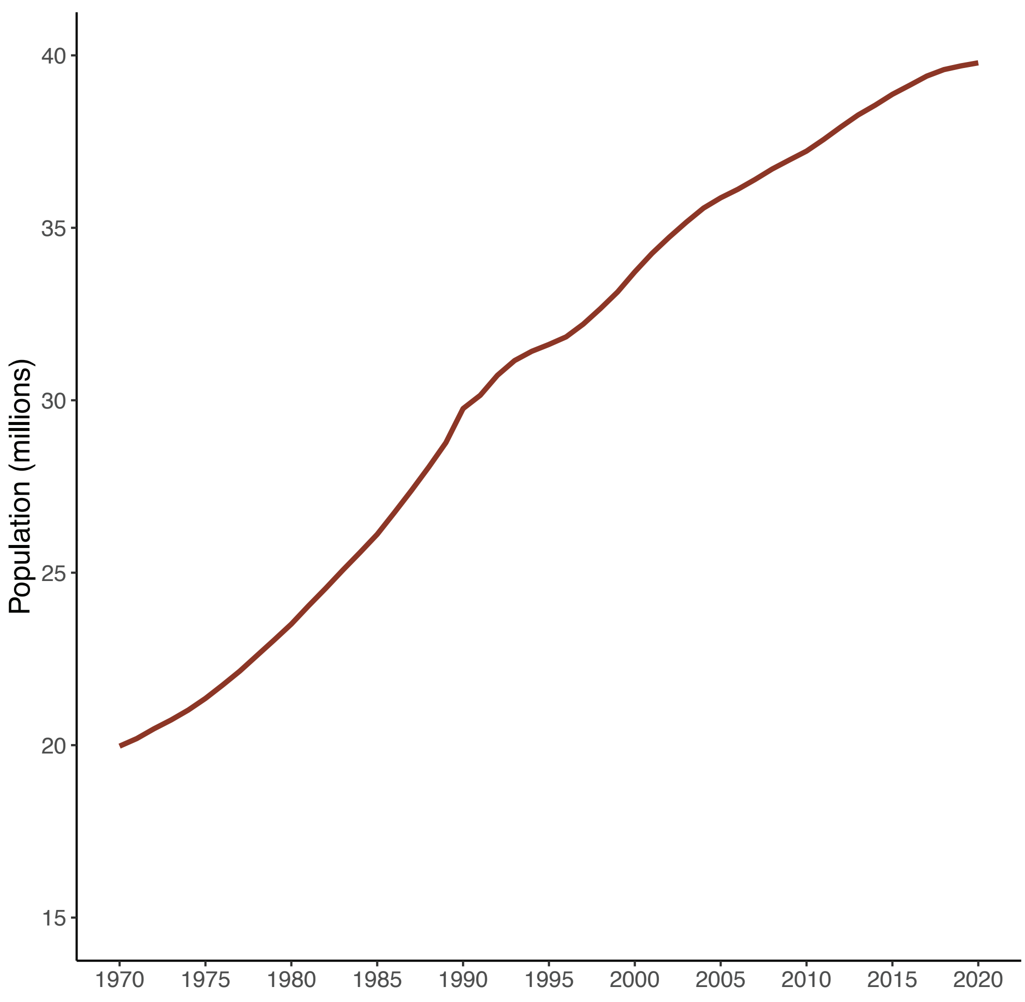

Figure 2.4: California population growth since 1970. *Source: California Department of Finance (2020).*

Finding: *Human-caused changes in land use and land cover have significantly altered natural fire regimes across the state.*

Conclusion: *Increases in fire occurrence, area burned, size, and severity in mixed conifer forests are largely the result of climate change and a legacy of fire suppression that has dramatically increased fuel loads, making many forests more susceptible to burning.*

Conclusion: *Given the drivers and variability of fire regimes in the state, and increasing wildfire activity due to past management strategy, successful strategies for reducing the cost of wildfire must consider strategies beyond exclusion or suppression.*

Recommendation: *To successfully reduce the cost of wildland fire, agencies should embrace a strategy of contextually-appropriate fire management, rather than relying on exclusion or suppression in all cases.*

2.4 Projections of Future Wildfire Regime

Predicting and projecting wildfire activity over the coming decades is an inherently challenging task because wildfire events are the result of a number of short-term and long-term natural and human-caused conditions. For example, climate change is expected to increase temperatures across the state. Several analyses have examined the effect of changing climate conditions on wildfire activity. The most comprehensive projections of climate change on California fire regimes are the simulations for California's Fourth Climate Change Assessment, published in August 2018 (Westerling, 2018). Annual area burned for the state is expected to increase across all climate scenarios, particularly in forested areas such as the Sierra Nevada and southern Cascades (Figure 2.5). Conservative climate projections point to a doubling of the annual area burned in the Sierra Nevada, with more extreme warming projections predicting a quadrupling of annual area burned. While other characteristics of the fire regime may be different, it is worth noting this projected increase would be in the range of area burned during natural conditions and prescribed burning practices of indigenous tribes. Projections show that more aggressive fuel treatments may mitigate some of this increased wildfire activity. Other studies have supported this general finding (Spracklen et al., 2009). As with the Fourth Climate Assessment, the anticipated effects are much more pronounced in California's forested ecosystems. Projections of area burned and climate may hold for montane forest landscapes, but not necessarily low-elevation, low-latitude parts of the state (Keeley & Syphard, 2016; Syphard et al., 2019b). It is important to note that what happens in any ecosystem is a combination of future climate and human factors, such as development and ignition patterns.

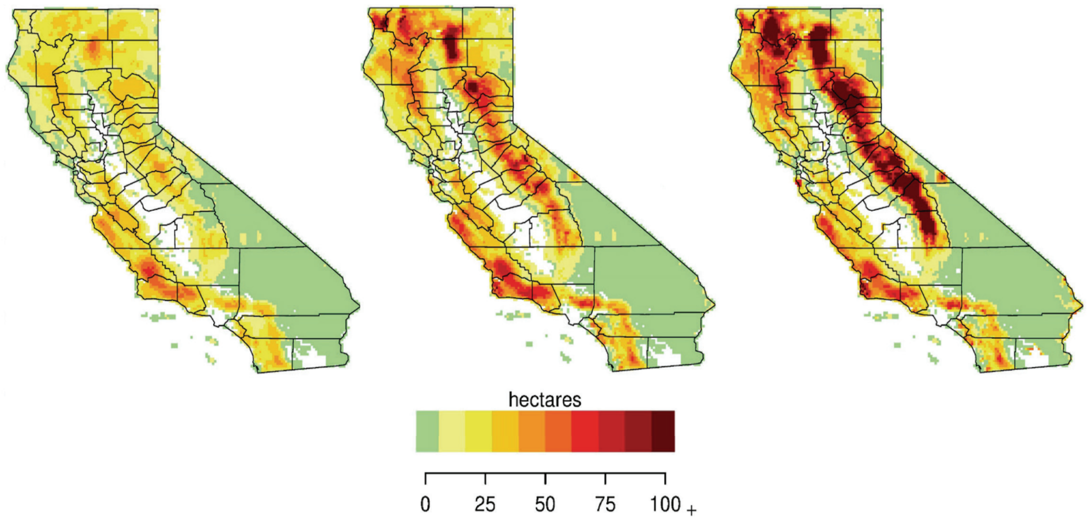

Figure 2.5. *Modeled average annual burned area in hectares using four General Circulation Models and 30-year periods for RCP 8.5, mid-range population growth. Source: Figure 8 from Bedsworth et al. (2018).*

The forests of the Sierra Nevada are an area of particular concern, with a projected increase in area burned and fire occurrence activity for studies analyzing federally managed lands. These findings are consistent with studies of past trends suggesting that higher fuel loads associated with California's legacy of fire suppression, bark beetle infestation, and increasing temperatures and aridity from climate change pose a particularly unique threat to this ecosystem. More broadly, academic research has focused on the importance of vegetation in the climate-vegetation feedback, although many of the methods currently in use do not yet factor in these dynamics (Bowman et al., 2014; Syphard et al., 2018; Brotons & Duane, 2019).

An analysis of state-managed landscapes in California revealed striking differences across ecoregions. Modeling by Fried et al. (2004) anticipated increases in wildfire intensity in forests in Humboldt and Santa Clara Counties, but suggested that these outcomes would be mitigated by greater fire response, suggesting no net change in area burned for these forested areas. However, grass and brushlands in Santa Clara and Amador Counties were expected to increase substantially in area burned, along with woodland areas in Amador County.

Future projections suggest that trends in lengthening fire seasons are expected to continue (Westerling, 2018). Drier summers are more likely to remove moisture from forested regions, creating a higher proportion of days and regions in the state of extreme fire danger. The increase in warm days is anticipated to drive increased extreme fire danger days, even as slight increases in precipitation are projected (Yoon et al., 2015). However, other research provides evidence that some fuel-rich areas may become so hot and dry that there are eventually decreases in fire (Mann et al., 2016). Further, some currently fuel-limited areas could increase in fire activity due to more precipitation driving vegetation growth.

> ***Finding:*** *Projections of future wildfire activity largely predict a continuation of past trends of increased wildfire incidence, severity, and size, with the forested regions of the Sierra Nevada especially at risk.*

> ***Conclusion:*** *Given the role of anthropogenic drivers such as fire suppression and land use in influencing fire regime, wildfire activity in California may continue to increase without changes in management approach.*

> ***Recommendation:*** *California should evaluate fire management strategies based on their ability to address not just the status quo but also the degree to which they can stabilize or even reverse trends in wildfire activity and consequences.*

2.5 Data for Tracking Wildfire Activity

Data on wildfire activity in California, and across the United States, is well-documented in a series of government datasets and documents that are updated each year. Table 2.1 summarizes these available datasets, including those that only track wildfires in California. The two main datasets for tracking individual wildfires in the state are CAL FIRE Fire and Resource Protection Program's (FRAP) perimeter dataset and the Monitoring Trends in Burn Severity (MTBS), which is jointly produced by the U.S. Geological Survey and the USFS. The FRAP perimeter set has a lower acreage cutoff for including fires, and thus tracks more fire than the MTBS product, but unlike MTBS, does not include information on fire severity. Two additional national products, Burned Area Emergency Response (BAER) images and Rapid Assessment of Vegetation Condition (RAVG) also track wildfire severity for large fires. The main differences in the three products are the years of coverage and the amount of time post-fire at which they measure vegetation changes.

Data on wildfire smoke in California are also fairly well tracked in consolidated databases. First, California's Air Resources Board (CARB) and the U.S. Environmental Protection Agency (EPA) have an extensive network of air monitoring stations that continuously track air quality. While the network does not uniformly cover all parts of the state, and gaps remain in remote regions where wildfires may occur, the air quality monitoring stations form the backbone of the state's air quality measurement system and inventory. The CARB and EPA monitoring programs do not attribute elevated pollution to a specific source. Other data sources are available for tracking wildfire emissions and dispersion. The most comprehensive is the Hazard Mapping System (HMS) product constructed and maintained by the National Oceanic and Atmospheric Administration (NOAA). HMS tracks daily wildfire plumes across the state and provides a categorical estimate of the plume's density. Emissions and plume detection are an active area of academic research and finer scale products are beginning to become available which will continue to improve wildfire smoke measurement and monitoring capacity.

Post-fire debris flows are systematically tracked at the national level by the U.S. Geological Survey (Mirus et al., 2020; USGS, 2020a; USGS, 2020c). Further, the USGS maintains a national landslide inventory (U.S. Landslide Inventory, 2020). Realtime and periodic measurements of particularly susceptible locations are tracked through USGS monitoring stations (USGS, 2020b) At the state level, the California Department of Conservation (DOC) maintains several databases for tracking landslides and debris flow. The Landslide Inventory maintains an up-to-date database of landslides (DOC, 2020a), a map of fire perimeters and deep landslide susceptibility (DOC, 2020b), and a landslide information warehouse (CGS Information Warehouse: Landslides, n.d.).

Table 2.1 Datasets available on California wildfire activity.

Name	**Agency**	**Criteria**	**Regime Indicators Reported**	**Years**
		Wildfire Events		
Monitoring Trends in Burn Severity (MTBS)	U.S. Geological Survey, U.S. Forest Service	>1,000 acres	Date, Occurrence, Extent, Severity	1984–present
Burned Area Emergency Response (BAER)	National Interagency Fire Center	Only for large fires where a BAER team was requested	Date, Occurrence, Extent, Severity	2001–present
Rapid Assessment of Vegetation Condition (RAVG)	U.S. Forest Service	>1,000 acres, national forest service land only	Date, Occurrence, Extent, Severity	2013–present
California Fire Perimeters	CAL FIRE Fire and Resource Assessment Program (FRAP)	Timber fires >10 acres Brush fires >30 acres Grass fires >300 acres	Date, Occurrence, Extent	1950–present
Fire Return Interval Departure (FRID)	US Forest Service	Timber fires >10 acres	Fire frequency, Fire return interval	N/A
		Wildfire Smoke		
Hazard Mapping System (HMS)	National Oceanic and Atmospheric Administration (NOAA)	Based on satellite imagery and wildfire attribution criteria	Wildfire plume occurrence, Smoke density	2003–present
	California Air Resources Board		Hourly measurements for select pollutants (e.g. PM2.5, PM10, ozone)	
		Debris Flow		
Post-Fire Debris Flow Hazard Assessments	U.S. Geological Survey	Available by request from federal, state, local authorities	Probability and volume of debris flows in a burned area	2013–present
U.S. Landslide Inventory	U.S. Geological Survey	Comprehensive	Slide type, thickness, direction of movement	1900–present (varies by state)
California Landslide Inventory	California Department of Conservation	Comprehensive	Slide type, thickness, direction of movement	~1990–present

2.6 Conclusion

There is substantial variability in the trends and drivers of fire activity across California. While trends of increased wildfire activity throughout the state are expected to continue, it is clear that the substantial uncertainty relative to future wildfire conditions—in part due to complex feedbacks among humans, vegetation, and climate—will continue to make future predictions challenging. Given the inherent feedbacks between natural and anthropogenic drivers of these trends, including suppression strategy, the enormous year-to-year variability in outcomes will continue to challenge agencies responsible for managing wildfire throughout the state. Optimal strategies for reducing the cost of wildfire will consider regional variability and balance efforts to address the underlying causes of wildfire with the need to provide adequate suppression resources.

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Chapter 3

Fire Prevention, Mitigation, and Suppression

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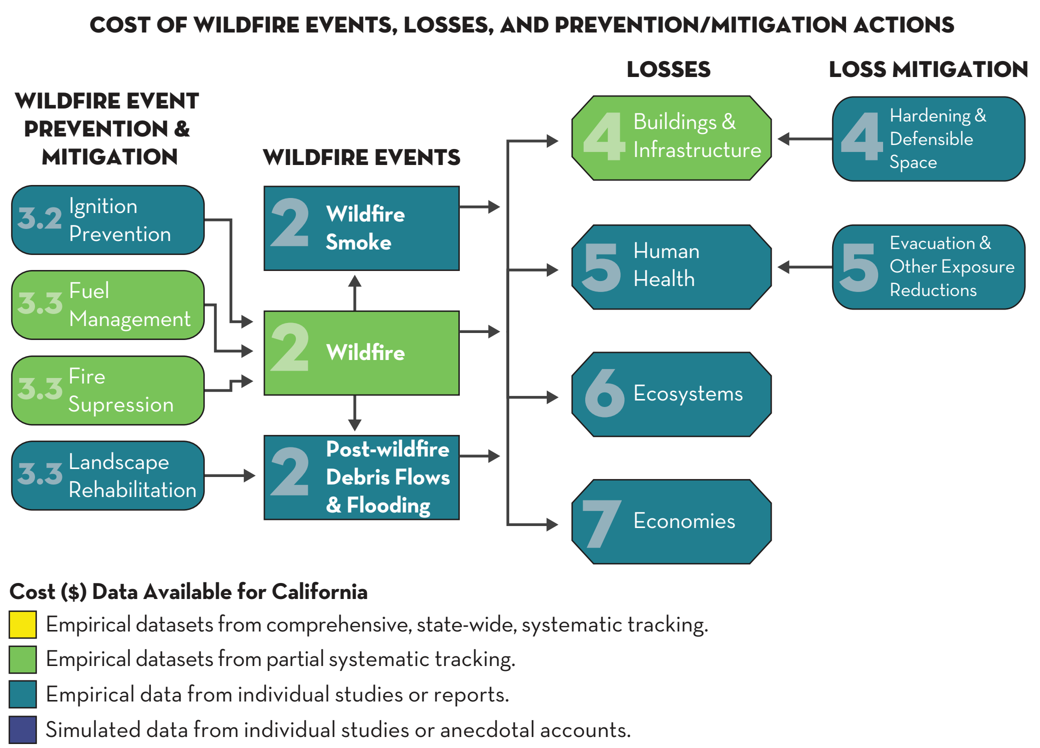

***Figure 3.1.** The colors in this figure indicate the category of California-specific datasets available to characterize the dollar value costs associated with prevention and mitigation actions intended to affect the behavior of wildfire events. Large numbers in the filled shapes indicate the chapter where each topic is discussed. Fuel Management and Fire Suppression cost estimates of specific losses from specific wildfires in California are available in ongoing systematic tracking efforts (green). Ignition Prevention and Post-wildfire Landscape Rehabilitation cost estimates of specific losses from specific wildfires in California are available in individual studies or reports (blue). Comprehensive, state-wide cost estimates of all prevention and mitigation activities to reduce wildfire losses in California are currently unavailable in the research literature or other publicly available resources.*

3.1 Chapter Scope

Prevention and mitigation activities in California include a complex network of numerous local, state, federal, and tribal efforts to manage wildfires before and after they occur. Due to time constraints, a comprehensive literature review of data availability for all prevention and mitigation activities, their associated costs, and their cost-effectiveness at reducing wildfire losses was beyond the scope of this report. Instead, we focus on several areas of particular importance (as shown in Figure 3.1) that will help frame the general scope of the costs associated with avoiding losses from catastrophic events that are described in Chapters 4–7.

3.1.1 Prevention and Mitigation Definitions

This chapter reviews the use and costs of prevention and mitigation actions that directly affect wildfires and reduce losses. Wildfire prevention is the range of actions taken to prevent a wildfire event from occurring, and primarily consists of public education and industrial programs to prevent human-caused wildfire ignitions. Wildfire mitigation refers to actions taken in order to reduce the losses of the wildfire event after a wildfire begins. Actions taken to prevent wildfires are relatively brittle and binary, meaning they may reduce the quantity of total ignitions but once a fire begins, prevention has no effect on the consequences of the wildfire. In contrast, mitigation actions are combined into a dynamic, holistic approach to wildfire management that have direct impact or can mitigate the consequences of the wildfire event. Prevention is stopping an unwanted event from occurring; mitigation is modifying an unwanted outcome to a level that is sustainable, survivable, or nearly nonexistent.

3.1.2 Elements of Mitigation

Mitigation actions generally occur along one or more of the following dimensions: the built environment (Section 3.3.2), the natural environment (Section 3.3.3), the social environment (3.3.4), and the response environment (3.3.5).

- The **built environment** refers to the features of buildings, roads, infrastructure, and other physical assets that influence wildfire losses. Mitigation actions primarily intended to reduce losses to the built environment are briefly introduced in this chapter, but Chapter 4 provides a more complete discussion and related findings, conclusions, and recommendations.

- The **natural environment** refers to the fuels, weather, terrain, and other natural aspects of wildfire regimes that influence fire behavior. This report focuses on vegetation management efforts specifically intended to reduce wildfire losses (e.g. fuel load reductions and defensible space). Other efforts to influence the natural environment, such as vegetation management to promote wildfire benefits by restoring forest health, or mitigation of anthropogenic climate change, are beyond the scope of this report.

- The **social environment** refers to the cultural and behavioral components that impact fire such as the laws, policies, and regulations that guide land use and planning decisions. Also included are community education, insurance requirements, research, and other behavioral actions. Underlying factors that exist pre-fire, such as relative health, economic stability, and community sustainability, can also affect the success of post-fire recovery.

- The **response environment** includes wildfire suppression (or firefighting) strategies as well as evacuation and other mitigations to protect public health and safety. Response environment mitigation strategies are often the main focus of public attention in wildfire mitigation and are also the most extensively funded strategies. Mitigation actions primarily intended to reduce public health losses are briefly introduced in this chapter, but see Chapter 5 for a more complete discussion and related findings, conclusions, and recommendations.

3.2 Ignition Prevention

There are two broad categories of ignition prevention activities outlined in this section: public education programs to reduce human-caused wildfire ignitions and industrial programs to prevent ignitions from utility equipment. Figure 3.2 shows the five-year average of wildfires by cause for fires to which the California Department of Forestry and Fire Protection (CAL FIRE) was assigned between 2014–2018.[1] While more than a quarter of all wildfires were of undetermined cause, natural ignitions (lightning strikes) account for fewer than 10% of the remaining fires, indicating a large proportion of fires are potentially preventable.[2]

The primary focus of this section is to detail wildfire ignition prevention spending for the state's largest utilities since this is where most expenditures have occurred in recent years. State expenditures on prevention activities are quite small and are not discussed in depth.

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1. It's important to note that the five-year average of excess powerline ignitions is partially driven by the extraordinary fire weather events of 2017 and 2018. Historically, CAL FIRE has assigned a lower fraction to power line fires. Ignition data is collected by individual fire departments, and methodology and uniformity has varied over time. Causes of the extreme variation in fraction purportedly have to do with the switch to electronic data reporting, which went through two generations of databases. For additional information see https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M290/K365/290365326.PDF

2. Almost half of all ignitions in the CAL FIRE dataset were either of undetermined or miscellaneous cause. For a more detailed analysis of wildfire ignitions in California, see Keeley & Syphard (2018). CAL FIRE maintains a record, dating back to 2004, of all ignitions in California reported within the CAL FIRE Direct Protection Areas and contracting counties, regardless of ultimate fire size. This dataset, known as California Incident Data and Statistics Program (CalStats) is available at https://osfm.fire.ca.gov/divisions/wildfire-planning-engineering/california-incident-data-and-statistics-program/

Local government expenditures on ignition prevention programs can also be significant but are not documented in detail in this report. Examples of local programs include the Oakland special fire district spending enacted after the Tunnel Fire, the recently established Marin Wildfire Prevention Authority, and the Montecito Fire Protection District. Local government prevention examples are illustrative of major local efforts where citizens implement taxes in order to improve public safety. Federal expenditures on prevention activities are available in the U.S. Forest Service budget but are not reported in depth here. Data on private landowner (including industrial-size landowners and small landowners) prevention expenditures are not readily available and also excluded from this section. We found no systematic analysis of prevention efforts by private landowners in California; however, this category may be significant as timberland and rangeland managers may take actions to prevent losses to wildfires on these lands. Prevention spending by small landowners and homeowners can also be quite large in order to make properties fire safe. Further analysis of available datasets (e.g. through Fire Safe Councils, FireWise Communities, or other programs) should be conducted.

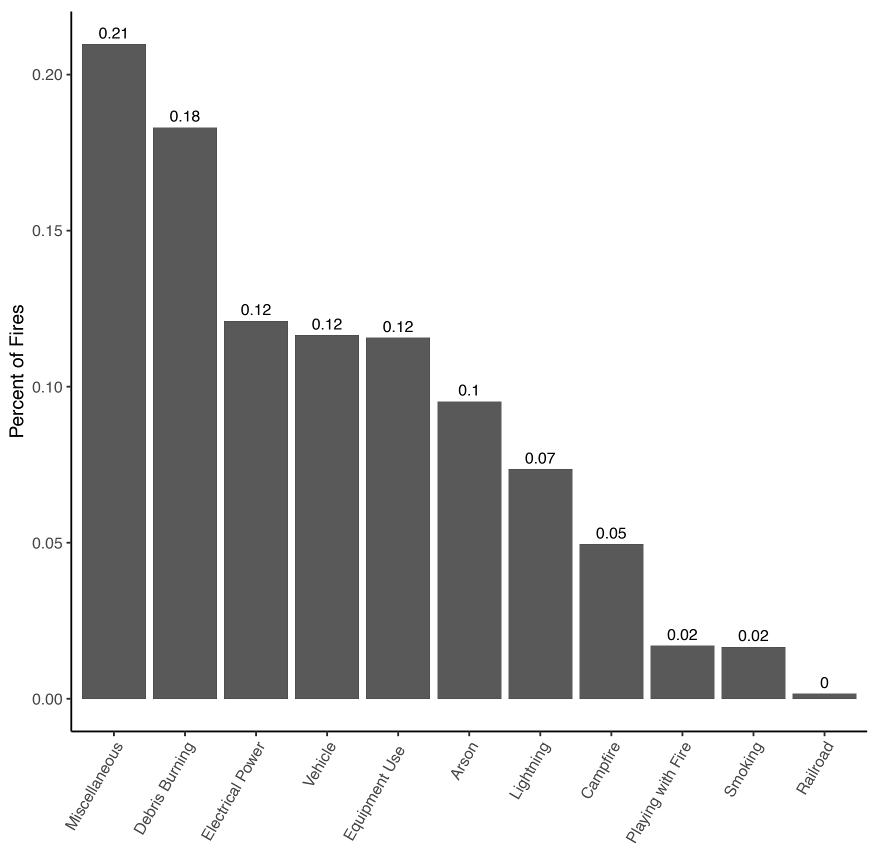

Figure 3.2. *The five-year average (2014–2018) of CAL FIRE fires by cause. Only fires with known causes are included. Wildfires of unknown causes account for approximately 25% of total ignitions. Miscellaneous ignitions include any ignition not in one the other categories. Source: CAL FIRE 2018 wildfire activity statistics.*

3.2.1 Public Education Programs

Sources of accidental human-caused wildfire ignitions include debris burning, campfire escapes, smoking, and sparks from vehicle and equipment use (Butry & Prestemon, 2019). Public education campaigns to reduce these types of unintentional ignitions have a long history in the United States. Public awareness and education include a vast array of activities such as public service announcements, public campaigns, and direct outreach to specific groups. While many are familiar with certain wildfire awareness campaigns—such as the iconic Smokey Bear campaign—total expenditures by local, state, and federal government agencies do not appear to be systematically tracked. Furthermore, public education programs are largely decentralized and spread across a number of state and federal agencies (see examples in Table 3.1) so adding up total education program expenditures is not a straightforward task. This prevents an understanding of whether ignition prevention efforts through educational awareness in California is cost-effective and in line with the state's wildfire plans.

Table 3.1. *Public education programs in California.*

Program	Agency	Description
Ready for Wildfire	CAL FIRE	Educational website for preventing and responding to wildfire.
Fire Adapted Communities Learning Network (FACNET)	USFS	Network for sharing wildfire resilience strategies.
Ready, Set, Go	International Association of Fire Chiefs (IAFC)	Program promoting education and engagement between fire agencies and local communities.
Living with Fire	University of Nevada, Reno	Educational program to promote wildfire readiness and resilience.
Firewise USA	National Fire Protection Association (NFPA)	Voluntary program that provides resources to help homeowners adapt to living with fire.
Fire Safe Councils and Community Wildfire Protection Plans	State/Local	Local, community-led organizations for wildfire preparedness.
Ready.org	FEMA	National public awareness campaign for helping citizens prepare for and mitigate disasters.

There is some peer-reviewed evidence that public education programs are both effective at reducing the incidence of unintended wildfire ignitions and that these programs are cost-effective. For example, Prestemon et al. (2010) examined a suite of wildfire education programs in Florida and found that the avoided suppression costs justified the program expenditures. Abt et al. (2015) reached a similar conclusion based on an analysis of wildfire education programs on tribal lands. There appears to be no peer-reviewed evidence for the effectiveness of public education campaigns on unintentional wildfire ignitions in California (although Kolden & Henson (2019) allude to public education programs in a case study of the 2017 Thomas fire). Additionally, the many varied programs utilize different terms and perspectives to communicate to the public, which may result in confusion of messaging.

Finding: *Fire prevention educational campaigns are spread across a wide range of local, state, and federal governments, and private organizations, with limited coordination among the entities.*

Conclusion: *Greater coordination among fire prevention educational campaigns may improve the effectiveness and efficiency of these activities.*

Recommendation: *Detailed analysis is needed to understand the budgetary scope of the different educational programs and their effectiveness at preventing wildfires and mitigating impacts.*

3.2.2 Electrical Infrastructure Ignition Prevention Programs

From 2007 to summer 2020, powerline-caused wildfires have resulted in 31,138 structures lost across California. Powerline fires are a particular problem in areas subject to strong winds during fire season, known as Foehn winds or more commonly as "Santa Ana," "Sundowner," or "Diablo" winds. Extreme winds can damage utility equipment directly (particularly if it is faulty or has not been inspected), and can blow nearby trees and branches into lines. Equipment damage or contact often results in arcing, which deposits hot metal or burning vegetation onto a dry fuel bed. The conditions most likely to create an ignition are the same as those that lead to explosive fire growth (Mitchell, 2013; Syphard & Keeley, 2015; Abatzoglou et al., 2018).

The liability from these fire events was a major factor in the establishment, in 2019, of the Wildfire Safety Division in the California Public Utility Commissions (CPUC).[3] One important result of this effort was the requirement for public utilities in California to prepare Wildfire Mitigation Plans (WMPs) beginning in 2019. WMPs are a regulatory vehicle by which utilities must assess their risk to wildfire and report planned actions to mitigate this risk. In their WMPs, available publicly through the CPUC's website, utilities report wildfire-related expenditures according to nine standardized expenditure categories (CPUC, 2020). These increased expenditures will be paid for, at least in part, by increased rates for customers.

Total reported and planned expenditures for the State's three largest utilities—Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E)— are shown in Table 3.2. Based on reported customers, 2019 spending per account would be approximately $507/customer, $306/customer, and $285/customer for

3. The Wildfire Safety Division is scheduled to be transitioned to the Natural Resources Agency by July 2021, and will be renamed the Office of Energy Infrastructure Safety.

PG&E, SCE, and SDG&E, respectively.[4] PG&E has indicated that they intend to continue spending at approximately these levels for the next decade. These estimates include both existing wildfire expenditures and new expenditures based on lessons learned from the 2017 and 2018 wildfire seasons. They also include new capital expenses, which are likely to be amortized into the future. In 2019, these three utilities reported approximately $4.7 billion in combined expenditures. Planned expenditures from the state's many municipal utilities are also required to submit WMPs and are available through the CPUC's website. Several of these utilities, such as the Los Angeles Department of Water and Power (LADWP) and Sacramento Municipal Utility District (SMUD), operate in high-risk wildfire areas and are also likely to spend significant amounts on prevention.

PG&E and SCE have the largest service territories in California and spending by these two Investor-Owned Utilities (IOUs) is especially high in the next few years as the wildfire programs ramp up and the utilities catch up on deferred maintenance. Spending for these two utilities may gradually decline after this initial pulse in spending. The main programs adopted by the utilities to reduce and mitigate powerline-ignited wildfire aim to reduce the major causes, including equipment failure, vegetation contact, traffic collisions, and third-party contractors. Some of these causes tend to dominate under extreme fire weather and are typically the ones that lead to the ignition of catastrophic powerline wildfires. Utility programs generally consist of hardening programs, which make equipment more resilient to environmental insult (including covered conductor, which significantly reduces chances of vegetation ignition), vegetation programs including tree trimming, and public safety power shutoffs (PSPS).

Table 3.2. Total actual and planned spending on wildfire mitigation ($ million). Calculated based on submitted 2020 Wildfire Mitigation Plans for each large public utility. Source: Individual utility Wildfire Mitigation Plans.

	2019	**2020**	**2021**	**2022**
	(actual)	(planned)		
Pacific Gas & Electric (PG&E)	$2,776.5	$2,989.6	$2,931.8	$3,041.0
Southern California Edison (SCE)	$1,538.9	$1,582.6	$1,377.3	$1,469.8
San Diego Gas & Electric (SDG&E)	$399	$456	$460.2	$459.4

Table 3.3 breaks down the reported wildfire spending by mitigation category for 2019 and planned spending for 2020. Most spending is on grid design and system hardening,

4. Based on U.S. Energy Information Administration estimates of customers for PG&E (5.48 million electric power customers) and Southern California, Edison (5.07 million electric power customers). Available at https://www.eia.gov/todayinenergy/detail.php?id=40913. For SDG&E, we assume there are 1.4 million electric power customers (https://www.sdge.com/more-information/our-company/about-us)

vegetation and asset management, and inspections. For example, PG&E's reported spending for these categories account for 61%, 26%, and 8% of all wildfire mitigation expenditures, respectively. Note when comparing across categories that some expenditures will occur in the year they are reported (e.g., vegetation management), while other expenditures will incur large capital costs that will be spread over several years or more in the future (e.g., grid design and system hardening).

Table 3.3. Utility spending (actual and planned $ million) by mitigation category. Source: Wildfire Mitigation Plans.

Mitigation Category	**PG&E**		**SCE**		**SDG&E**	
	2019 actual	2020 planned	2019 actual	2020 planned	2019 actual	2020 planned
Risk assessment and mapping	Not Reported		Not Reported		$0.3	$1.1
Situational awareness and forecasting	$28.8	$48.3	$2.0	$2.6	$94.4	$96.5
Grid design and system hardening	$1,690.1	$1,696.9	$993.2	$1,088.4	$226.7	$217.1
Asset management and inspections	$235.1	$162.1	$123.9	$85.6	$13.6	$51.7
Vegetation management and inspections	$709.5	$857.1	$330.3	$200.6	$50.3	$49.9
Grid operations and protocols	$18.5	$71.3	$7.6	$91.7	$8.8	$21.0
Data governance	$36.1	$88.2	$2.4	$11.7	$0.0	$0.3
Resource allocation methodology	Not Reported		$61.6	$78.5	$0.1	$10.8
Emergency planning and preparedness	$19.7	$36.9	$17.9	$23.5	$4.7	$7.7
Stakeholder cooperation and community engagement	$38.8	$28.7	Not Reported		Not Reported	

Finding: *The investor-owned utilities do not currently assess risk on a fine enough scale to enable regulators to determine what mitigations are most cost effective, nor are they able to make the same determination based on geography or circuit.*

Conclusion: *In order to most effectively use ratepayer funds, utilities need to conduct risk and spending calculations based on a finer-grained assessment of their programs and their infrastructure.*

Finding: *The methodology used by utilities to estimate fire risks and mitigation cost varies and cannot be compared in a straightforward matter.*

Conclusion: *Common methodologies should be developed that allow the wildfire mitigation activities of different utilities to be directly compared.*

Recommendation: *The Wildfire Safety Division and the CPUC should continue to drive the development of common frameworks and methodologies for utility risk and cost estimates.*

3.2.2.1 Public Safety Power Shutoffs

In addition to the direct wildfire prevention expenditures by utilities, there are also economic costs and public safety impacts of power disruptions. During the 2019 fire season, major investor-owned utilities in California, including PG&E and SCE, turned off large segments of the power grid when severe fire weather was present (Abatzoglou et al., 2020). These service disruptions are referred to as Public Safety Power Shutoffs (PSPS). PSPS events impose large economic costs on utility customers and are an important opportunity cost of wildfire prevention activities. One approach proposed by economists to estimate the cost of the PSPS is measuring the “value of lost load” (VLL) (Sullivan et al., 2018). The value of lost load is the value of the electricity that consumers wanted to consume but could not due the shutoff. VLL can vary considerably across electric power users. For example, the power used for ventilators in hospitals has an inherently different value than the power for an average residential customer. Methods and data for estimating VLL from PSPS events is currently subject to considerable uncertainty, primarily because past outages have been unexpected and for short durations. Existing tools for estimating VLL are based on these data and assumptions.[5] Using this methodology, a back of the envelope estimate of all of PG&E’s PSPS events in 2019 suggested that the value of lost load was approximately $10 billion, or 0.3% of Gross State Product (Wara, 2019). There were no studies that estimated VLL based on multi-day outages and outages for which notice was provided.[6]

There are additional opportunity costs of PSPS events to both utilities, customers, and the state in general. For example, utilities may need to provide backup generators for community hospitals and other essential operations, run cooling and charging centers, and deliver PSPS outreach notifications.

There are likely to be other service disruptions costs, such as impacts to medically vulnerable customers, disruption to evacuation traffic and preparation, loss of communication ability for both receiving warnings and placing 911 calls, increased potential for generator, candle, and barbecue fires, and loss of water pressure for fire-fighting and structure defense (CPUC, 2009). Costs of PSPS events to the state may include air quality impacts from the widespread use of natural gas, propane, and diesel for backup power, heating, and cooking fuel, and the negative impact that has on the state’s efforts to reduce GHG emissions and reach carbon neutrality goals. While many of these issues have been raised with regard to de-energization, none of them have yet been adequately quantified so that they can be directly compared to the reduction of utility wildfire ignition risk.

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5. The Interruption Cost Estimate (ICE) calculator, developed by researchers at Lawrence Berkeley National Laboratory and Nexant, Inc., is one tool used by researchers to estimate losses associated with wildfire-related power disruptions and PSPS events. Available at icecalculator.com.

6. For examples of VLL calculations for earthquakes in California, see Sue-Wing and Rose (2020) and Sullivan et al. (2013).

> ***Finding:*** *PSPS events, utilized as a wildfire prevention measure, impose a large opportunity cost to society.*

> ***Conclusion:*** *Current data sources and methods are insufficient to adequately measure the costs and safety impacts of PSPS events.*

> ***Recommendation:*** *The state should support research into the behavior of utility customers before, during, and after PSPS events as well the costs of these interruptions, especially in cases where advance notice was given by the utility.*

3.2.2.2 Additional Costs of Utility Wildfire Liability

In addition to the direct prevention costs discussed above, there are also indirect costs to utilities from greater liability for wildfires. California's investor-owned utilities have sought to raise rates in order to offset this increased liability exposure. In California, this liability caused one of the State's largest utilities, PG&E, to file for bankruptcy in 2019. The professional fees associated with bankruptcy proceedings can be quite substantial and in this specific case are likely directly attributable to wildfires. An estimate for PG&E's administrative costs was not found although is likely available in CPUC proceedings. The peer-reviewed literature suggests that professional fees from bankruptcy proceedings can be around 1% of a corporation's total assets (Lubben, 2008; Lopucki & Doherty, 2011).

There are additional indirect costs of wildfire mitigation including the need to contribute to the wildfire fund on the part of ratepayers and shareholders. As PG&E's budget constricted under bankruptcy, the corporation reduced budgets for contracted goods and services. This affected contracted companies, and likely triggered other supply chain and income effects. These opportunity costs do not appear to have been systematically studied.

3.3 Mitigation

3.3.1 Hazard vs. Risk and the Role of Mitigation

While wildfire prevention activities focus on actions taken to prevent wildfires from occurring, mitigation refers to actions taken in order to manage the losses of wildfires when they do occur. Mitigation encompasses a wide variety of activities ranging from fire suppression to vegetation management to managing the built and social environments in which wildfires take place. This section reviews the literature on the costs of various mitigation actions.

Appropriate, cost-effective mitigation requires an understanding of the concepts of hazard vs. risk. It is common to confuse hazard with risk. Wildfire hazard refers to a wildfire environment that has the potential to cause harm to people and physical assets. While there are different measures for characterizing wildfire hazard, fire intensity is a commonly used metric (Scott et al., 2013). Risk, on the other hand, generally refers to the potential outcome of the event and consists of two components: the probability of the event occurring and the severity of the impacts of that event. In the case of wildfires, risk is the burn probability multiplied by the associated potential losses associated with the wildfire. For example, a home can be “at-risk” if the probability of a wildfire is high or if damages from a potential wildfire are high (or both). Mitigation actions are designed to manage all of these components—the fire intensity, the burn probability, and the possible damages to human health and physical or ecological assets.

Fire Hazard Severity Zones (FHSZ) for state and local responsibility areas are shown in Figure 3.3. These designations, built upon a specific hazard model, show the potential wildfire hazard across the state. Specifically the Moderate, High, and Very High Fire Hazard Severity Zones, where a more intense wildfire is likely to occur and impact people or physical assets (buildings, utilities, watersheds, timber, etc.). The assessment of FHSZ does not include the effects of any mitigation actions. While a severe fire may be very likely to occur in a certain place, the impact of that fire is not measured for these maps because they do not measure the mitigations such as a strong fire suppression response, well-managed fuel breaks, hardened homes, evacuation routes, defensible space, community education, spaced housing, or any number of actions that reduce fire impact. It is also important to note that the FHSZ maps do not include areas that are already urbanized. Therefore, many potentially fire-prone neighborhoods that are somewhat close to the WUI are not given a FHSZ classification.

Currently, the closest effort to a statewide risk assessment is the CPUC’s fire threat mapping effort, which designates elevated and extreme threat regions based on a variety of factors, including the risk to people and property.[7] Additionally, in 2018, the California Governor’s Office of Emergency Services developed a statewide hazard mitigation plan (OES, 2018) that does include broad recommendations for risk reduction. Private companies have also conducted wildfire risk mapping exercises, primarily to explore property at risk in the state. As an example, see CoreLogic’s 2019 Wildfire Risk Report (Jeffery et al., 2019).

7. Fire threat maps and associated methodology are available at https://www.cpuc.ca.gov/firethreatmaps/

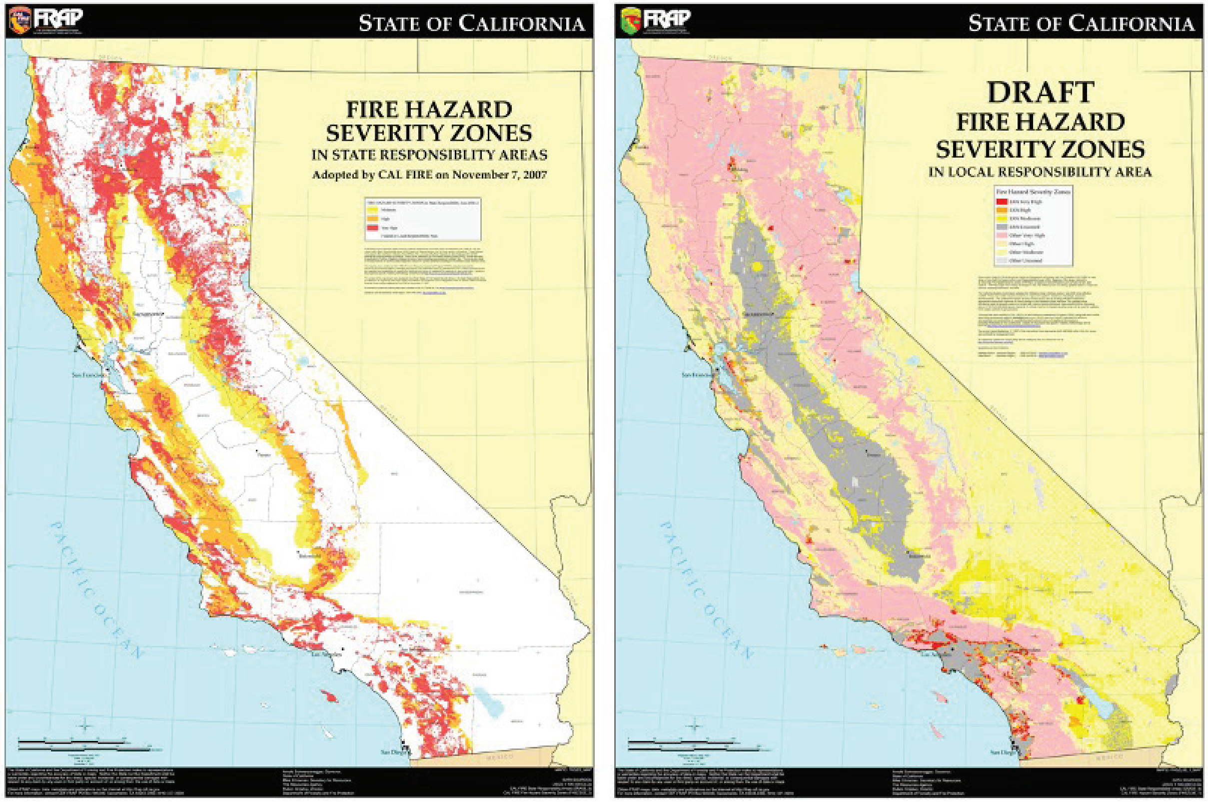

Figure 3.3. *CAL FIRE Fire Hazard Severity Zone maps for State Responsibility Areas (left) and Local Responsibility Areas (right).*

> ***Finding:*** *The state has multiple agencies statutorily tasked with reducing losses from wildfire through a variety of plans, programs, and assessments.*

> ***Conclusion:*** *To date, there is only a statewide hazard assessment of wildfire, but not a correlating statewide risk assessment that reflects the many mitigation programs actively pursued in California.*

> ***Conclusion:*** *Without a statewide model for assessing wildfire risk, there will be many independent approaches which lead to confusion about the impacts of mitigation investments.*

> ***Recommendation:*** *The state should direct the appropriate agency to develop a statewide Fire Risk Map that mirrors the Fire Hazard Severity Map and accurately reflects the reduced wildfire risk created by public and private investment. All risk assessments should always clearly articulate the risk that is being assessed and the core variables calculated in that risk assessment.*

3.3.2 Built Environment

When wildfires do occur, they can cause damage or destruction to the built environment, including buildings, roads, water and utilities infrastructure, and other physical assets. Associated costs include costs to repair or replace the physical assets and any personal property or inventory that was also lost, costs to clean up debris and hazardous waste, and costs to provide temporary accommodations or services. Losses to the built environment can be mitigated through several complementary strategies: (1) land use planning and urban development; (2) structure hardening; (3) defensible space; and (4) system redundancy to reduce service disruptions. Chapter 4 has an in-depth discussion of these topics and our related findings, conclusions, and recommendations.

3.3.3 Natural Environment

The natural environment includes physical and biological features of the environment such as topography, weather, and vegetation. Natural environment mitigations for wildfires typically focus on actively managing the vegetation and naturally-occurring features to reduce fire severity, behavior, and susceptibility. Also included in this category, but not in the scope of this report, are efforts to mitigate anthropogenic climate change to avoid predicted changes in weather conditions that increase the risk of catastrophic wildfires. Vegetation management encompasses a broad category of activities to restore ecosystem health, promote the benefits of wildfire, and reduce the losses. In Section 3.3.3.1, we focus on fuels management (prescribed fire and thinning), a subset of vegetation management activities that are typically carried out to influence the behavior of wildfires in ways that reduce the risk of wildfire losses. In Chapter 4 we discuss the construction of fuel breaks and defensible space, vegetation management activities that are typically carried out to reduce the risk of wildfires near physical assets (homes, roads, utility lines, etc.).

3.3.3.1 Fuels Management

Vegetation management refers to a suite of practices to modify vegetation on the landscape to modulate wildfire behavior in ways that promote ecosystem health, increase the benefits of fire, and decrease the risk of losses. In this section we focus on a subset of fuel management activities primarily intended to reduce the amount of flammable vegetation and other biomass material on the landscape. The two main types of fuel treatment are thinning excess vegetation and prescribed or managed fire. Thinning of vegetation can be achieved in a number of ways, including the use of hand labor, equipment, chemicals, or even grazing animals such as goats (Hunter et al., 2007). Prescribed fires are intentionally started fires to remove vegetations—these fires are lit during low-risk days (high humidity, negligible winds, etc.), and are carefully monitored and controlled. Managed fires are unintentionally ignited fires, such as by lightning, that are allowed to burn under supervision to achieve fuels reduction and other ecological goals while minimizing losses (Boisramé et al., 2017).

By modifying the density, structure, and composition of living and dead vegetation on the landscape, fuels management can reduce the severity and intensity of subsequent fires and reduce the risk of losses. The majority of the literature on fuels management is focused on the mixed-conifer forests found at mid-elevations of the Sierra Nevada. Other habitats, such as chaparral and oak woodlands have received less attention despite the prevalence of wildfire in these habitats.

Fuel treatments for wildfire management has a long history and wide implementation in California. Indigenous tribes across the state regularly used prescribed fire to manage natural resources prior to the enforcement of fire suppression policies. Contemporary forest management policies in California incorporate fuels management to promote benefits of fire and to avoid losses. Fuels management projects can vary greatly in size and are carried out in California by a range of entities including federal, state, local, and tribal agencies, private landowners, timber companies, and utility companies. The cost of implementing fuel treatments depends on the size of the project, management goals, treatment type, terrain, proximity to roads, and revenue from the sale of any wood products generated by the treatment (González-Cabán & McKetta, 1986; Hunter et al., 2007; Collins et al., 2011; Forest Climate Action Team, 2018).

There is no comprehensive inventory of fuel treatment projects or their costs for California. Several entities that regularly conduct fuel treatments in California maintain their own inventories of projects and costs (Table 3.4). The USFS maintains an inventory of hazardous fuels reduction projects including costs per acre that can be filtered by state (BAER, n.d.). The National Fire Plan Operations and Reporting System tracks fuel reduction projects across public and Tribal Lands (USGS, 2018). The Prescribed Fire Information Reporting System (PFIRS) web site maintained by CARB tracks approved and planned burns in the state (CARB, n.d.). Reports and research papers document additional fuel treatments projects and costs that have been conducted in California (Table 3.4).

> ***Finding:*** *Data on select California fuel treatment projects and costs can be found interspersed across multiple datasets, including inventories maintained by federal and state entities and those compiled for individual reports and research papers.*

> ***Finding:*** *It is not clear from our review whether all fuels management projects in the state—and their associated costs—are represented by the datasets and inventories described above.*

> ***Conclusion:*** *There is no comprehensive state-wide database tracking California fuel management projects or their associated costs.*

> ***Conclusion:*** *An estimate of total state-wide costs of fuel treatments conducted in California for the purpose of fire management would require compiling existing data from multiple sources, and possibly collection of new data, to produce the necessary dataset for analysis.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track the dates, locations, and impacts of all fuel treatment projects*

> *across all jurisdictions (including state, federal, tribal, and private lands) that are relevant for meeting the state's fire management goals.*

3.3.3.2 Effectiveness of Fuel Treatments in California

A strong body of literature demonstrates that fuel treatments can be effective at modifying wildfire behavior and reducing the risk of losses, particularly for forest ecosystems (Stephens, 1998; Miller & Urban, 2000; Finney, 2005; Stephens & Moghaddas, 2005). However, the effectiveness of fuel treatments depends heavily on the probability of a wildfire intersecting the treatment and the prevailing weather conditions during the wildfire. Fuel treatments are unlikely to meaningfully reduce losses from wildfire when treatments are located far from the assets at risk or during wind-driven wildfire events (Baker & Rhodes, 2008; Schoennagel et al., 2009).

Table 3.4 lists a selection of California based-studies on the effectiveness of fuel treatments on modifying wildfire behavior, reducing wildfire smoke, and reducing post-wildfire watershed impacts. These studies include empirical evidence from the effect of real fuels treatments on real wildfires and predictions from models of simulated fuel treatments and/or simulated wildfires.

We also found numerous California-based studies that assess the effectiveness of fuel treatments on avoided suppression efforts and/or avoided losses. For example, in an assessment of the 2007 Angora Fire, firefighters reported that existing fuel treatments reduced wildfire behavior from a crown fire to a surface fire, which improved the effectiveness of fire suppression efforts to save houses and improved the effectiveness of evacuation for public safety (Murphy, 2007). However, because the individual studies vary in context, methodology, and metrics, making direct comparison of effectiveness of fuel treatments between studies is difficult without additional analyses.

Studies on the effectiveness of real fuel treatments on reducing losses of real fires have found fuel treatments effective at improving suppression efforts (Moghaddas & Craggs, 2007; Murphy, 2007; Syphard et al., 2011); avoiding watershed losses (Wohlgemuth, 2001; Boisramé et al., 2017); avoiding home losses (Murphy, 2007); improving emergency evacuation (Murphy, 2007); and reducing smoke exposure of populations (Schweizer & Cisneros, 2014; Schweizer, et al., 2019). Studies that rely on models of simulated fuel treatments and/or simulated wildfire losses have additionally found fuel treatments are effective at avoiding carbon emissions, ecosystem services losses, infrastructure and road damage, and timber losses.

> ***Finding:*** *Empirical research has found fuel treatments can be effective at modifying wildfire events and reducing select losses of wildfire in California's forests.*

> ***Finding:*** *Case studies in non-forested ecosystems have found that fuels management is most effective in strategic locations around communities where firefighters can access them for defensive actions.*

3.3.3.3 Cost-Effectiveness of Fuel Treatments in California

Cost-benefit analyses of fuel treatments compare the cost of fuels treatment projects against avoided costs of suppression, avoided costs of losses, and receipts from sale of any materials generated by the project (Finney et al., 1997; Schaaf et al., 2004; Buckley, 2014; Thompson et al., 2017). The estimated potential savings of avoiding catastrophic fires can be enormous (Mason et al., 2006; Buckley, 2014; Thompson et al., 2017). An assessment of the potential benefits of fuel treatments on the Mokelumne watershed estimated the savings from avoided losses, including reduced suppression costs, avoided property damage, and avoided ecosystem services losses, was 2–4 times greater than the costs of the proposed fuel treatments (Buckley, 2014).

In addition to economic costs of vegetation management, there are also ecological costs and benefits that differ across the state depending on the habitat. In mixed conifer forests that have experienced substantial fuel accumulation, vegetation thinning is generally consistent with ecological services, although it may be harmful to specific species with habitat preferences for high fuel loads. However, fuels management in non-forested landscapes, such as chaparral, has no ecological benefit and instead constitutes an ecological loss—or, a resource sacrifice aimed to protect human assets. This is largely because native shrublands are removed and replaced with invasive grasses that exacerbate issues with increasingly flammable landscapes and habitat type conversion (Brennan & Keeley, 2015; Meriam et al., 2006).

We found no studies based in California that assessed the cost-effectiveness of real-world fuel treatments on avoided losses from real wildfire (Table 3.4). Several of the California-based studies we did find predict the cost-effectiveness of simulated fuel treatments and simulated wildfire suppression costs or losses. These studies include various combinations of cost estimates of avoided suppression; watershed impacts and rehabilitation; natural resource losses; building, infrastructure, and property damage; and timber losses. We found no studies that estimated the cost-effectiveness of fuels treatments on avoided health losses.

> ***Finding:*** *We found no California-based studies that evaluate the cost-effectiveness of real-world fuel treatments at reducing the losses of real-world wildfires.*

> ***Finding:*** *Models of simulated fuel treatments and simulated wildfires predict fuels treatments can be cost-effective at avoiding select losses from wildfires in California forests.*

> ***Conclusion:*** *Comprehensive, state-wide estimates of the total cost-effectiveness of real-world fuel treatments at avoiding wildfire losses would require additional research on benefits and losses in a representative diversity of habitats to produce the necessary datasets.*

> ***Recommendation:*** *California should consider supporting research into economic and ecological outcomes to evaluate the cost-effectiveness of different fuel treatments in different ecosystems to reduce losses from wildfire.*

Recommendation: *The State should consider developing a method for valuing and verifying fuel treatment losses and benefits within a larger framework to value and monetize ecosystem services, resource sustainability, and impacts to local, statewide, and global climate management.*

Table 3.4. *California-specific literature relevant to fuels management activities to reduce wildfire losses.*

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

					Effectivness of mitigation on modifying wildfire events or reducing wildfires losses:															
			Measure of Mitigation Action		Fire Behavior	Smoke	Post-fire Debris Flows	Chapter 3: Supression		Chapter 3: Landscape Mitigation		Chaper 4: Buildings and Infrastructure		Chapter 5: Health		Chapter 6: Ecosystems		Chapter 7: Economic	
Source	Wildfire	Activity	Numeric	Dollars	Numeric	Numeric	Numeric	Numeric	Dollars	Numeric	Dollars	Numeric	Dollars	Numeric	Dollars	Numeric	Dollars	Numeric	Dollars
Boisramé et al., 2017	Managed wildfires	Managed Fire	2	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Buckley, 2014	Simulated Wildfires	Simulated Thinning & Fire	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1
California Fire Science Consortium	NA	Thinning & Fire	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Collins et al., 2011	Simulated Wildfires	Simulated Thinning & Fire	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elliot et al., 2016	Simulated Wildfires	Simulated Thinning	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Executive Order N-05-19	NA	Thinning	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Finney et al., 1997	Simulated Wildfires	Simulated Thinning & Fire	1	1	1	0	1	1	1	1	1	1	1	0	0	0	0	1	1
Jones et al., 2008	Simulated Wildfires	Simulated Thinning & Fire	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kobziar et al., 2009)	Simulated Wildfires	Thinning & Fire	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lasaux and Kocher, no date	NA	Thinning	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moghaddas & Craggs, 2007	2005 Bell Fire	Thinning	2	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Murphy, 2007	2007 Angora Fire	Thinning & Fire	2	0	2	0	0	2	0	0	0	2	0	2	0	0	0	0	0
North et al., 2012	NA	Thinning & Fire	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinchot Institute for Conservation, 2013	1999-2010 Wildfires	Thinning & Fire	2	2	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0
Prescribed Fire Information Reporting System	NA	Prescribed Fire	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Safford et al., 2009	2007 Angora Fire	Thinning & Fire	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Safford et al., 2012	2005-2011 Wildfires	Thinning & Fire	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schaaf et al., 2004	Simulated Wildfires	Simulated treatments	1	1	1	1	0	1	1	0	0	0	0	0	0	1	1	0	0
Schmidt et al., 2008	Simulated Wildfires	Simulated Thinning & Fire	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schweizer and Cisneros, 2014	2011 Lion Fire	Managed Fire	2	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0
Schweizer, et al., 2019	2010-2016 Wildfires	Prescribed Fire	2	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0
Scott et al., 2016	Simulated Wildfires	Simulated treatments	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Stephens et al., 2009	Simulated Wildfires	Thinning & Fire	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Stephens et al., 2012	Simulated Wildfires	Thinning & Fire	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Stephens et al., 2014	Simulated Wildfires	Thinning & Fire	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stevens et al., 2016	Simulated Wildfires	Simulated Thinning & Fire	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Syphard et al., 2011	1980-2007 SoCal Wildfires	Fuel Break	2	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Thompson et al., 2017	SImulated Wildfires	Simulated Thinning & Fire	1	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0
USFS Hazardous Fuels Reduction Inventory	NA	Thinning & Fire	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
USGS 2018	NA	Thinning & Fire	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vaillant et al., 2006	Simulated Wildfires	Prescribed Fire	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vaillant et al., 2013	Simulated Wildfires	Thinning & Fire	2	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wiedinmyer & Hurteau 2010	California Wildfires	Simulated Rx Fire	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wohlgemuth 2001	2003 Old Topanga Fire	Prescribed Fire	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0

3.3.3.4 Landscape Management

Fire can alter and mobilize soils and sediments leading to changes in volume of runoff and sediment and increasing the risk of post-fire landslides (Moody & Martin, 2004; Ren et al., 2011; Hallema et al., 2018). Immediately following wildfires, teams conduct evaluations of realized and potential losses to human life, property, cultural resources, and/or environmental and habitat values from post-fire erosion, landslides, or flooding. Teams may also recommend or implement mitigation effort to reduce the risk of downstream losses. The Burned Area Emergency Rehabilitation (BAER) program is responsible for post-wildfire rehabilitation of federal lands, whereas the California Watershed Emergency Rehabilitation Teams (WERT) program is responsible for non-federal land (private, state, and local jurisdictions).

BAER and WERT reports recommend actions to mitigate losses and may also include requested costs of recovery work and estimated value of losses with and without mitigation actions. Note that these reports generally do not include actual spending. An online database of BAER reports is maintained by the USFS Moscow Forestry Sciences Laboratory and includes over 600 California wildfires between 1969 and 2019 (BAER, n.d.). The State Water Board website advises that WERT reports can be found online by doing an internet search that includes the term "WERT" and the name of a specific fire of interest.[8]

> ***Finding:*** *Data on select California post-wildfire landscape management projects and costs can be found in BAER and WERT reports and in datasets that have been compiled for analysis in individual reports and research papers.*

> ***Finding:*** *It is not clear from our review whether all post-wildfire landscape management projects in the state—and their associated costs—are represented by the reports and studies mentioned above.*

> ***Conclusion:*** *There is no comprehensive state-wide database tracking California post-wildfire landscape management projects or their associated costs with the goal of reducing losses from catastrophic wildfires.*

> ***Conclusion:*** *An estimate of total state-wide costs of post-wildfire landscape management projects conducted in California would require compiling existing data from multiple sources, and possibly new data collection or research.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track all post-wildfire landscape management projects across all jurisdictions (including state, federal, tribal, and private lands).*

8. https://www.waterboards.ca.gov/centralvalley/water_issues/wildfire_response/faq/

3.3.3.5. Effectiveness of Post-wildfire Landscape Management in California

A comprehensive review of the literature on the effectiveness of BAER and WERT mitigation was outside the scope of this report due to time constraints. However, in the course of other literature reviews we came across two California-based studies that we include in Table 3.4 as a starting place for readers interested in this topic (Miles et al., 1989; Wohlgemuth & Robichaud, 2007).

Table 3.5. *California-specific literature relevant to post-wildfire landscape rehabilitation actions to reduce losses.*

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Measure of Mitigation Action		Effect on Post-fire Debris Flows
Source	**Wildfire**	**Numeric**	**Dollars**	**Numeric**
BAER Burned Area Reports Database	Wildfires on federal land	2	2	0
CA Watershed Emergency Response Team (WERT)	Select California Wildfires	2	2	0
Miles et al., 1989	1987 Shasta-Trinity Fires	2	2	2
SAWPA, 2003	2003 Grand Prix, Old, and Padua Fires	2	2	0
Wohlgemuth & Robichaud, 2007	1999 Mixing Fire, 2002 Williams Fire, 2003 Cedar Fire	2	0	2

3.3.4 Social Environment

Understanding the social context in which wildfires occur, including the social vulnerability and adaptive capacity of a community, is critical to developing a comprehensive and effective mitigation strategy for California. The social environment includes the interwoven effect of public perception, demographic and cultural influences, law and policy, and human behavior. Social vulnerability refers to socioeconomic factors that make some groups more sensitive to wildfire hazards (Coughlan et al., 2019). Factors influencing social vulnerability to wildfire include socioeconomic status, race, gender, age, housing conditions, linguistic barriers, citizenship status, isolation, incarcerated status, ability, access to healthcare, access to transportation, and adaptive capacity (Cooley et al., 2012; Davies et al., 2018; Morton et al., 2003; Palaiologou et al., 2019). For example, across the United States, wildfire vulnerability (defined as a combination of wildfire hazard potential and adaptive capacity) is 50% greater in census tracts that are majority Black, Hispanic or Native American compared to other census tracts (Davies et al., 2018). Adaptive capacity refers to socioeconomic factors that affect the ability to respond to wildfires and take action to mitigate losses (Kolden & Henson, 2019; Paveglio et al., 2015).

Current wildfire management policy in California is focused primarily on protecting life and property. Mitigation actions are therefore tied to the social environment in which wildfires occur. Examples of social environment mitigations include land use regulation and zoning, targeted behavioral influence programs such as defensible space awareness or evacuation training (Kolden & Henson, 2019). It also includes recognizing and planning for the profound differences that demographic factors such as age, income, and educational background create in terms of wildfire susceptibility (Coughlan et al., 2019).

The social context is a critical factor in driving wildfire mitigation success. For example, in a mitigation context, decisions will vary based on community and individual understanding of risk, social awareness of wildfire behavior, community preparedness for wildfire events, trust in the various wildfire response agencies, and numerous other complex social factors. There is a growing body of research on the social aspects of wildfire mitigation. McCaffrey et al. (2012) provides a detailed review of this literature. Key findings include:

- Communities in fire-prone areas often have a fairly sophisticated understanding of the nuances of fire behavior and the role of fire in ecological systems.

- The public generally trusts government information of wildfire activity, including mitigation and response, with a preference for more localized information when possible.

- Communities in fire-prone regions are generally supportive of other wildfire mitigation efforts, such as fuels reduction projects and defensible space policies.

These findings paint a picture of a nuanced public that understands many dimensions of the wildfire challenge. One large shortcoming in this literature is its focus on communities living in fire-prone regions. Less is known about the social context for communities that live far from the perimeter of the wildfire but are nevertheless impacted by wildfire smoke, service disruptions, closures of recreational areas, out-migration and other associated outcomes from wildfire.

Some of the most recent wildfire social mitigation efforts in California have been directed through agencies such as the Office of Planning and Research and California Volunteers/Listos to address exposure to wildfire in disadvantaged communities. Grassroots organizations such as Fire Safe Councils work at the neighbor-to-neighbor level to influence social perspectives and skills at wildfire preparation.

> ***Finding:*** *The social environment has a fundamental influence on perceptions of and willingness to take action to mitigate wildfire risk at the individual- and the policymaking-level.*

> ***Conclusion:*** *The social environment is very influential in determining future wildfire consequences, especially in terms of fire survivability of communities and infrastructure.*

> ***Recommendation:*** *A statewide systematic review, definition, development, and dissemination of the social component of mitigation could serve as the foundation for a comprehensive wildfire mitigation plan for California.*

3.3.5 Response Environment

The response environment refers primarily to wildfire suppression (firefighting) strategies, which are often the main focus of public attention in wildfire mitigation. It also encompasses staffing, equipment, training, and planning necessary for wildfire suppression.

When wildfires do occur, they can cause injury, illness, and death to the general public, outdoor workers, firefighters, and other emergency response personnel. Public health losses can be mitigated through complementary strategies to reduce exposure, including evacuation, reducing outdoor activities, or use of masks or air filters. See Chapter 5 for an in-depth discussion of these topics and our related findings, conclusions, and recommendations.

Several federal and state agencies are responsible for wildfire suppression in California (Table 3.6). At the federal level, the U.S. Forest Service and the Department of the Interior both conduct wildland fire suppression operations in the State. Based on 2018 data, 60% of the area burned was under the jurisdiction of CAL FIRE and CAL FIRE contract counties[9]. Another 37% of the area burned was under the jurisdiction of the U.S. Forest Service. Department of the Interior (DOI) agencies (National Park Service, Bureau of Land Management, Bureau of Indian Affairs, and Fish and Wildlife Service) were responsible for 3% of the area burned. A small fraction (<1%) of area burned was the responsibility of the US military. One important driver of suppression costs is the presence of homes and other structures (Davis, 1995; Gebert et al., 2007; Liang et al., 2008; Gude et al., 2013; Baylis & Boomhower, 2019).

Wildfire suppression costs include all costs of all activities associated with suppressing a wildland fire. Suppression activities range from hand and bulldozer crews cutting fire lines, to management logistics, to aerial support. Total suppression costs in California are not systematically tracked by a single agency, however, individual firefighting agencies do appear to track these expenditures.

9. For six counties in southern California (Kern, Los Angeles, Marin, Orange, Santa Barbara, Ventura), CAL FIRE contracts wildland firefighting services through county agencies. The role of contract counties is discussed in detail in Chapter 2.

Table 3.6. Wildfire and areas burned by agency in 2018. Source: CAL FIRE (2018).

Agency	Number of Fires	Acres Burned
CAL FIRE	6,208	1,068,111
CAL FIRE contract counties	433	113,437
U.S. Forest Service	965	728,895
National Park Service	90	51,618
Bureau of Land Management	115	4,616
Bureau of Indian Affairs	121	4,634
Fish and Wildlife Service	9	15
Military	7	3,770
Total	7,948	1,975,086

Figure 3.4 shows CAL FIRE's suppression spending since the 2005–2006 fiscal year. The Fire Protection category includes primarily suppression and the emergency fire suppression (E-Fund) expenditures are additional suppression expenditures that are utilized once the base budget is exhausted.[10] Suppression expenditures by CAL FIRE have exceeded $2 billion per year since the 2017-2018 fiscal year and are expected to exceed $3 billion for the first time in 2020-2021. Fire suppression expenditures, in the base budget and E-Fund, account for the vast majority of CAL FIRE's expenditures.

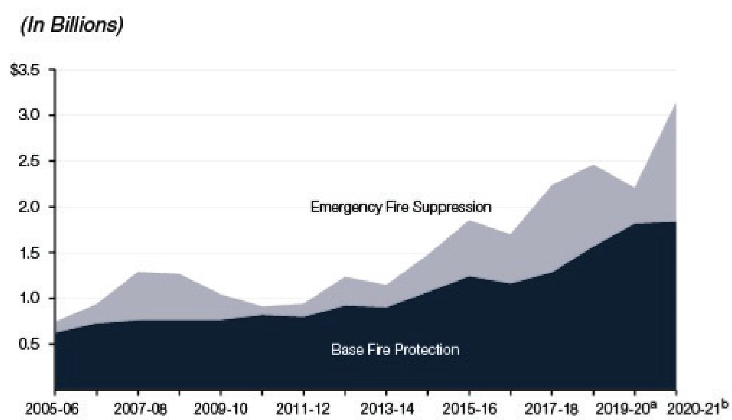

Figure 3.4. *CAL FIRE suppression expenditures since 2005-06. 2020–2021 estimates include the enacted budget and estimated E-Fund expenditures through September 2020. 2019-2020 E-Fund figures are CAL FIRE estimates and not yet finalized. (Source: Figure 3 in LAO, 2020)*

10. E-Fund expenditures are available on the CAL FIRE website at https://www.fire.ca.gov/media/8641/suppressioncostsonepage1.pdf - Base budget estimates are available from the Department of Finance at http://www.ebudget.ca.gov/

Federal suppression spending by the U.S. Forest Service and Department of the Interior agencies is not reported separately for California (designated by the USFS as the Region 5, the Pacific Southwest). However, wildfire suppression cost data for the entire country is compiled by National Interagency Fire Center (NIFC) and is broken down by U.S. Forest Service expenditures and Department of the Interior expenditures (Figure 3.5). Average annual federal suppression spending from 2015–2019 was $2.34 billion. Approximately 84% of these costs were incurred by the Forest Service.

Data on wildfire suppression expenditures are tracked by several agencies. CAL FIRE reports annual E-Fund suppression expenditures on its website and tracks incident-level suppression expenditures that are available by public records requests. Wildfire incident reports are also available from the National Fire and Aviation Management Web (FAMWEB) Database. Detailed incident reports, including estimated suppression costs, are available for all fires over 300 acres. There was no central statistical report that provided a detailed summary of wildfire suppression costs across all agencies with suppression responsibilities in California. The raw FAMWEB incident reports also include several duplicated fire entries and single fires that merged into complexes, which may double count some costs. More detailed analysis would be required to account for these issues.

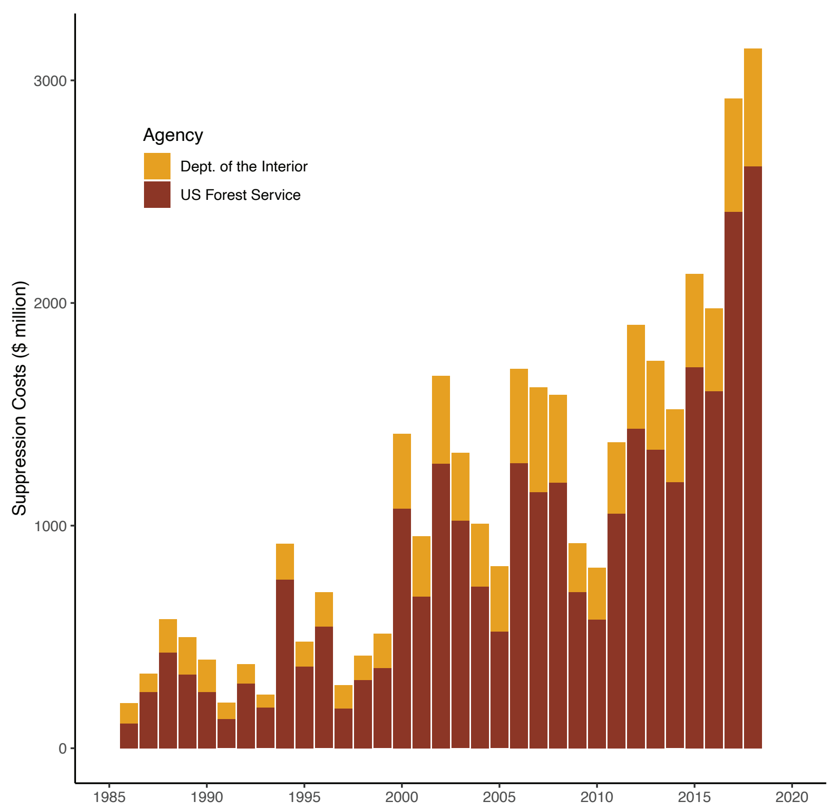

Figure 3.5. National wildfire suppression costs for federal agencies.

> ***Finding:*** *The vast majority of CAL FIRE's budget goes to wildfire suppression. Suppression expenditures also far exceed prevention and mitigation expenditures in the state budget.*

> ***Finding:*** *Though suppression cost data is well-tracked across federal and state government agencies, it is stored in a format that does not allow for an accessible, detailed understanding of suppression expenditures in California. Local suppression expenditures are not reported in a centralized location.*

3.3.5.1 Effectiveness of Wildfire Suppression in California

Although a comprehensive review of the literature on the effectiveness and cost-effectiveness of wildfire suppression in California was outside the scope of this report, the large imbalance in California between suppression expenditures and prevention/mitigation expenditures warrants discussion of the topic. From an economic perspective, the effectiveness of suppression can be conceptualized as the avoided losses from suppression vs. the costs of suppression activities (Lueck & Yoder, 2016). Measuring the avoided losses from fire suppression is an inherently difficult empirical task, which is one reason other metrics, such as suppression cost per acre burned, are used. Such metrics are operationally useful but do not provide insight on the cost-effectiveness of suppression. From a technical and operational perspective, when considering suppression effectiveness, it is important to note that suppression is not a binary wildfire response activity. It is an extremely complex set of activities that are specific to each wildfire threat and depends on the management goals of responding agencies. Suppression costs vary based on these complexities (Gebert et al., 2007).

Two important questions to consider are (1) whether suppression is cost-effective relative to a no suppression alternative and (2) whether suppression is cost effective relative to other mitigation and prevention strategies. Research has suggested that when the expected damage from a wildfire is low, limiting suppression when a fire ignites can also reduce future suppression costs since it provides a "free" fuel treatment (Houtman et al., 2013). One study analyzed the suppression effectiveness of large airtanker suppression strategies, although it did not quantify the cost effectiveness of this suppression strategy (Calkin et al., 2014). There do not appear to be any detailed cost-effectiveness analyses of wildfire suppression in California (Thompson et al., 2012). Future research should include regionally-appropriate studies addressing this issue. The optimal suppression strategy is likely to vary considerably across the state.

Contemporary Considerations: COVID-19 and Fire Management Strategy

Protecting firefighters and communities: structural changes to fire management strategies

In order to reduce impacts of wildfire smoke on public health and to prevent the outbreak of large wildfires, California has shifted fire management policy to an increased emphasis on rapid suppression of wildland fires and efforts to keep fires small (McDowell, 2020; Office of the Governor, 2020). Controlled burns will be reduced or canceled to reduce smoke exposure and aerial firefighting will be increased to suppress fires in areas that may have otherwise been left to burn, in an effort to reduce wildfire smoke (McDowell, 2020; Office of the Governor, 2020).

3.4 California State Budget: Prevention and Mitigation

As the costs and losses of wildfires grow in California, the state budget has changed to reflect the growing priority of prevention and mitigation. A number of state government programs allocated resources to mitigation efforts in the proposed 2020–2021 budget (Table 3.6). For example, SB 45 authorized a climate resiliency bond which allocated more than $2 billion to wildfire prevention and mitigation. However, due to a failure to approve the bill during the 2019–2020 legislative session, this bond measure will not be on the November 2020 ballot. The budget allocated approximately $208 million from the Greenhouse Gas Reduction Fund for various healthy forest grants and fuels reduction projects (Brown, 2020). The ultimate allocations to these programs will depend on cap-and-trade auction revenue, which declined precipitously after the COVID-19 pandemic began. The June 2020 enacted budget includes the full proposed funding for these programs. The original 2020–2021 budget included nearly $362 million prevention and mitigation spending from the General Fund (Peters, 2020). Some of these programs, such as the home hardening program and the LiDAR Imaging program, were fully cut in the final budget.

Table 3.6. *Wildfire in the California budget. Source: Proposed and Enacted 2020-2021 budget for the state of California. Source: Ebudget (2020)*

	January 2020 Budget Proposal	**June 2020 Enacted Budget**
SB 45 Wildfire Bond		
Critical Facilities	$500 million	$0
Forest Grants	$250 million	$0
Community Resilience	$250 million	$0
Greenhouse Gas Reduction Fund		
Healthy Forests	$165 million	$165 million
Prescribed Fire/Fuel Reduction	$35 million	$35 million
2019 Fire Safety Legislation	$8 million	$8 million
General Fund		
Key CAL FIRE Priorities	$120 million	$90 million
California Disaster Assistance Act	$17 million	$38 million
Wildfire Threat Intelligence	$9 million	$2 million
CPUC Wildfire Safety Division	$50 million	$50 million
Home Hardening	$110 million	$0
Community Power Resiliency	$50 million	$50 million
OES Disaster Response	$9 million	$0 million
LiDAR Imaging Program	$80 million	$0

From 2011–2017, most of the state's ignition prevention expenditures were financed by the State Responsibility Area Fire Prevention Fee (SRAFPF), a fee on habitable structures in wildfire prone regions of the state. The last SRAFPF report, in 2017, showed that the $384.6 million in annual expenditures from revenues raised through the FPF went primarily to fire prevention activities and grants (43%), defensible space inspections (16%), and vegetation management (8%).

SRAFPF was eliminated and replaced with revenues from California's cap-and-trade auction, which are allocated through the Greenhouse Gas Reduction Fund (GGRF). In other words, funding for SRAFPF programs was replaced with GGRF revenues. However, COVID-19 has reduced economic activity in the state and the demand for emissions permits. Revenue from the May 2020 auction was approximately $25 million, a small fraction of the more than $600 million raised on average in individual auctions over the past three years. Demand for auction allowances increased substantially in the August 2020 auction and the state collected approximately $474 million in proceeds (CARB, 2020). It is not yet clear what the short- and long-term impacts of this dramatic revenue reduction will be on the various state-funded wildfire prevention and mitigation programs.

> ***Finding:*** *State spending on wildfire mitigation is a small fraction of state spending on wildfire suppression.*

> ***Finding:*** *Funding for prevention and mitigation is unstable and not sustainably funded.*

> ***Conclusion:*** *Without defined mitigation funding that includes both direct and indirect costs and benefits, California will systematically underinvest in risk reduction and as a result be compelled to overinvest in suppression.*

> ***Conclusion:*** *California currently lacks a cost-benefit framework in which to evaluate prevention and mitigation investments against suppression investments.*

> ***Recommendation:*** *The state should consider establishing a process to determine an optimal budget for prevention and mitigation spending that includes both direct and indirect costs and benefits, with a goal of minimizing total costs.*

> ***Recommendation:*** *Because of the long history of underinvestment in prevention and mitigation, the state should consider establishing an accountability mechanism such as a defined ratio of mitigation to suppression spending similar to FEMA requirements for post-disaster spending.*

Metrics of evaluation of environmental vulnerability, socioeconomic status, and demography play an important role in the delineation of government assistance for fire prevention and mitigation. For example, per the mandate of SB 535, 25% of available money from the Greenhouse Gas Reduction Fund go to projects that provide a benefit to disadvantaged communities, and a minimum of 10% of projects located within disadvantaged communities (Monserrat, 2015a). Further, AB 1550 also mandates that 25% of California Climate Investments must go to projects that provide a benefit to disadvantaged communities and 10% to projects located in low-income communities (based on census tract income level) (CARB, 2018). In both cases, disadvantaged communities are designated based on a combination of pollution burden and population characteristics as communicated by Version 3.0 of the California Communities Environmental Health Screening Tool (Faust et al., 2017). Yet, existing metrics of evaluation of disadvantaged communities from an environmental justice perspective, notably the CalEnviroScreen, which is used to implement SB 535 and AB 1550, does not explicitly take into account the impacts of wildfire smoke as a form of pollution (Monserrat, 2015b; CalEPA, 2017). Thus, communities with sensitive populations and socioeconomic factors characteristic of a disadvantaged communities, that have a high fire risk or fire smoke exposure but a low risk of industrial and agricultural pollution, will not necessarily be designated as disadvantaged and are less likely to receive state aid for environmental and climate investments (CalEPA, 2017). Better systems for tracking wildfire impacts on smaller geographic and population scales are needed, and increased volume of such data. (Mazur et al., 2010). Future research could explicitly investigate how wildfire impacts disproportionately affect disadvantaged communities in California.

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Chapter 4

Buildings and Infrastructure

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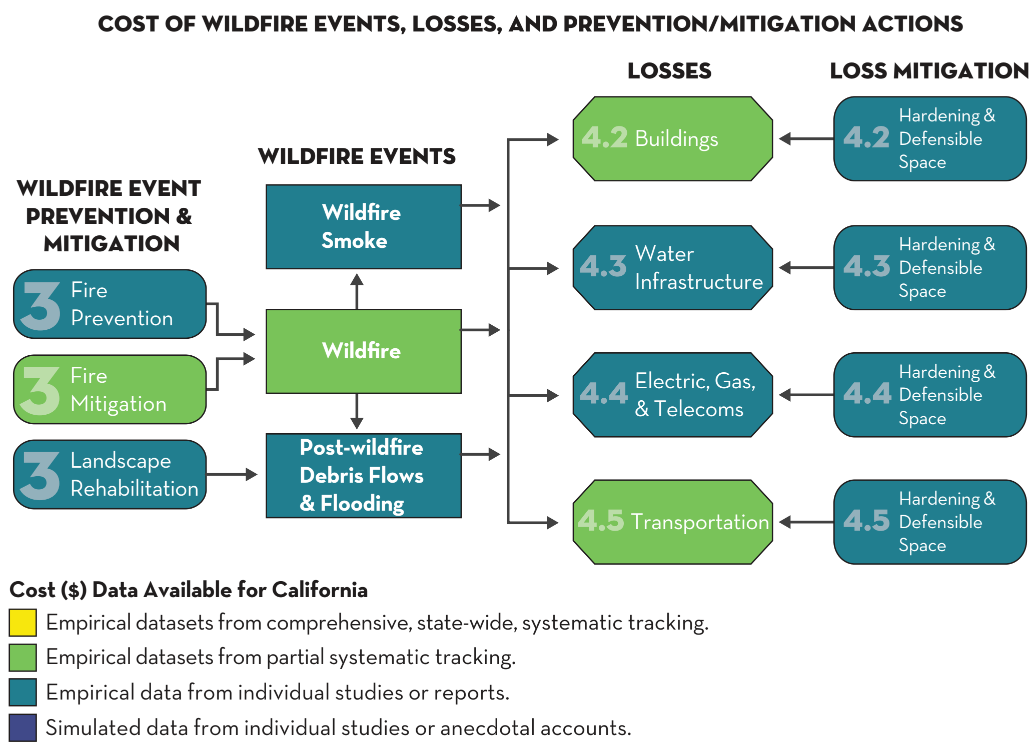


Figure 4.1. *The colors in the above figure indicate the category of California-specific datasets available to characterize the dollar value costs associated with the built environment, and mitigation actions to reduce losses. Building and Transportation Infrastructure cost estimates of specific losses from specific wildfires in California are available in ongoing systematic tracking efforts (green). Cost estimates of Water Infrastructure losses, Utility Infrastructure losses, and mitigation activities to reduce losses from specific wildfires in California are available in individual studies or reports (blue). Comprehensive, state-wide cost estimates of built environment losses and all mitigation activities to reduce wildfire losses in California are currently unavailable in the research literature or other publicly available resources.*

4.1 Chapter Scope

Chapter 4 reviews physical losses of buildings, infrastructure, and other physical assets caused by catastrophic wildfire events (shown in Figure 4.1). Losses include physical damage or destruction from wildfires, wildfire smoke, post-wildfire debris flows (mudslides), and post-wildfire flooding. Loss of property value as a result of a wildfire event is covered in Chapter 7. This chapter does not include liability cost that utilities or other entities may incur as a result of wildfires caused by infrastructure.

4.1.1 Assessing losses

Determining a count for the number of structures or other infrastructure damaged or destroyed by wildfire is a relatively straightforward process, particularly if the objective is to simply determine whether the structure survived, was damaged, or was destroyed. Of structures that are burned by wildfires, approximately 90% of them are fully destroyed, while the other 10% are damaged (Syphard & Keeley, 2019). Those that are damaged are somewhat more difficult to assess in terms of degree. This is particularly the case for smoke impacts that may not be immediately visible.

4.1.2 Assessing full costs of building and infrastructure losses

The costs of building and infrastructure losses include costs to repair damage or to replace physical assets that are destroyed. Additional costs include the value of personal property or inventory that was damaged along with the home or commercial building, costs associated with temporary accommodations or service disruptions, and costs related to toxic material and debris cleanup. When infrastructure losses cause service disruptions, the costs can be borne by customers and communities far from the perimeter of the wildfire. Including these additional costs is important for valuing the cost-effectiveness of mitigation efforts to reduce building losses because, if those mitigation actions are effective, not only are the building and contents saved, but the additional associated costs are avoided.

4.2 Building Losses from Wildfire

4.2.1 Exposure

The first condition that needs to be met for a structure to be damaged or destroyed in a wildfire is simply being exposed to the fire. Wildfire exposure, which includes exposure to flames, heat, embers, and smoke, is a function both of where fires are most likely to start and spread and of where the assets at risk are located relative to the location of those fires (Caton et al., 2017). With rapid population growth and expansion of residential development in the last several decades, there has been a massive increase in the number of homes exposed to wildfire. This is largely due to the juxtaposition of structures interspersed within wildland vegetation - areas typically referred to as the Wildland Urban Interface (WUI) (Radeloff et al., 2005; Radeloff et al., 2018).

The WUI refers to the area where houses meet or intermingle with undeveloped wildland vegetation (USDA and USDI, 2001; Radeloff et al., 2005; see also Ch 2 for more discussion). Although the WUI can be defined according to a range of criteria, the underlying relationship is the spatial correlation between housing arrangement (i.e., density, configuration, and edge) and location with areas particularly prone to wildfires (Miranda et al., 2020). Low- to intermediate- housing density is where most structures are destroyed in wildfires (Syphard et al., 2012; Syphard & Keeley, 2019), not only in California but in other locations (Kramer et al., 2018), because those are the areas where houses are most exposed to flammable vegetation. These are also the locations where fire frequency tends to be highest (Syphard et al., 2007). Research shows that in areas where fire burns repeatedly, or where large fires are likely to occur, homes are also more likely to be destroyed (Syphard et al., 2012; Syphard & Keeley, 2019). The number of buildings exposed to wildfire have increased over time in part due to the expansion of development into the WUI, with nearly a third of all new homes in the U.S. being built in this space (Radeloff et al., 2018). This trend is expected to continue into the future.

Despite the strong relationship between low-intermediate housing density and structure destruction, there is a threshold at which this density relationship can flip. That is, if a development is exposed to wildfire, and there is high density of older and more flammable structures, then once buildings in a neighborhood do catch fire, they can become a primary fuel source for the wildfire. This condition can allow the wildfire to then spread directly from structure-to-structure, particularly under severe wind-driven wildfire events (Cohen & Stratton, 2008; Keeley et al., 2004, 2009; Price & Bradstock, 2013).

Another important consideration in terms of exposure is that the majority of building losses from wildfire are not the result of direct exposure to flames or radiant heat but from exposure to windborne embers that ignite flammable materials on or near the building (Foote et al., 2014; Koo et al., 2010; McMillan et al., 2008; Suzuki et al., 2012). As the spatial extent and number of structures within the WUI increase, the exposure of those structures to these windborne firebrands also increases.

The number of buildings exposed to wildfire in California is systematically tracked by the CAL FIRE Damage INSpection (DINS) Program. For all fire events in California that involve the damage or destruction of buildings worth $10,000 or more, a team of trained inspectors collect information on the extent of damage, defensible space before the fire, and other building characteristics for all structures exposed to the fire (Syphard & Keeley, 2019). Estimates of the dollar value of the buildings or of the damage is not included in the dataset. The DINS data collection processes have become more comprehensive and complete over time, and much information is verified through ancillary county data. The DINS data are available through a public records request. Additional data on select wildfires is available in individual studies and reports (Table 4.1).

> ***Finding:*** *State-wide data on building exposure to wildfires is systematically tracked by the CAL FIRE DINS program for wildfires that cause at least some damage in California.*

> ***Finding:*** *Although the DINS program records data for select unburned structures close to ones that were damaged or destroyed, the number is relatively small, although the DINS program grows and improves every year.*

> ***Finding:*** *Thorough assessment of building characteristics can be challenging because the level of destruction was so complete.*

> *Finding: Better identification of structures exposed but not damaged will enable better identification of effective mitigation actions.*

> ***Conclusion:*** *Developing a standardized working definition of structure exposure and a systematic approach for increasing the number of exposed, surviving structures surveyed via DINS could improve the robustness of statistical comparison and analysis of destroyed and unburned structures.*

> ***Recommendation:*** *California should consider systematically reporting summary statistics on the buildings that have been exposed to wildfires.*

4.2.2 Losses—the physical buildings

Building losses from wildfires in California have been systematically tracked by the CAL FIRE DINS program. Summary statistics on structure losses are publicly available through the online CAL FIRE incidents inventory and in the annual CAL FIRE Wildfire Activity Statistics ("Redbook") reports. Additionally, numerous surveys have been conducted of building losses from wildfire in California (Table 4.1). Methods for documenting building losses are not standardized among these efforts and, for this reason, there may be minor discrepancies in counts of losses reported by different studies and the CAL FIRE datasets for a given wildfire (e.g., J. D. Cohen & Stratton, 2008). Discrepancies in counts are typically due to differential treatment of non-residential structures that may or may not be included in the counts. Studies typically focus on home losses. However, see Schulze et al. (2020) for damage to school and hospital buildings from the 2018 Camp Fire.

The number of structures lost to wildfire per year in California is highly variable from year to year (Figure 4.2). Between 1950–2000, CAL FIRE estimated approximately 500 structures per year were lost in Southern California (CAL FIRE, 2000). From 2000–2018, that number increased to ~2,700 per year across the state (Syphard & Keeley, 2019). Although this jump suggests structure losses are increasing over time, one caveat is that these numbers largely reflect the many thousands of structures lost in 2017 and 2018, which were atypical in the history of destructive California wildfires. Additional years of structure loss data will be required to determine whether the 2017 and 2018 losses represent rare outlier events or are reflective of an increasing trend of losses.

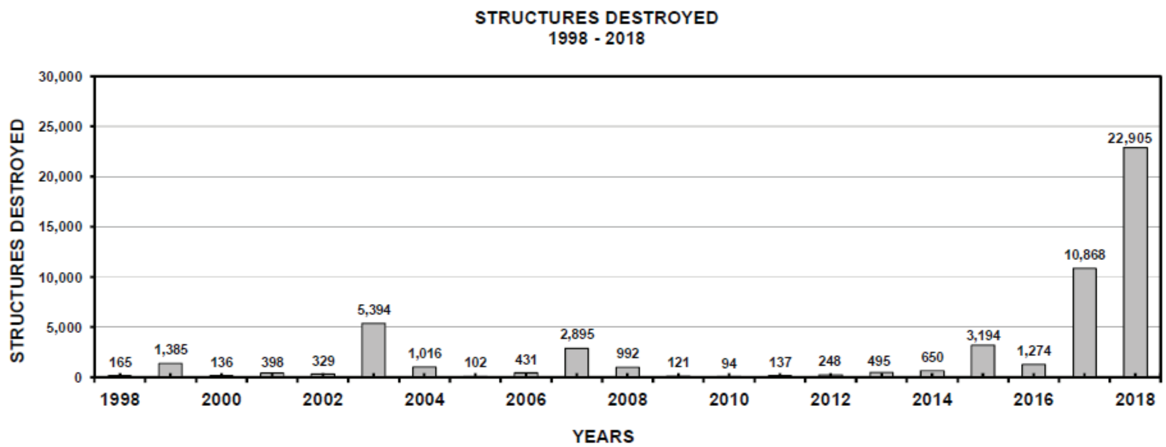


Figure 4.2. *Annual count of structures destroyed in California wildfires from 1998-2018. Source: CAL FIRE 2018 Wildfire Activity Statistics (Redbook) report.*

The costs associated with the physical damage or destruction of structures are not systematically tracked for California. CAL FIRE's annual Redbooks can include summary statistics for the value of buildings and personal property losses. Redbooks include estimates of the "total property and contents dollar loss in terms of replacement in like kind and quantity. This estimation of the dollar loss includes property and contents damaged by fire, smoke, water, and overhaul." Several entities including the California Department of Insurance (CDOI) and the Insurance Information Institute (III), have provided estimates of insured property losses for select highly destructive wildfires. The costs specifically associated with uninsured or underinsured property losses are generally unknown. Recent settlements in the PG&E bankruptcy of insured and uninsured losses were approximately equal in value. This indicates that at least for the 2017 and 2018 utility-caused wildfires in Napa, Sonoma, and Butte Counties, uninsured and underinsured value may be very significant relative to insured losses. It is also important to recognize that due to differences in social vulnerability, the dollar value of property losses does not in and of itself convey the economic burden felt by the individual households. For example, low income households are more likely to lose all of their assets in a wildfire and less likely to have adequate insurance to cover the cost of losses as compared to higher income households (Mazur et al., 2010; Niemi & Lee, 2001).

> ***Finding:*** *State-wide data on building losses caused by wildfires is systematically tracked by the CAL FIRE DINS program for buildings worth at least $10,000 in California.*

> ***Finding:*** *The costs associated with the actual repair or replacement of buildings damaged or destroyed by wildfires is not systematically tracked for California.*

> ***Finding:*** *Summary statistics on the estimated costs associated with physical building losses for wildfires are available from several entities including CAL FIRE, CDOI, and the III.*

> ***Conclusion:*** *Published estimates of property losses are likely an underestimate of total costs associated with building damages.*

4.2.3 Losses—the clean up

Cleanup of debris and hazardous materials from damaged and destroyed structures following wildfire occurs in two stages. In phase one, household hazardous waste from burned homes—including batteries, pesticides and fertilizers, paint thinners, and asbestos siding—are removed from the property. In California, all toxic waste removal is contracted under the oversight of the Department of Toxic Substances (DTSC). DTSC's Public Dashboard mapping system provides updates on the phase one cleanup process, but does not include cleanup costs. DTSC releases biennial reports of hazardous waste cleanups, which are a summation of filed reports across the state and are available upon request.

After the hazardous waste is removed in phase one, CalRecycle oversees the phase two removal of non-toxic debris and recyclables from the property. Information on the tons of waste removed, the type of waste removed, and/or the cost of waste removal for select wildfires are reported in press releases available on the CalRecycle website. For cleanups before 2016, data is available upon request only. Following the 2018 Camp Fire, CalRecycle was also tasked with the safe removal of fire-damaged trees that could endanger public health by falling on public rights of way, public facilities, or private roads that serve as critical access for services or residents. An estimated 600,000 hazard trees were identified for removal following the 2018 Camp Fire (National Academies Press, 2019).

Funding for these cleanup efforts comes from the State. There can also be significant federal funding from FEMA, and the U.S. Army Corp of Engineers. Individual homeowners can also personally clean or hire cleanup teams to remove debris in phase two. The costs associated with clean up are not systematically tracked in California but cost data on select wildfires can be found in individual reports and new articles. The Sacramento Bee has published a list of estimated cleanup costs for select California wildfires based on data compiled from CalRecycle, U.S. Army Corp of Engineers, and FEMA (Bizjak, 2019). As of January 2019, estimated costs ranged from $1.4 billion to at least $2 billion for the 2018 Camp Fire.

> ***Finding:*** *Data on post-wildfire clean up of building losses and associated costs have been compiled in individual reports and studies for select California wildfires.*

> ***Finding:*** *It is not clear from our review whether the available data is comprehensive of all clean up efforts and costs in the state.*

> ***Conclusion:*** *There is no single, comprehensive database systematically tracking data on post-wildfire clean up of building losses or their associated costs for wildfires in California.*

> ***Conclusion:*** *An estimate of the total state-wide costs of post-wildfire clean up of building losses in California would require compiling existing data from multiple sources, and possibly new data collection.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track all post-wildfire clean-up efforts and their associated costs.*

4.2.4 Losses—temporary accommodations

Once the immediate emergency ends and there is no longer a risk of wildfire exposure, people who have lost their homes, and businesses who have lost their commercial buildings, will continue to require temporary accommodations until permanent arrangements are made. Data on the displacement of people, businesses, and other entities as a result of building losses from wildfire—and the associated costs—are not systematically tracked for California. Data may be included in insurance claims and FEMA individual assistance grants, but this information is not generally available to the public. Due to time constraints, a thorough review of the literature on temporary displacement as a result of building losses from wildfire was outside the scope of this report.

4.2.5 Mitigation

There are three main strategies for reducing structure losses when wildfires burn in or near populated areas: (1) land use planning and urban development; (2) structure hardening; and (3) defensible space (Alexandre et al., 2016; Hakes et al., 2017; Syphard et al., 2013, 2014).

Given that housing location has been documented as the most significant factor explaining historical structure loss in California (Alexandre et al., 2016; Syphard et al., 2012; Syphard & Keeley, 2019), land use planning could potentially provide substantial reduction of future housing exposure to wildfire, thereby fully preventing losses (Moritz & Butsic, 2020; Syphard et al., 2013; Syphard et al., 2019). However, this strategy has yet to be implemented in California, so there are no cost estimates associated with it. While it could potentially be more effective at preventing future housing loss (and wildfire ignitions) than existing strategies, it is also perceived to be difficult to achieve due to challenges with aligning public support, policies, and other governmental priorities (Mockrin et al., 2020). It also cannot protect the large amount of existing development already within the WUI.

The primary role of home hardening is to prevent structure ignitions from exposure to firebrands (or embers) that are blown from the wildfire (Foote et al., 2014; Manzello et al., 2012; Suzuki et al., 2012) or to prevent ignition from exposure to radiant heat of a wildfire (Cohen, 2000; Cohen & Butler, 1998; Quarles et al., 2010). Laboratory studies find that ignition and/or fire-resistant building materials for roofs, walls, windows, vents, and bird-stops reduce the risk of structure ignition from firebrands (Babrauskas, 2007; Cohen, 2000; Manzello et al., 2007, 2008, 2009, 2012). The cost of retrofitting existing buildings to incorporate hardening strategies can cost tens of thousands of dollars, whereas the cost of building new homes with hardening strategies is comparable to the construction costs of a typical home without wildfire protections (Quarles, 2018).

The California Building Standards Commission, acting on a proposal by the Office of the State Fire Marshal in 2008, adopted the first comprehensive statewide ignition-resistant building code in the country, often referred to as Chapter 7A for its location in the California Building Code (CBC). All new construction in the CAL FIRE designated Fire Hazard Severity Zones (FHSZ) in State Responsibility Areas (SRA), and Very High Fire Hazard Zones in Local Responsibility Areas (LRA), was required to be built to new code. The revised 2008 building codes benchmark a significant shift in California housing susceptibility from that date, as housing is now separated into the post-2008 construction with improved chances of wildfire survival, and the pre-existing housing that does not have hardened features. A few exceptions are local jurisdictions in Southern California that have adopted more stringent building codes prior to the 2008 statewide adoption, but they are usually not as comprehensive in scope. Also included in the Chapter 7A effect is the correlating Chapter 49 of the California Fire Code (CFC), which is considered a maintenance code rather than a building code but does work in tandem with Chapter 7A.

The primary role of defensible space around the perimeter of a home or property is to create well-maintained buffers of thinned and irrigated vegetation. Reduced vegetation that is also well-irrigated lowers the risk of the immediate area around a structure from igniting during a fire and exposing the structure to flames, heat, and embers (CAL FIRE Defensible Space, PRC 4291). Additionally, by keeping the fire away from the structure, defensible space may also provide safe firefighter access to the property and increase the effectiveness of suppression efforts.

The creation of defensible space around a property, according to specific horizontal and vertical spacing criteria, is required by state law in State Responsibility Areas and in High Fire Hazard Severity Zones in Local Responsibility Areas, and/or by local ordinance. The specific requirements for defensible spaces are found in the Public Resources Code 4290-4294 within California Building Code: Chapter 7A. Amendments to the CA building code in 2005, 2008 (SB 1595 Kehoe, Chapter 366, Statutes of 2008) and 2018 (AB 2911 Friedman, Chapter 641, Statutes of 2018) provided major updates to the code that increased defensible space requirements, including increasing the defensible space up to 100 feet and requiring more intense fuel management within the first 30 feet around a structure. State law applies fines of no less than $100 for a first infraction, increasing to a potential misdemeanor charge and a fine of no less than $500 for a third infraction. State law also allows insurance carriers to require more restrictive defensible space criteria than the 100-foot criteria in California's building code. There is no statewide audit of defensible space compliance with the state requirement and anecdotal evidence suggests compliance is uneven.

The cost of defensible space to individual home-owners is highly specific to a given property.

We found no datasets that systematically track the prevalence or costs of home hardening and defensible space practices across the state. The DINS dataset includes information on defensible space for structures that have been exposed to wildfire. Individual studies and reports document mitigation efforts to reduce building losses primarily at the level of counties or neighborhoods in California (Table 4.1), but none of these studies include data on the associated costs.

> ***Finding:*** *Data on select building hardening and defensible space actions to reduce building losses can be found in the CAL FIRE DINS database, and in datasets that have been compiled for analysis in individual reports and research papers.*

> ***Finding:*** *We found no California-based studies that estimate the costs associated with building hardening and defensible space actions that have been implemented in the state to reduce building losses from wildfire.*

> ***Conclusion:*** *There is no single, comprehensive, state-wide database tracking building hardening and defensible space actions or their associated costs.*

> ***Conclusion:*** *An estimate of the total state-wide costs of building hardening and defensible space conducted in California for the purpose of reducing building losses from wildfire would require compiling existing data and collection of new data.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track all building hardening and defensible space actions conducted in California.*

4.2.6 Effectiveness at reducing losses

There is no state-wide database that tracks the effectiveness of home-hardening and defensible space to reduce structure losses from wildfires in California. Several case studies find that home hardening and defensible space can be effective at reducing the risk of building losses (Table 4.1). Post-wildfire analysis using the DINS data has shown that, in a real wildfire situation, the structural characteristics that provided the highest likelihood of home survival were those that either prevented embers from penetrating structures (e.g., vent screens and enclosed eaves) or likely had protection from radiant heat (e.g., double pane windows provided significantly more protection than single pane windows) (Syphard & Keeley, 2019).

Empirical studies that assessed historical structure destruction relative to different distances and types of defensible space in Southern California (Miner, 2014; Syphard et al., 2014) found that defensible space provided significant protection up to 5–20 meters (16–66 feet), but anything more than that added no additional benefit. Irrigation and spacing may also provide as much protection as vegetation clearance (Gibbons et al., 2018). Some of the most important factors to consider are trees overhanging roofs (which can generate flammable litter that ignites if an ember lands) or vegetation touching the structure (Syphard et al., 2014). Research suggests the most important zone to focus on for effective mitigation is the first five feet around the structure. Empirical research in Southern California, comparing the relative importance of defensible space, building construction characteristics, and landscape-scale variables for explaining structure loss, found that housing density explained more than any other variable (Syphard et al., 2017).

We found no datasets or studies that assessed the cost-effectiveness of home hardening or defensible space efforts at reducing building losses from wildfire (Table 4.1).

> ***Finding:*** *Case studies based on empirical evidence have found building hardening and defensible space can be effective at reducing building losses from wildfire in California.*

> *Finding: We found no studies that establish the cost-effectiveness of building hardening or defensible space at reducing losses from wildfires.*

> ***Conclusion:*** *Comprehensive estimates of the total cost-effectiveness of building hardening and defensible space at avoiding losses from wildfire in California would require additional research.*

> ***Recommendation:*** *California should consider supporting research to evaluate the cost-effectiveness of different building hardening and defensible space treatments to reduce the costs of wildfire in California.*

Table 4.1. Summary of select California-specific literature relevant to building losses from wildfire, from this review.

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Exposure	Losses		Prevention and Mitigation Actions		Effectiveness at Reducing Losses	
Source	**Wildfire**	**Numeric**	**Numeric**	**Dollars**	**Numeric**	**Dollars**	**Numeric**	**Dollars**
Bizjak, 2019	Select large wildfires	0	2	2	0	0	0	0
California Department of Insurance	Select large wildfires	0	2	2	0	0	0	0
CAL FIRE Damage INSpection Program	California Wildfires	3	3	3	3	0	0	0
CalRecycle Phase II Cleanup	Select large wildfires	0	2	2	0	0	0	0
Cohen and Stratton, 2008	2007 Grass Valley Fire	0	2	0	0	0	0	0
DTSC Phase I Hazardous Waste Removal	California Wildfires	0	3	0	0	0	0	0
FEMA Disaster Assistance	Federally declared disasters	0	3	3	0	0	0	0
The Insurance Information Institute (I.I.I.)	Top 10 most costly fires in the U.S.	0	0	2	0	0	0	0
Kasler, 2019	2018 Camp Fire	0	2	0	2	0	2	0
Kolden and Henson, 2019	2017 Thomas Fire	2	2	0	2	2	0	0
Foote and Manzello, 2014	2007 Angora Wildfire	2	2	0	0	0	0	0
Maranghides et al., 2013	2007 Guejito and Witch Fires	0	2	0	2	0	2	0
McCaffrey and Winter, 2011	NA	0	0	0	2	0	0	0
McMillan et al., 2008	2007 SoCal Wildfires	2	2	0	2	0	2	0
Schulze et al., 2020	2018 Camp Fire	2	2	0	2	0	0	0
Syphard et al., 2012	2001-2010 San Diego Wildfires	2	2	0	0	0	0	0
Syphard et al., 2013	Simulated Wildfires	0	1	0	1	0	1	0
Syphard et al., 2014	2001-2010 San Diego Wildfires	2	2	0	2	0	2	0
Syphard et al., 2017	2003, 2007 San Diego Wildfires	2	2	0	2	0	2	0
Syphard & Keeley, 2019	2013-2018 California Wildfires	2	2	0	2	0	2	0
Winter et al., 2006	NA	0	0	0	2	0	0	0

4.3 Water Infrastructure

Wildfire events can physically damage water infrastructure including pipes, water meters, dams, spillways, and other structures and equipment (Sham et al., 2013). Costs associated with water infrastructure losses include repair costs, clean-up costs, and costs related to service disruptions. Mitigation actions specifically to reduce water infrastructure losses primarily include infrastructure hardening and defensible space.

Water infrastructure damage can also cause contamination of drinking water supplies that can pose a risk to public health. A new phenomenon was documented in the 2017 Tubbs Fire (Sonoma County) and 2018 Camp Fire (Butte County) in which toxic levels of volatile organic compounds (VOCs, including benzene) were found within the water distribution system, likely as a result of burning plastic water pipes and meters (Macler et al., 2020; Proctor et al., 2020). Health losses associated with post-wildfire drinking water contamination are discussed in Chapter 5. Those health losses that are a direct consequence of water infrastructure damage should be included in assessments of the effectiveness of Mitigation actions to reduce water infrastructure losses discussed here.

In addition to physical damage to water infrastructure, wildfire events can also impact watersheds and cause increased runoff, erosion, and sedimentation in the watershed that can lead to increased treatment costs of drinking water sources or increased dredging of reservoirs. These types of watershed losses are distinct from physical damage and discussed in Chapter 6.

Water infrastructure exposure, losses, mitigation actions, and effectiveness at reducing losses are not systematically tracked in California but some information is available in individual studies and reports (Table 4.2).

> ***Finding:*** *Data on water infrastructure exposure to wildfire, losses due to wildfire, mitigation actions to reduce losses have been compiled in individual reports and studies for select California wildfires.*

> ***Conclusion:*** *There is no single, comprehensive database systematically tracking data on water infrastructure losses or their associated costs for wildfires in California.*

> ***Conclusion:*** *An estimate of the total state-wide costs of water infrastructure losses in California would require compiling existing data from multiple sources and new data collection.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track all water infrastructure losses and their associated costs for wildfires in California.*

Table 4.2. Summary of select California-specific literature relevant to water infrastructure losses from wildfire.

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

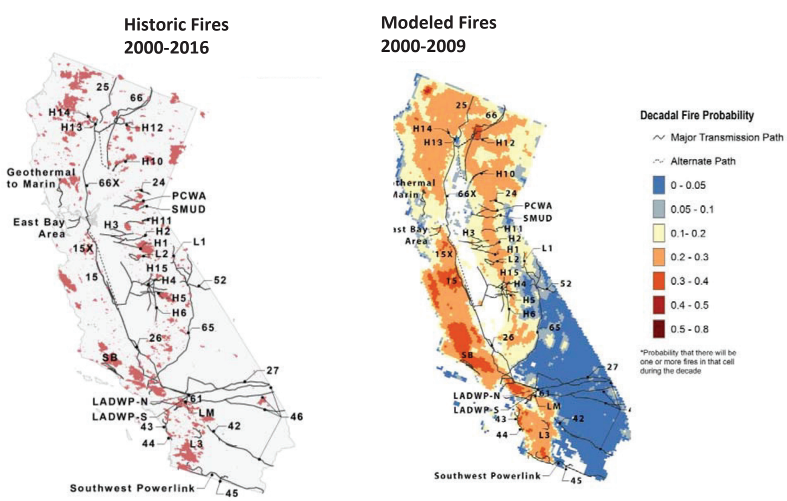
		Exposure	Losses		Prevention and Mitigation Actions		Effectiveness at Reducing Losses	
Source	**Wildfire**	**Numeric**	**Numeric**	**Dollars**	**Numeric**	**Dollars**	**Numeric**	**Dollars**
Macler et al., 2020	2017 Tubbs Fire, 2018 Camp Fire	0	2	0	0	0	0	0
Proctor et al., 2020	2017 Tubbs Fire, 2018 Camp Fire	0	2	2	0	0	0	0
SAWPA, 2003	2003 Grand Prix, Old, and Padua Fires	2	2	2	2	2	0	0
Sham et al., 2013	Various Wildfires	2	2	0	2	0	0	0

4.4 Electric, Gas, and Telecommunications

4.4.1 Exposure

Wildfires can damage or destroy gas, electric, and telecommunications infrastructure including poles, towers, lines, pipes, and other physical assets (Cal OES, 2018). Damage is primarily caused by direct exposure to the flames and heat from the fire, but carbon build-up and particulate matter from wildfire smoke can also damage components used to deliver electricity (Aspen Environmental Group, 2008; Sathaye et al., 2011). Furthermore, flame retardants and firefighting techniques used to suppress fires can also damage utility infrastructure (Sathaye et al., 2011).

Utility infrastructure spans the state, with distribution infrastructure at risk of exposure when wildfires burn in more populated areas, and transmission infrastructure at risk of exposure from wildfires that burn in more rural areas. Thus, wildfires that result in few fatalities or building losses can cause significant losses to utility infrastructure. Regulated utilities in California are required to file annual Wildfire Mitigation Plans as directed in California SB 901 and CPUC Rulemaking 18-10-007. The Wildfire Mitigation Plans contain extensive detail of utility infrastructure at risk to wildfires as well as mitigation strategies (e.g., monitoring) and programs (e.g., undergrounding) expected to take place during the coming years. Figure 4.3 depicts historic and modeled fires and their location relative to major transmission pathways in California. Figure 4.4 shows natural gas pipeline exposure to wildfires in the past (1953–2005) and expected change in exposure in future (2047–2099) under two scenarios.



Source: FRAP 2017

Source: Westerling, 2018 CANESM2 RCP8.5 model

Figure 4.3. *Exposure of California electricity transmission pathways to wildfires. Source: Figure 5 from Dale et al. (2018).*

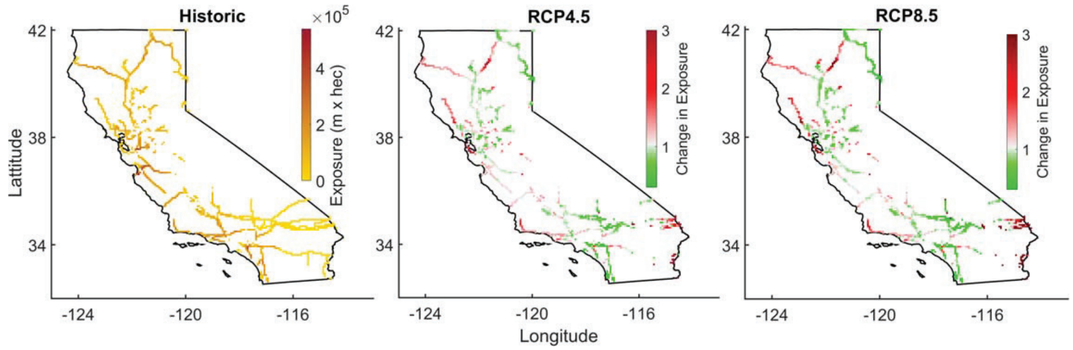


Figure 4.4. Exposure of California natural gas pipelines to wildfires in the past and future. Source: Figure 2 in Moftakhari & AghaKouchak (2019).

> ***Finding:*** *State-wide data on utility infrastructure exposure to wildfires in California have been compiled for individual reports and research papers.*

> ***Conclusion:*** *There is no comprehensive state-wide database tracking utility infrastructure exposure to wildfires in California.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track utility infrastructure exposure to wildfires.*

4.4.2 Losses

Losses caused by wildfire include damage or destruction of poles, towers, lines, pipelines, and other physical equipment and assets. Damage to infrastructure can cause subsequent losses including service disruptions to customers and clean up efforts to remove hazardous waste and other debris. Costs associated with infrastructure losses include the costs to repair or replace equipment, cleanup costs, and costs associated with any service disruptions caused by infrastructure damage.

Utilities restoration costs—and customer losses due to service interruptions—from wildfire-related damage are not systematically or comprehensively tracked in California. There are very few consultant reports or studies in the academic literature on this topic. One such study, Dale et al. (2018), reported that more than $700 million in wildfire-related damage occurred to the state's transmission and distribution systems from 2000-2016.

Information on the cost of regulated electric and gas utility infrastructure damaged from wildfires and other disasters can be found in regulatory filings related to cost-recovery requests submitted to the California Public Utilities Commission (CPUC). Immediately following disaster declarations, regulated utilities in California may record costs associated with “repairing, restoring, or replacing damaged facilities…in a Catastrophic Event Memorandum Account (CEMA)…[which allows utilities to]…later request permission from the CPUC to recover these costs from ratepayers” (Kousky et al., 2018).

For example, PG&E provided notice to the CPUC that it was recording costs in a CEMA to repair facilities and restore service associated with the Camp Fire (PG&E, 2018). According to PG&E, the Camp Fire was estimated to have damaged:

- ~5,700 electric distribution facilities
- ~10,600 gas meters
- One gas regulator station
- Three gas regulators
- Seven power generation facilities

Approximately 25,000 electricity customers and 12,000 gas customers had service disrupted during this single disaster (PG&E, 2018). Preliminary estimates of restoration costs for the Camp Fire were significant—approaching $700 million—and do *not* include utility liabilities, service disruption-related costs to customers, or recovery (e.g., rebuild) costs (Table 4.3).

Table 4.3. Estimated restoration costs to PG&E infrastructure from the Camp fire. Source: PG&E (2018).

Utility infrastructure category	Estimated restoration cost	Comments
Electric distribution	>$300 million	At least $150 million in capital-related costs and $150 million in other expenses
Gas transmission and distribution	>$68 million	At least $47.5 million in capital-related costs; $20.6 million in other expenses
Power generation	>$17.4 million	$14.8 million in capital-related costs and $2.6 million in other expenses

It is important to note, however, that costs recorded in the CEMA cannot include liabilities to the utility, customer costs associated with service disruptions, or any pre-fire mitigation activities or investments. Electricity customer interruption costs—specifically associated with wildfire damage to utility infrastructure—can be estimated using Berkeley Lab’s Interruption Cost Estimate (ICE) Calculator, but there is no known research that has produced such estimates.

During a catastrophic wildfire, the Federal Communications Commission (FCC) may activate its Disaster Information Reporting System (DIRS) and telecommunication providers may report the status of their service and infrastructure including damage to towers. Information submitted by providers is treated as confidential, and the FCC may compile public status reports using aggregated data. Additional information can also be found in press releases and newspaper articles, but we did not conduct a comprehensive review of these anecdotal sources.

> ***Finding:*** *Data on select utility infrastructure losses caused by wildfires and their associated costs can be found in individual regulatory filings submitted to the CPUC and in datasets that have been compiled for analysis in individual reports and research papers.*

> ***Conclusion:*** *There is no comprehensive state-wide database tracking utility infrastructure losses caused by wildfires or their associated costs in California.*

> ***Conclusion:*** *An estimate of total state-wide costs of utility infrastructure losses in California would require compiling existing data from multiple sources, and possibly collection of new data.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track utility infrastructure losses caused by wildfires.*

4.4.3 Mitigation

In addition to action to reduce catastrophic fires (Chapter 3), mitigation actions to specifically reduce physical damage to utility infrastructure in the event of a wildfire includes, but is not limited to:

- Undergrounding equipment—see the Wildfire Mitigation Plans filed annually by the regulated utilities (PacifiCorp, 2020; PG&E, 2020; SDG&E, 2020).
- Replacing wood poles with steel poles. Steel poles are more resistant to fire and are taller, which raises conductors higher above potential ground fires (ICF, 2018; Johnson, 2014).
- Defensible space to keep fires away from infrastructure (Butler & Wallace, 2015).
- Voluntarily disrupt service to isolate and prevent further damage (ICF, 2018).

Many of these infrastructure hardening and defensible space actions are also deployed by utilities to prevent wildfire ignitions sparked by infrastructure. Information on the use and costs of mitigation actions to reduce losses from wildfire can be found in wildfire mitigation plans submitted to the CPUC, but they are frequently commingled with ignition prevention efforts.

In the event of a loss of service, alternative or backup generation of services can help mitigate subsequent losses. These may be deployed by the utility or by individuals. Examples include running backup generators until electricity service is restored or deploying mobile telecommunications towers to restore coverage.

> ***Finding:*** *Data on select infrastructure mitigation actions and associated costs to reduce wildfire losses can be found in wildfire mitigation plans submitted to the CPUC.*

> ***Conclusion:*** *There is no single, comprehensive, state-wide database tracking infrastructure mitigation actions or their associated costs.*

> ***Conclusion:*** *An estimate of the total state-wide costs of infrastructure hardening, defensible space, and temporary service replacement conducted in California for the purpose of reducing infrastructure losses from wildfire would require compiling existing data and collection of new data.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track all mitigation actions to reduce utility infrastructure losses from wildfires in California.*

4.4.4 Effectiveness at reducing losses

Very little information is available on the effectiveness of strategies or investments to reduce utility losses associated with wildfires. We found one study in the peer-reviewed literature that assessed the effectiveness of mitigation actions to reduce infrastructure losses of wildfire in California (Butler & Wallace, 2015); one report assessing the effectiveness of fuel treatments in the Mokelumne watershed that included avoided wildfire damage to utility infrastructure (Buckley et al., 2014); and one graduate school thesis that assessed the potential cost-effectiveness of infrastructure hardening on repair costs (Johnson, 2014). Larsen (2016) evaluated the costs and benefits of a mandate to underground all transmission and distribution (T&D) lines for regulated utilities across Texas. The study did account for the economic value of avoiding damage to overhead infrastructure and service disruptions to electric utility customers, but the focus was on risk to overhead lines from severe weather more generally (tornadoes, hurricanes, wind storms) and not wildfire-related risk to T&D lines.

> ***Finding:*** *We found no California-based empirical studies that evaluate the effectiveness or cost-effectiveness of mitigation actions to reduce infrastructure losses of wildfires.*

> ***Finding:*** *Models of simulated mitigation actions predict that infrastructure hardening and defensible space could be effective at avoiding select losses from wildfire.*

> ***Conclusion:*** *Comprehensive estimates of the total cost-effectiveness of infrastructure hardening and defensible space at avoiding losses from wildfire in California would require additional research.*

Recommendation: *California should consider supporting research to evaluate the cost-effectiveness of different infrastructure hardening and defensible space treatments to reduce the costs of wildfire in California.*

Table 4.4. Summary of select California-specific literature relevant to electric, gas, and telecommunications infrastructure losses from wildfire, from this review.

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Exposure	Losses		Prevention and Mitigation Actions		Effectiveness at Reducing Losses	
Source	Wildfire	Numeric	Numeric	Dollars	Numeric	Dollars	Numeric	Dollars
Buckley et al., 2014	Simulated Wildfires	0	1	1	1	1	1	1
Butler & Wallace, 2015	Simulated California Wildfire	0	1	0	1	0	1	0
California Public Utilities Commission (CPUC)	Select California Wildfires	0	2	2	2	2	0	0
Christin et al., 2017	2016 Loma Fire	0	0	2	0	0	0	0
Dale et al., 2018	200-2016 California Wildfires	2	2	2	0	0	0	0
FCC Disaster Information Reporting System (DIRS)	Select California Wildfires	0	2	2	0	0	0	0
ICF, 2018	2017 California Wilsdfire, 2018 Montecito Mudslide	2	2	0	2	0	0	0
Johnson, 2014	Simulated California Wildfire	0	1	1	1	1	1	1
Kolden and Henson, 2019	2017 Thomas Fire	2	2	0	2	2	0	0
Moftakhari & AghaKouchak, 2019	1953-2005 California Wildfires	1	0	0	0	0	0	0

4.5 Transportation Infrastructure

Wildfire events can physically damage transportation infrastructure including roads, bridges, guardrails, signage, culverts, and other structures and equipment (Lissade, et al., 2019). Additionally, infrastructure such as roads can be damaged by increased traffic of heavy vehicles, and vehicles that exceed weight limits, used during emergency response or recovery efforts. Costs associated with transportation infrastructure losses include repair costs, clean-up costs, and costs related to service disruptions. Mitigation actions specifically to reduce transportation infrastructure losses primarily include infrastructure hardening and defensible space (Lissade, et al., 2019).

Transportation infrastructure exposure, losses, mitigation actions, and effectiveness at reducing losses, are not systematically tracked in publicly available dataset for California and we found no studies in the peer-reviewed literature on this topic (Table 4.5). CalTrans maintains an internal database on contracts to repair damaged transportation infrastructure within their jurisdiction that includes damage from wildfire. Information on losses may also be included in BAER and WERT reports.

Finding: *We found no databases or studies on the exposure of transportation infrastructure to California wildfires.*

> ***Conclusion:*** *An estimate of the total transportation infrastructure that has been exposed to wildfires in California could be calculated with existing datasets of wildfire perimeters and road networks.*

> ***Finding:*** *Select data on transportation infrastructure losses and mitigation actions to reduce losses is collected by CalTrans and can be found in BAER and WERT reports.*

> ***Conclusion:*** *There is no single, comprehensive database systematically tracking data on transportation infrastructure losses or their associated costs for wildfires in California.*

> ***Conclusion:*** *An estimate of the total state-wide costs of transportation infrastructure losses, and mitigation actions to reduce losses in California, would require compiling existing data from multiple sources, and possibly new data collection.*

> ***Recommendation:*** *California should consider creating and maintaining a comprehensive state-wide database to track all transportation infrastructure losses and their associated costs for wildfires in California.*

Table 4.5. Summary of select California-specific literature relevant to transportation infrastructure losses from wildfire, from this review.

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Exposure	Losses		Prevention and Mitigation Actions		Effectiveness at Reducing Losses	
Source	**Wildfire**	**Numeric**	**Numeric**	**Dollars**	**Numeric**	**Dollars**	**Numeric**	**Dollars**
BAER Burned Area Reports Database	Wildfires on federal land	0	1	1	1	1	1	1
Buckley et al., 2014	Simulated Wildfires	0	1	1	1	1	1	1
CA Watershed Emergency Response Team (WERT)	CA wildfires on non-federal land	2	2	2	2	2	0	0
Caltrans	Select California Wildfires	0	3	3	0	0	0	0
Kolden and Henson, 2019	2017 Thomas Fire	2	2	0	2	2	0	0
Lissade, et al., 2019	Large Wildfires	0	2	2	0	0	0	0

4.6 Losses from Wildfire Smoke and Post-wildfire Landslides

Wildfire smoke and post-wildfire landslides can damage buildings and infrastructure, resulting in costs associated with damage repair, clean up, and service disruptions (Table 4.6) (Aspen Environmental Group, 2008; Kean et al., 2019; Sathaye et al., 2011). Losses can be avoided through prevention and mitigation of wildfires and post-wildfire landscape rehabilitation to reduce the risk of landslides (Chapter 3). There do not appear to be any specific mitigation actions to reduce losses when buildings and infrastructure are exposed to wildfire smoke or post-wildfire landslides.

Building and infrastructure exposure, losses, mitigation actions, and effectiveness at reducing losses for wildfire smoke and post-wildfire landslides are not systematically tracked in California but some information is available in individual studies and reports (Table 4.7). Most of available information is for the 2018 Montecito mudslide (ICF, 2018; Kean et al., 2019; Lukashov et al., 2019; Niehaus, 2018; Tiwari et al., 2020).

Table 4.6. List of notable historic landslides in California. Post-fire landslides marked in red. Source: 2018 California State Hazard Mitigation Plan

Location	Year	Impact[a]
Montecito	2018	Post-Thomas Fire debris flows. 129 homes destroyed, 307 homes damaged, 21 fatalities.*
Camarillo Springs	2014	Post-Springs Fire debris flows. 10 homes destroyed, 6 homes damaged.
La Canada	2009-2010	Post-Station Fire debris flows with early damage claims at $58 million and Los Angeles County cleanup costs at over $30 million (2009 dollars).
Pacifica	2007	Devil's Slide: bypass construction of $325 million (See: San Francisco Chronicle).
La Conchita	2005	30 homes destroyed, 10 fatalities.
Laguna Beach	2005	18 homes destroyed, 8 homes damaged. Slide repair cost: $21 million. Cost of damage: $35 million.
San Bernardino	2003	Post-Grand Prix/Old Fire debris flows on Christmas Day. 16 fatalities, 52 homes and 32 trailers damaged; more than $100 million in damages.
Mission Peak	1998	--
Laguna Niguel	1998	9 homes and 57 condominiums destroyed. $12 million awarded to homeowners in lawsuit; $16 million to stabilize slope[b]
Rio Nido	1998	37 homes destroyed. 140 residents evacuated[c]
Laguna Beach	1998	18 homes destroyed, damaged 300 others. Two fatalities.
El Dorado County Hwy 50	1997	Destroyed Highway 50; $32 million in repair and economic losses.[i]
La Conchita	1995/2005	6 homes destroyed.[e]
Anaheim Hills	1993	30 homes destroyed, 200 homes damaged. Cost: $12 million.
Bay Area	1982	Debris flows and landslides on private and public property Cost: $172 million[j]
Big Rock Mesa	1979/1983	13 homes destroyed. Cost: $114 million. Damage to Highway 1 cost: $1.26 billion[f]
Laguna Beach	1978	19 homes destroyed, 45 homes damaged. Cost: $62 million[g]
San Fernando	1971	Cost: $354 million
Saugus-Newhall	1971	Cost: $312 million
Palos Verdes	1956, intermittently	More than 100 homes severely damaged or destroyed. Cost: $34 million; $68 million in damage settlements[h]

Source: California Geological Survey, or as noted

> ***Finding:*** *We found no datasets that systematically track building and infrastructure losses and costs from wildfire smoke or post-wildfire landslides in California.*

> ***Conclusion:*** *An estimate of the total state-wide costs of building and infrastructure losses and costs in California would require compiling existing data from multiple sources, and possibly new data collection.*

> ***Recommendation:*** *California should consider including losses from wildfire smoke and post-wildfire landslides in state-wide datasets tracking the losses and associated costs of wildfires.*

Table 4.7. Summary of select California-specific literature relevant to building and infrastructure post-wildfire landslide losses, from this review.

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Exposure	Losses		Prevention and Mitigation Actions		Effectiveness at Reducing Losses	
Source	**Wildfire**	**Numeric**	**Numeric**	**Dollars**	**Numeric**	**Dollars**	**Numeric**	**Dollars**
ICF, 2018	2018 Montecito Mudslide	2	2	0	2	0	0	0
Kean et al., 2019	2018 Montecito Landslide	2	2	0	0	0	0	0
Lukashov et al., 2019	2018 Montecito Landslide	0	2	2	0	0	0	0
Niehaus, 2018	2018 Montecito Landslide	2	2	2	0	0	0	0
Tiwari et al., 2020	2018 Montecito Landslide	0	2	2	0	0	0	0

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Chapter 5

Health Impacts

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5.1 Chapter Scope

This chapter provides an understanding of the health consequences of wildfires and the mechanisms by which they degrade human health. Wildfires pose significant health threats to communities through multiple, interdependent pathways (Figure 5.1). Expressed in terms of morbidity (disease) and mortality (death), the health effects of wildfire are startling. In particular, the pernicious effects of smoke constitute a massive public health burden—one that disproportionately places disadvantaged and minority communities at risk. After looking at the societal and human costs of fires and discussing the limitations of current research, this chapter examines the impact of fires under contemporary conditions, including the COVID-19 pandemic and seasonal influenza. Drawing throughout from peer-reviewed and government sources, the chapter concludes with the most important findings of this literature review as well as an examination of the research gaps and recommendations for policymakers.

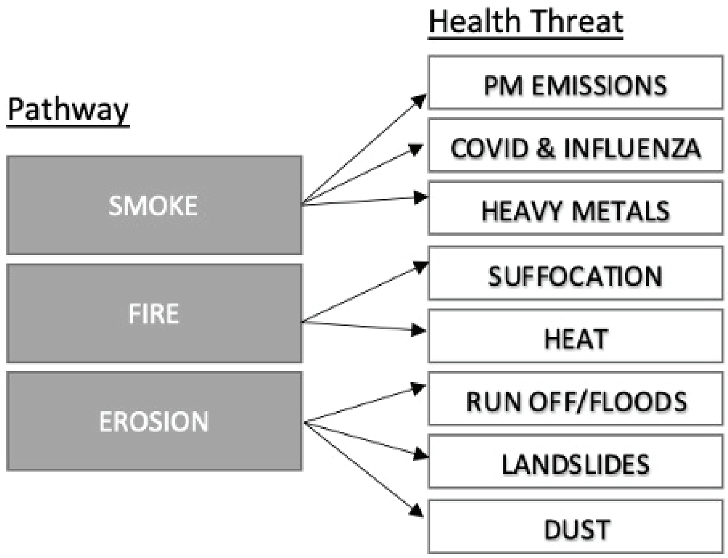

Figure 5.1. *Pathways and mechanisms by which wildfires threaten public health.*

5.2 Health Impacts of Wildfire Smoke

Smoke is a primary pathway by which wildfires threaten public health. When wildfires burn they release tremendous amounts of particulate matter, with both short-term (acute) and long-term (chronic) health consequences (Table 5.1). In the short-term, inhalation of wildfire smoke can cause mild symptoms, such as a burning throat, or may even result in death, such as sudden cardiac arrest, in people as young as 35 years old (Jones et al., 2020). The chronic impacts of wildfire smoke, such as diabetic complications (Yao et al., 2020) or cancer, are still being understood.

One dangerous component of wildfire smoke is particulate matter of 2.5 microns or less ($PM_{2.5}$), which is roughly 1/30th the width of a human hair. The 2011 National Emissions Inventory conducted by the U.S. EPA found wildfire smoke was the largest contributor of $PM_{2.5}$ in the United States (EPA, 2011). $PM_{2.5}$ is small enough to travel to the base of the lungs and cross over into the bloodstream, making it capable of reaching every organ in the body.

The health impacts of decreased air quality, particularly the impacts of $PM_{2.5}$, have been extensively studied in the broader literature on air pollution. Globally, $PM_{2.5}$ is estimated to have caused 4.2 million premature deaths in 2016 (Schraufnagel, 2018). Exposure to $PM_{2.5}$ is associated with a wide range of health impacts depending on the intensity and exposure duration. Health impacts vary in type and severity including lung inflammation, cardiovascular disease, stroke, allergies, autoimmune disorders, diabetes, Alzheimer's disease, lower childhood IQ, autism, lung cancer, bladder cancer, and childhood leukemia (Figure 5.2; Wu, 2018).

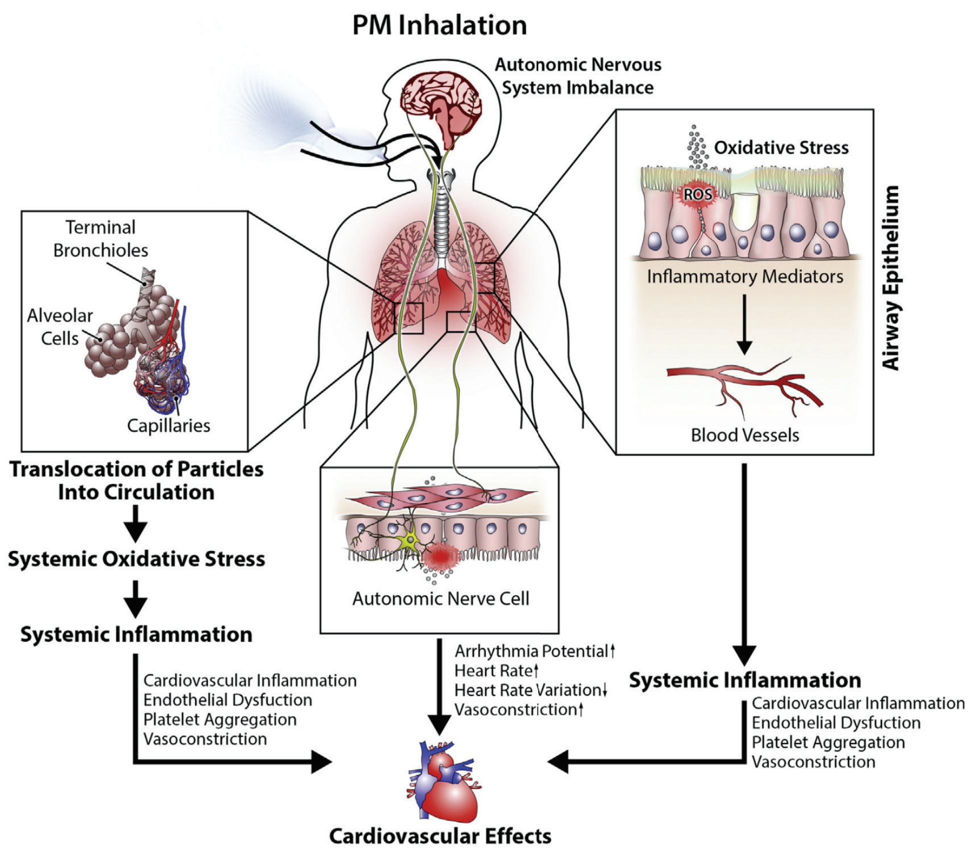

Figure 5.2. *Health impacts of $PM_{2.5}$. Particulate matter is inhaled and deposits in the deep lung. The smallest particles in $PM_{2.5}$ can enter circulation via the bloodstream at the level of the alveoli in the lung, resulting in oxidative stress and subsequent lung and systemic inflammation. Source: Wu (2018).*

Studies focused on California wildfires have associated wildfire smoke with both excess deaths (mortality) and excess illnesses (morbidity), primarily as a result of increased respiratory (e.g., asthma, pneumonia), cardiovascular (e.g., heart attacks), and cerebrovascular (e.g., stroke) complications (Youssouf et al., 2014; Liu et al., 2015; Reid et al., 2016; Cascio, 2018). See Table 5.1 for a non-exhaustive summary of health impacts from wildfires. The increase in $PM_{2.5}$ during the 2008 Northern California wildfires was associated with an increase in emergency room visits for respiratory diseases such as asthma and chronic obstructive pulmonary disease, or COPD (Figure 5.3). A rise in out-of-hospital cardiac arrests has also been linked to increased $PM_{2.5}$ exposure (Jones et al., 2020). Preliminary evidence suggests even young adults show an increase in inflammatory biomarkers (associated with many types of diseases) when exposed to a wildfire (Prunicki, 2020). Exposure to wildfire smoke may also negatively impact pregnancy and result in a decreased birth weight, as occurred during the 2003 Southern California wildfires (Holstius et al., 2012). Particularly vulnerable populations demonstrate the most profound complications stemming from smoke exposure. (Prunicki, 2020; Holstius et al., 2012).

Table 5.1. *Examples of health impacts from wildfire smoke exposure.*

Health Outcome	**Population**	**Exposure**	**Finding**	**Reference**
Respiratory/ Cardiovascular	All Ages	10-µg/m3 increase in PM2.5 from wildfire	Increased ambulance dispatches during wildfires for respiratory and cardiac issues within 1 hour of exposure.	Yao, 2020
Respiratory	Children 0-12 y/o	Santa Ana wind-driven Lilac Fire in 2017	Increase in respiratory-related clinic and ER visits	Leibel, 2020
Respiratory	All Ages	Southern California wildfires of 2003	Most for ages 65– 99 years and ages 0–4 years, followed by ages 20–64 years. Increase of 70 ug/m3 PM assoc with 34% increase in asthma admissions;	Delfino, 2009
Cardiovascular	> 65 y/o	Wildfires in CA, 2015	Increased cardiovascular (ischemic heart disease, dysrhythmia, heart failure, PE) and cerebrovascular (stroke)	Wettstein, 2019
Cardiovascular	> 35 y/o, male and female, low socioeconomic status trends	Heavy wildfire smoke across multiple days, strongest on lag day 2	Increase in out-of-hospital cardiac arrests (heart suddenly stops, 92% die immediately) from wildfire exposure	Jones, 2020
Respiratory/ Cardiovascular	Adults	0-5 days of wildfire exposure	Increase in asthma, chronic obstructive pulmonary disease (COPD), pneumonia, acute bronchitis, cardiopulmonary symptoms and heart failure	Rappold, 2011
Pregnancy	Neonates	Colorado fires, 2007–2015	Exposure to wildfire smoke Decreased birth weight or pre-term birth depending on the trimester of wildfire smoke exposure	Abdo, 2019
Pregnancy	Neonates	California's South Coast Air Basin, 2001-2005	Smoke exposure linked to lower birth weights	Holstius, 2012

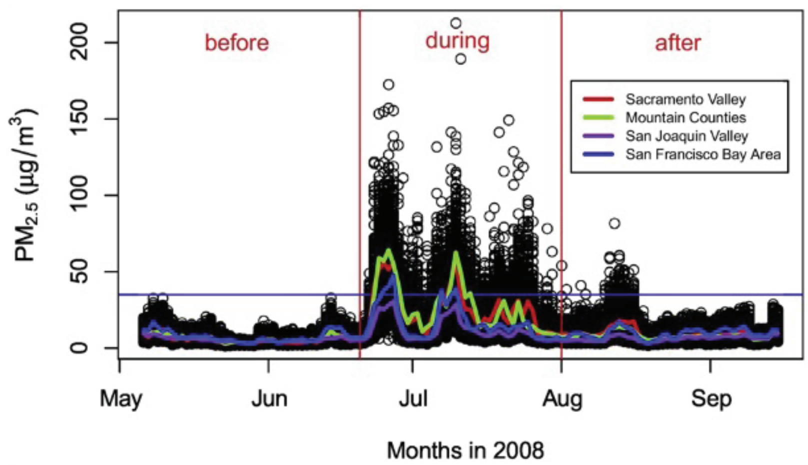

Figure 5.3. *$PM_{2.5}$ levels from the Northern California wildfires June 20–July 31, 2008. An increase of 10 µg/m3 during the wildfires was associated with increased risk of an emergency room visits for asthma and COPD. Source: Reid (2016).*

While particulate matter is the most researched constituent in smoke, it is important to note that other harmful compounds, like benzene and volatile organic compounds (VOCs) can be present and pose significant health threats. There is evidence that benzene and other VOCs can be created by burning biomass and flame contact with structures (Hill et al., 2020). Wildfire smoke can also contain carbon monoxide, lead, mercury, and other heavy metals and toxins (Viswanathan et al., 2006; Kristensen and Taylor, 2012; Broyles, 2013), all of which have been associated with detrimental health impacts. For example, ash collected from the 2012 Williams Fire in Los Angeles contained substantial remobilized trace metals. These trace metals may be carried by winds and deposited in water bodies, increasing exposures for humans and aquatic organisms (Odigie, 2014).

> ***Finding:*** *Wildfire smoke consists primarily of $PM_{2.5}$, which can enter the bloodstream and trigger dysfunction throughout the body.*

> ***Finding:*** *Widespread health impacts of wildfire smoke exposure range from mild illness to death. Both respiratory and cardiovascular emergency room visits and hospital admissions are associated with wildfire smoke exposure.*

> ***Finding:*** *Health outcome data is not easily accessible or available in real time, hindering the association with the health impacts of wildfire smoke exposure.*

> ***Conclusion:*** *Wildfire smoke exposure has both short-term and long-term health impacts. New discoveries regarding smoke impacts on health are ongoing and the field remains an active area of investigation.*

Conclusion: *Additional research to address gaps in both acute and chronic health impacts is needed.*

Conclusion: *Because the composition of the particulate matter and the composition of the smoke varies depending on the source, research is needed to determine the toxicity of various sources of wildfire smoke on health.*

Recommendation: *California should create a centralized mechanism to track real-time association of acute health outcomes (emergency room visits, hospital admissions, outpatient appointments, cardiac arrests) with wildfire smoke exposure to fully account for smoke impacts.*

5.2.1 Vulnerable Populations

Populations at greater risk of developing health complications from wildfire smoke exposure include the elderly (Delfino et al., 2009; Kochi et al., 2012; Wettstein et al., 2018; Jones et al., 2020), children (Delfino et al., 2009; Hutchinson et al., 2018; Leibel, 2019), people with pre-existing medical conditions (Künzli et al., 2006), and disadvantaged communities (Liu et al., 2017; Jones et al., 2020). Of 7,931 surveyed census tracts in California, every one of the 1,986 tracts considered socioeconomically disadvantaged ranked above the 75th percentile for pollution burdens (CalEnviroScreen 3.0, 2018). This chronic exposure is linked to a higher incidence of asthma and other comorbidities, making these communities more vulnerable to acute or triggering events like wildfires. Additionally, the lack of access to medical care characteristic of socioeconomically disadvantaged communities can worsen the effects of breathing conditions like asthma, increasing the chance of serious adverse outcomes, including death. Some populations are vulnerable as a result of an inability to take prevention or mitigation actions due to socioeconomic factors. These groups include outdoor workers, people experiencing homelessness, and others without access to clean air indoor spaces (CDPH, 2019; National Academies Press, 2019; Riden et al., 2020).

Finding: *Vulnerable populations are more susceptible to the health impacts of wildfire smoke exposure.*

Conclusion: *The impacts of smoke on vulnerable populations, as well as which additional populations are also at higher risk, is poorly understood. However, the body of evidence on these topics is rapidly advancing.*

Recommendation: *The State should consider supporting research to determine if additional previously unaccounted vulnerable populations exist and to target resources to mitigate their exposure.*

5.2.2 Special Consideration: Firefighters

Occupational exposure to wildfires and smoke can significantly impact the health of first responders. The risk is highest for those on the fire line (Broyles, 2013). However, support personnel positioned at incident command posts or base camps, which can house thousands of workers for weeks at a time, are also at elevated risk (McNamara et al., 2012; Navarro, et al., 2019). When responding to fires, firefighters often work 16-hour days and can spend more than two weeks on the fire line. This situation creates conditions for extremely high-intensity exposure for a sustained duration—conditions particularly damaging to health. The consequences of elevated exposure to smoke also extend to people who supply and coordinate the frontline firefighters.

Wildland firefighters face significant short- and long-term health losses as a result of occupational exposure. Short-term health losses include physical injury and burns, as well as effects related to smoke exposure of the respiratory and cardiovascular systems, exhaustion, and mental health (Aisbett et al., 2012; Adetona et al., 2016; Groot et al., 2019). Long-term consequences can include increased risk of hypertension, post-traumatic stress disorders, cancer, and cardiovascular disease (Pukkala et al., 2014; Tsai et al., 2015; Adetona et al., 2016; Navarro, Kleinman, et al., 2019). Long-term health losses from chronic exposure are relatively understudied in firefighters and other disproportionately exposed populations (Adetona et al., 2016).

Several entities systematically track firefighter injuries and fatalities from which cases associated with California wildfires can be extracted. Butler et al. (2017) provides a comparison of the types of data collected by these databases. The costs of injury and illness to firefighters includes medical costs and lost work, as well as costs to fire units and departments in terms of medical claims and reductions in staff due to injury or illness (Butry et al., 2019). In addition, incarcerated firefighters may be more likely to incur certain (object-induced and inhalation) injuries while fighting fire compared to non-incarcerated firefighters (Vesoulis, 2018). We found no studies that estimate the cost of health losses to wildland firefighters as a result of exposure to wildfires or wildfire smoke in California.

> ***Finding:*** *Chronic exposure to wildfire smoke in firefighters is associated with increased risk of acute and chronic adverse health outcomes, including cancer and mental health disorders.*

> ***Finding:*** *No research was identified that estimates the cost of health losses to wildland firefighters as a result of exposure to wildfires or wildfire smoke in California.*

> ***Conclusion:*** *Overall, large gaps in knowledge exist regarding the long-term health impacts from smoke exposure.*

> ***Conclusion:*** *Additional research is needed to understand the long-term health impacts of chronic smoke exposure, especially in firefighters.*

> ***Recommendation:*** *The State should monitor individual cumulative smoke exposure history for firefighters and others chronically exposed to wildfires.*

5.2.3 Smoke from Prescribed Fire

Smoke can also be produced during controlled burn or prescribed fire events, aimed to reduce fuel loads and mitigate risk of large wildfires. Given prescribed fires burn slower, are more controlled, and only utilized under moderate conditions, there are presumably more transient impacts on air quality; the controlled conditions allow for atmospheric dispersions to keep $PM_{2.5}$ concentrations low compared with those of wildfire (Liu et al., 2017). As a result, prescribed fires would tend to produce lower per-day emissions—with lower risk of adverse health and safety impacts—than potentially uncontrollable wildfires.

While there are few studies on the health impacts of prescribed fire, a connection between prescribed burns and increased hospital visits for asthma has been noted (Huang et al., 2019). A retrospective study found adolescents exposed to a wildfire had greater immune dysregulation and clinical symptoms than those exposed to a prescribed burn (Prunicki, 2020). These studies, however, do not extrapolate findings to estimating impacts of more frequent prescribed fires.

> ***Finding:*** *There is limited research on the health impacts of exposure to smoke from prescribed fire.*

> ***Finding:*** *Retrospective studies find that exposure to smoke from prescribed fires is associated with public health consequences, but given the strict regulations required for prescribed burning, the health impacts are expected to be less than uncontrolled wildfires.*

> ***Conclusion:*** *The balance in health impact tradeoffs between a significant scaling up of prescribed fire and uncontrolled wildfires is not fully realized.*

> ***Recommendation:*** *California should support research to better quantify the health-related impacts of exposure to smoke from prescribed fire.*

5.2.4 Wildfire Smoke Plume Spread

The population exposed to a smoke event can differ significantly from the population exposed to heat or flames. Depending on the terrain and weather conditions, wildfire smoke plumes can spread well beyond the perimeter of the wildfire and persist long after flames have been extinguished. Wildfires that primarily burn in unpopulated areas (e.g. the 2013 Rim Fire), can generate little heat exposure to the public while still producing a sizable smoke plume and expose large population centers to elevated particulate matter concentrations (Navarro et al., 2016). This phenomenon can be observed at very large scales; when smoke is carried by the wind, California populations can be impacted by wildfires burning outside of the state and vice versa (Miller et al., 2007; Moeltner et al., 2013). Figure 5.4 shows broadly-distributed smoke plumes generated from wildfires occupying a relatively small area.

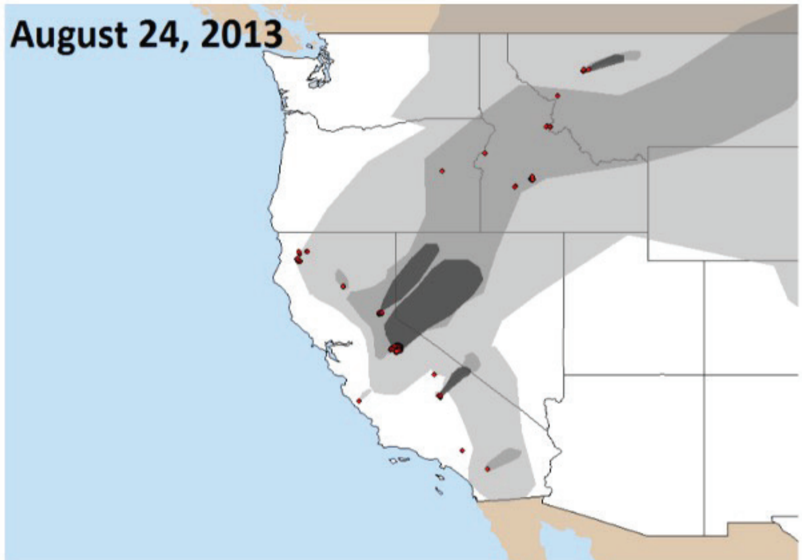

Figure 5.4. Smoke plume dynamics of the 2013 Rim Fire. Red spots show location of satellite detected wildfires, grey polygons show extent and density of wildfire smoke. The many wildfires burning in California occupied a small area of the state, but the smoke from those fires covered the majority of California and spread into several other states. Source: Figure 2 from Miller et al. (2007).

> ***Finding:*** *Wildfire smoke plumes can travel thousands of miles from the source and impact the health of those within and outside of California.*

5.2.5 Smoke Plume Tracking

Wildfire smoke plumes are tracked daily at the national level by the National Oceanic and Atmospheric Administration's (NOAA) Office of Satellite and Product Operations Hazard Mapping System (HMS Smoke), from which California-specific data can be extracted. Population exposure to wildfire smoke is not systematically tracked in California, but has been documented in individual reports and studies. Vargo (2020) provides a dataset of potential smoke exposure of U.S. populations for years 2010–2019 from which California data can be extracted. Strikingly, Vargo estimates that as many as 240 million people are exposed to some amount of smoke annually (Figure 5.5a). This study demonstrates wildfire smoke impacts all counties in California, with the greatest burden in Northern California, particularly Siskiyou County (Figure 5.5b). Additional studies at a regional or national scale find California to be one of states most severely affected by wildfire smoke (Miller et al., 2007; Liu et al., 2017; Fann et al., 2018).

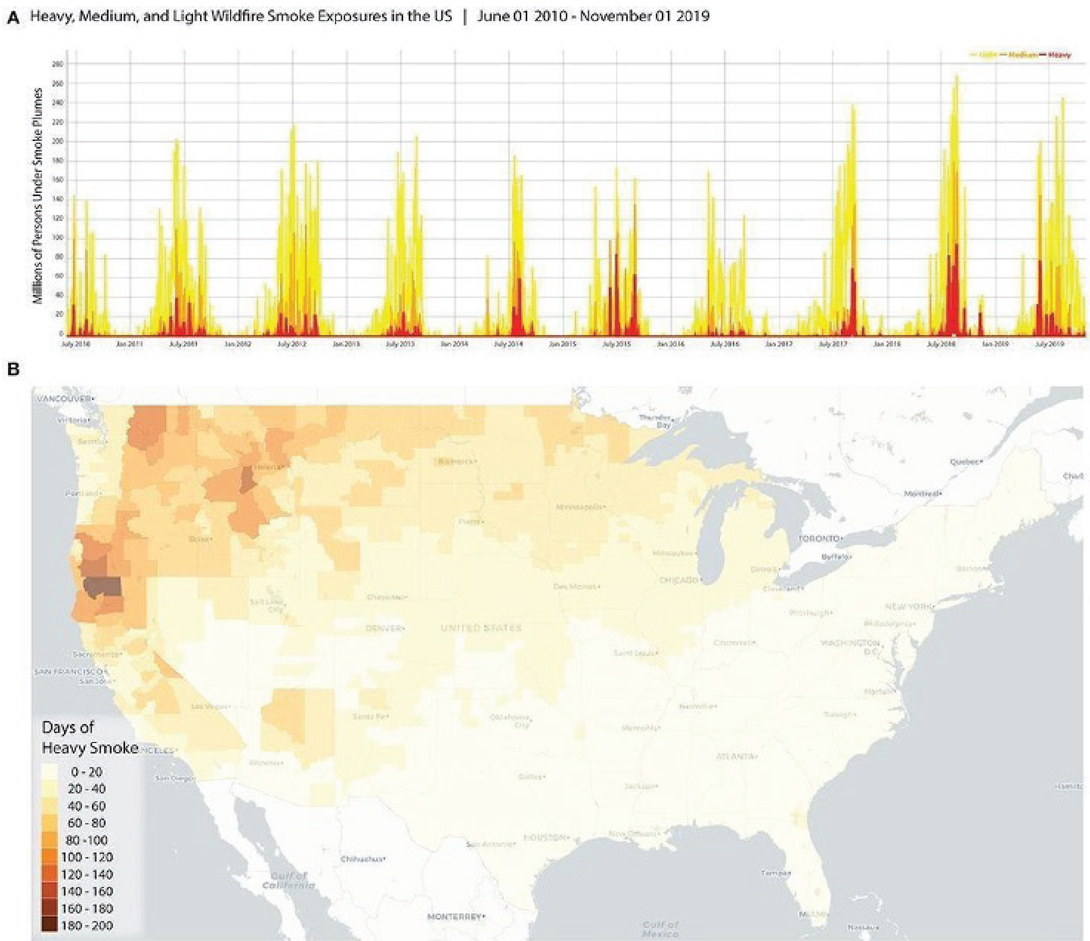

__Figure 5.5.__ Potential smoke exposure of populations. (a) Estimates of number of individuals exposed to light, medium, and heavy smoke from 2010-2019. (b) Geographic distribution of multi-day smoke exposures, by county. Source: Vargo (2020).

Many studies estimate smoke exposure from satellite images or simulations. These datasets demonstrate the area and number of people affected, but cannot directly measure the severity or extent of the exposure (Liu et al., 2015; National Academies Press, 2019). Regulatory stationary air quality monitors offer more precise, ground-level measures but may not provide adequate spatial or temporal coverage to capture the boundaries of a dynamic smoke plume. Emerging technologies, such as PurpleAir, offer personal stationary air quality monitors and publicly accessible data, and may represent a way to fill these gaps.

> ***Finding:*** *Centralized tracking of pollutant exposures due to wildfire smoke does not exist at the state level.*

5.2.5.1 Quantifying Social Burdens and Health Impacts from Smoke Exposure

Public healthcare datasets offer a limited picture of excess cases of illness or death related to smoke exposure. These metrics are only a subset of the possible health outcomes, representing the most severe cases while omitting the consequences of repeated or chronic exposure, including diminished quality of life. Therefore, the full public health impact and social burden of wildfire smoke is systematically undercounted due to its difficulty to measure (Figure 5.6). Morbidity and indirect mortality from wildfire smoke are not systematically tracked in California.

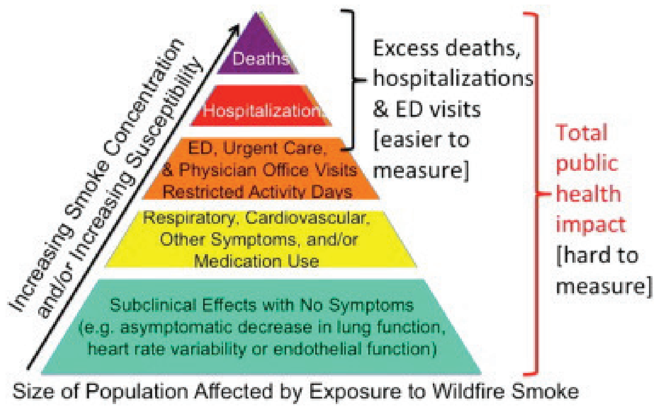

Figure 5.6. *Clinical and sub-clinical impacts of wildfire smoke or $PM_{2.5}$. Source: Cascio (2018).*

Wildfire smoke from numerous fires over the past three decades have impacted health across California, indicating health losses from wildfire smoke are a common and chronic issue (Kochi et al., 2012; Richardson et al., 2012; Fann et al., 2018; Limaye et al., 2019). For example, smoke from the 2003 Southern California wildfires caused 133 excess cardiorespiratory-related deaths (Kochi et al., 2012). This excess fatality count is roughly 5.5 times greater than the 24 fatalities attributed to heat exposure during this event—and 1.5 times as many deaths as the 85 heat exposure fatalities reported in California's deadliest wildfire on record (CAL FIRE). One economic analysis of Colorado fires in 2012, in which 174 fatalities occurred, placed an upward estimate of the costs at $4.27 billion (Limaye et al., 2019). Similarly, a 2018 paper attempted to estimate the total cost of short-term and long-term wildfire consequences in the United States, based on exposure to $PM_{2.5}$ from wildfire (Figure 5.7). These authors estimated the annual national short-term costs of wildfire smoke at between $12 and 20 billion and the long-term costs due to fires in a single year at between $76 and 130 billion (Fann et al., 2018). Another study valued the smoke impacts from the 2009 Station Fire to be $9.50 per person per day using a "cost of illness" method and $84.42 per person per day using a "willingness to pay" method (Richardson et al., 2012).

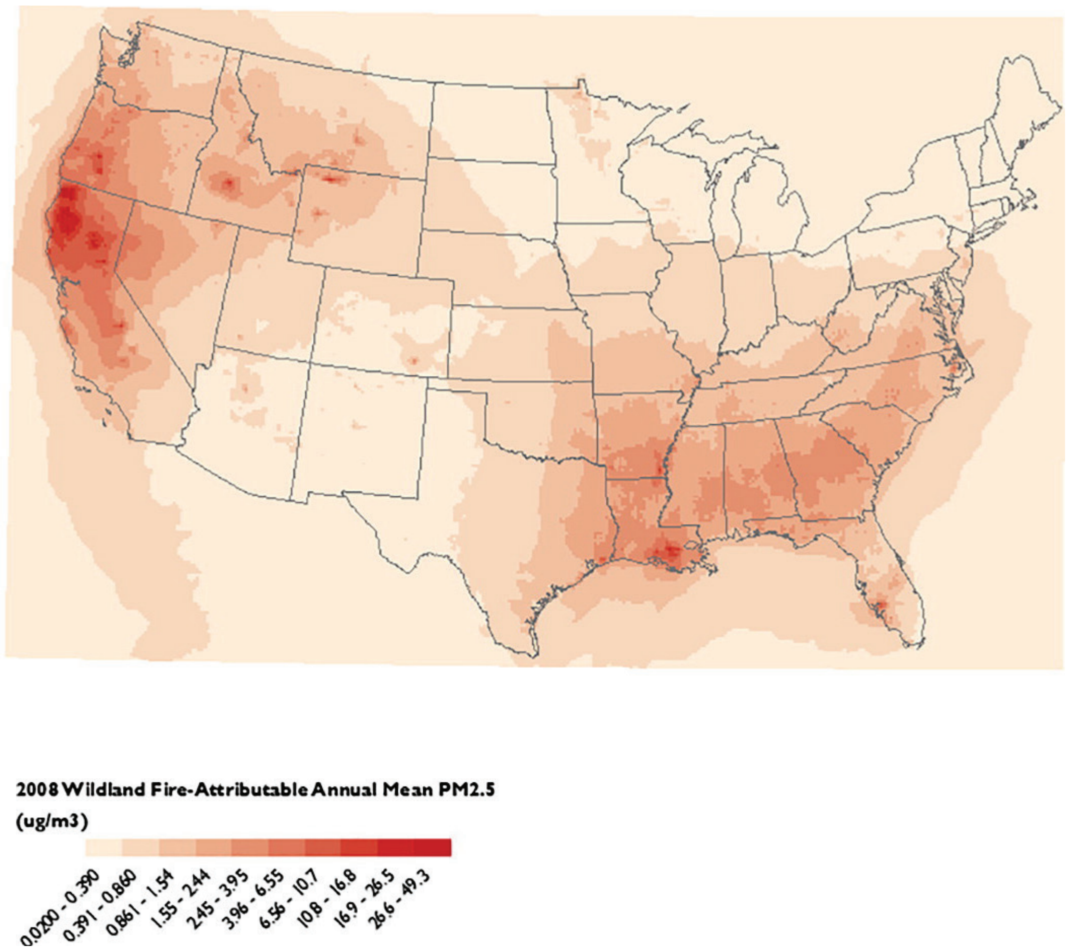

Figure 5.7. *Annual $PM_{2.5}$ concentrations attributable to wildfires. Source: Fann et al. (2018).*

> ***Finding:*** *The immediate and long-term economic consequences from wildfire smoke health impacts are estimated to approach $100 billion per year nationally.*

> ***Finding:*** *The health impacts from wildfire smoke are likely much greater than health impacts from heat or flame exposure.*

> ***Finding:*** *The full public health impact of wildfire smoke is systematically undercounted due to its difficulty to measure, and is not systematically tracked in California.*

> ***Conclusion:*** *There are large gaps in our understanding of the health impacts of wildfire smoke exposure and associated costs.*

> ***Recommendation:*** *The State should track healthcare costs and lost productivity associated with wildfires to more accurately account for the social and health burdens.*

5.3 Health Losses from Heat and Flame Exposure

5.3.1 Direct Heat Exposure

Direct exposure to flames and/or the intense heat generated by wildfires can cause physical injury and death. Wildfires that burn into populated areas can also cause injury and death by exposing the public to direct heat sources, burning debris, ash, and low oxygen conditions (Shusterman, et al., 1993; Thomas et al., 2017). Health losses from wildfire exposure include trauma, burns, smoke inhalation, and eye damage (Shusterman, Kaplan and Canabarro, 1993). Wildfire perimeters are systematically tracked at the national level by the US Geological Survey and the National Oceanic and Atmospheric Agency's Office of Satellite and Product Operations Hazard Mapping System. In California, the California Department of Forestry and Fire Protection (CAL FIRE) also respond to and map fire perimeters. Population exposure to wildfires in California is not systematically tracked at the state level.

5.3.2 Injuries and Fatalities from Heat and Flames

In recent years, there has been an associated increase in the lethality of wildfire—five of the 20 deadliest fires in California history have come in the past five years. Direct fatalities from wildfire are tracked by CAL FIRE. Cases of injury or death are typically documented in individual medical and coroner records. The CAL FIRE Incidents Dataset systematically tracks counts of civilian fatalities and injuries from wildfires responded to by CAL FIRE. Individual studies of specific wildfires provide additional details on health losses due to direct heat exposure. These datasets contain statistics like those of the 2018 Camp Fire, the deadliest wildfire in California, which killed 85 civilians (Table 5.2).

Official counts of injury and fatalities due to natural disasters, such as wildfires, are generally underestimated due to challenges in collecting data in the midst of an emergency and the difficulty in quantifying health losses that occur far from the disaster. And injury and death from exposure to wildfire are not limited to the time and place of the wildfire event itself. Reporting by the *Chico Enterprise-Record* suggests there could be at least 50 additional deaths due to the 2018 Camp fire based on wrongful death claims filed against PG&E (Kaenel, 2020). National organizations are currently undertaking studies to review best practices for assessing the full health impacts of disaster.

Table 5.2. *Top 20 deadliest California wildfires as of September 2020.*

	FIRE NAME *(CAUSE)*	DATE	COUNTY	ACRES	*STRUCTURES*	DEATHS
1	**CAMP FIRE** *(Powerlines)*	November 2018	Butte	153,336	18,804	**85**
2	**GRIFFITH PARK** *(Unknown)*	October 1933	Los Angeles	47	0	**29**
3	**TUNNEL - Oakland Hills** *(Rekindle)*	October 1991	Alameda	1,600	2,900	**25**
4	**TUBBS** *(Electrical)*	October 2017	Napa & Sonoma	36,807	5,643	**22**
5	**NORTH COMPLEX** *(Under Investigation)**	August 2020	Butte, Plumas, & Yuba	314,949	2,342	**15**
6	**CEDAR** *(Human Related)*	October 2003	San Diego	273,246	2,820	**15**
7	**RATTLESNAKE** *(Arson)*	July 1953	Glenn	1,340	0	**15**
8	**LOOP** *(Unknown)*	November 1966	Los Angeles	2,028	0	**12**
9	**HAUSER CREEK** *(Human Related)*	October 1943	San Diego	13,145	0	**11**
10	**INAJA** *(Human Related)*	November 1956	San Diego	43,904	0	**11**
11	**IRON ALPS COMPLEX** *(Lightning)*	August 2008	Trinity	105,855	10	**10**
12	**REDWOOD VALLEY** *(Power Lines)*	October 2017	Mendocino	36,523	544	**9**
13	**HARRIS** *(Undetermined)*	October 2007	San Diego	90,440	548	**8**
14	**CANYON** *(Unknown)*	August 1968	Los Angeles	22,197	0	**8**
15	**CARR** *(Human Related)*	July 2018	Shasta County, Trinity	229,651	1,614	**8**
16	**ATLAS** *(Powerline)*	October 2017	Napa & Solano	51,624	781	**6**
17	**OLD** *(Human Related)*	October 2003	San Bernardino	91,281	1,003	**6**
18	**DECKER** *(Vehicle)*	August 1959	Riverside	1,425	1	**6**
19	**HACIENDA** *(Unknown)*	September 1955	Los Angeles	1,150	0	**6**
20	**LNU Lightning Complex** *(Under Investiagation)**	August 2020	Napa/Sonoma/Yolo/Stanislaus/ Lake	363,220	1,491	**5**

** Fires with the same death count are listed my most recent. Several fires have had 4 fatalties, but only the most recent are listed.
***This list does not include fire jurisdiction. These are the Top 20 regardless of whether they were state, federal, or local responsibility.
* Numbers not final

10/1/2020

Costs associated with health impacts can be estimated using a variety of metrics including costs of healthcare, the willingness to pay to avoid the health impact, or the value of a statistical life. Regardless of method used, reasonable cost estimates rely on accurate counts. FEMA maintains a database of grants to individuals intended to help pay for medical, dental, and funeral expenses caused by federally declared disasters, including California wildfires. We found no studies that assess the costs of the physical health losses from wildfire, regardless of method.

> ***Finding:*** *We found no studies that reported the costs of health losses in California from heat and flame exposure, though FEMA databases may contain relevant data for further analysis.*

> ***Finding:*** *Counts of injury and fatalities due to direct heat and flame exposure are systematically tracked by CAL FIRE, but counts may not include wildfires in federal or local jurisdictions, and may undercount especially those deaths which occur later.*

5.3.3 Mental Health Impacts

Wildfires and related events—including landslides, emergency evacuations, and the loss of homes—are traumatic events that can impact mental health (National Academies Press, 2019). The mental health impacts include anxiety, depression, and post-traumatic stress disorder (PTSD). These symptoms can occur in both adults and children, and significantly degrade quality of life. Mental health impacts may span beyond those directly impacted; mental health impacts of secondary trauma can occur for those living adjacent to wildfire-affected areas, and even for those witnessing news media (Hill et al., 2020). Those with pre-existing mental illnesses may also be disproportionately vulnerable to the psychological trauma associated with wildfire events.

Post-wildfire mental health impacts are not systematically tracked in California, nor are the associated economic losses. One study found that after a wildfire, of 379 evacuees, 62.5% self-reported PTSD, whereas 29.1% met criteria for PTSD, 25.5% for depression, and 43.6% for insomnia (Belleville et al., 2019). Other studies confirm significant mental health impacts both short-term and long-term post-wildfire (Moosavi, 2019; Vio, 2020; Laugharne, 2011; Scher, 2009; Marshall, 2007; Jenkins, 2009). The literature we reviewed does not give estimates for mental health costs due to wildfire generally, or as case studies.

> ***Finding:*** *There is no research that estimates the costs associated with mental health impacts from wildfires in California.*

> ***Conclusion:*** *Understanding the prevalence, severity, and associated healthcare and productivity costs of the mental health impacts of wildfire exposure represents an important gap in the literature.*

5.4 Post-Fire and Secondary Health Consequences

5.4.1 Overview

Post-fire landscapes present multiple vulnerabilities, creating both near-term and long-term threats to individuals and communities. The destruction of the organic material that comprises topsoil and the foliage holding soil in place makes burned landscapes particularly prone to erosion. Water erosion can trigger landslides, debris flows, and floods threatening public health. Often triggered by the first large post-fire rain, these events begin within the burn perimeter, but can ultimately affect other areas at a significant distance. There are systematic assessments of post-fire landslide risk conducted for each wildfire by the California Department of Conservation (DOC 2020b).

Wind erosion of post-fire landscapes also represents an important but overlooked health threat. The bare soil following a fire readily emits ash, dust, and various other particulates into the air when wind is not broken by plants. Until topsoil is regenerated and new organisms have taken root, a process that can take several years, burn scars will continue emitting particulates.

A thorough understanding of the lingering effects of wildfires, the environmental and health consequences occurring after flames have been extinguished, should serve to challenge the common understanding of wildfires as acute events. The secondary and downstream effects of wildfires have the potential to pose even greater threats than wildfires themselves, and should serve to underscore the importance of prevention/treatment of these disasters.

5.4.2 Landslides

Landslides are tracked by the USGS and the California Department of Conservation, but are not attributed to wildfire, specifically. Cross-referencing wildfire and landslide datasets offers information on post-fire landslides and associated fatalities (Table 5.3). For example, the 2018 Montecito mudslide—triggered by heavy rain following the Thomas Fire—resulted in 23 deaths and at least 167 injuries. In comparison, the USGS reports an average of 25–50 people are killed by landslides of all types each year in the United States.

Table 5.3. *List of notable historic landslides in California. Post-fire landslides are marked on the left in red. Source: 2018 California State Hazard Mitigation Plan.*

Location	Year	Impact[a]
Montecito	2018	Post-Thomas Fire debris flows. 129 homes destroyed, 307 homes damaged, 21 fatalities.*
Camarillo Springs	2014	Post-Springs Fire debris flows. 10 homes destroyed, 6 homes damaged.
La Canada	2009-2010	Post-Station Fire debris flows with early damage claims at $58 million and Los Angeles County cleanup costs at over $30 million (2009 dollars).
Pacifica	2007	Devil's Slide: bypass construction of $325 million (See: San Francisco Chronicle).
La Conchita	2005	30 homes destroyed, 10 fatalities.
Laguna Beach	2005	18 homes destroyed, 8 homes damaged. Slide repair cost: $21 million. Cost of damage: $35 million.
San Bernardino	2003	Post-Grand Prix/Old Fire debris flows on Christmas Day. 16 fatalities, 52 homes and 32 trailers damaged; more than $100 million in damages.
Mission Peak	1998	--
Laguna Niguel	1998	9 homes and 57 condominiums destroyed. $12 million awarded to homeowners in lawsuit; $16 million to stabilize slope[b]
Rio Nido	1998	37 homes destroyed. 140 residents evacuated[c]
Laguna Beach	1998	18 homes destroyed, damaged 300 others. Two fatalities.
El Dorado County Hwy 50	1997	Destroyed Highway 50; $32 million in repair and economic losses.[i]
La Conchita	1995/2005	6 homes destroyed.[e]
Anaheim Hills	1993	30 homes destroyed, 200 homes damaged. Cost: $12 million.
Bay Area	1982	Debris flows and landslides on private and public property Cost: $172 million[j]
Big Rock Mesa	1979/1983	13 homes destroyed. Cost: $114 million. Damage to Highway 1 cost: $1.26 billion[f]
Laguna Beach	1978	19 homes destroyed, 45 homes damaged. Cost: $62 million[g]
San Fernando	1971	Cost: $354 million
Saugus-Newhall	1971	Cost: $312 million
Palos Verdes	1956, intermittently	More than 100 homes severely damaged or destroyed. Cost: $34 million; $68 million in damage settlements[h]

Source: California Geological Survey, or as noted

5.4.3 Water Contamination

Wildfires affect watersheds (Chapter 6) and damage drinking water infrastructure (Chapter 4), which can impact water quality in public and private water systems, including private wells (Hubbs and Murphy, 2019). Additionally, smoke can damage or destroy water distribution systems (Proctor et al., 2020). Following a wildfire, water must be tested for bacteria, heavy metals, and volatile organic compounds in municipal water distribution centers and lines, within residential homes, and in private wells (Waskom et al., 2013). The California Water Board Division of Drinking Water regulates public water systems and works to identify and mitigate changes in water quality due to wildfire. Local agencies also offer guidance to prevent contamination in public and private water systems. For example, Butte County published guidelines for testing and treating private wells following the 2018 Camp Fire (Butte County, 2019). The extent and duration of drinking water quality impacts of wildfire has not been studied.

Health losses due to water contamination can range from immediate (ingestion of harmful bacteria) to long-lasting impacts (ingestion of carcinogenic materials). Benzene, which contaminated drinking water systems following the Tubbs and Camp Fires, can cause nausea and dizziness in the short term and is a known carcinogenic which increases the risk of blood cancers with sustained exposure (Williams et al., 2002; Waskom et al., 2013; Siegler, 2019). In addition, post-wildfire water contamination can impose a substantial burden on communities with already precarious access to water resources. According to a study conducted by the California State Water Resources Control Board, more than one million Californians (mostly in rural counties) generally lack access to clean and reliable drinking water.

> ***Finding:*** *We did not find studies on the short- or long-term impact of post-fire water contamination on health.*

5.4.4 Particulates and Dust

The health consequences attributed to post-fire particulate matter emissions are not known, but they are highly relevant to the general population. The excess deaths attributed to smoke exposure from wildfire serves to underline the potentially severe health consequences of particulate matter exposure (Kochi, et al. 2012).

There is evidence suggesting dust from post-fire landscapes contains greater levels of $PM_{2.5}$ due to the presence of ash in the soil. As fires burn more intensely, the chances heat destroys the valuable topsoil and seed banks necessary to restore life to post-fire landscapes and lessen the degree of wind erosion increases (Wagenbrenner et al., 2017). A study of wind erosion of post-fire landscapes in the Great Basin found wind erosion alone could generate more $PM_{2.5}$ and PM_{10} annually than all smoke plumes from wildfires in the United States (Wagenbrenner et al., 2017). Furthermore, the authors demonstrate that burn scars can intermittently emit dust during wind events for more than a year after a fire occurs. These findings strongly suggest that even after fires are extinguished, their ability to emit harmful particulate matter remains. Figure 5.8 gives examples of post-fire dust events that impacted Boise, Idaho, following Great Basin wildfires.

It is important to note that only a small subset of post-fire landscapes may be capable of producing more particulate emissions than smoke plumes from wildfires (Wagenbrenner et al., 2017). However, if there is as much particulate matter released by wind events in post-fire landscapes as by the fire's smoke plume itself, then the true amount of morbidity and mortality could far exceed current estimates.

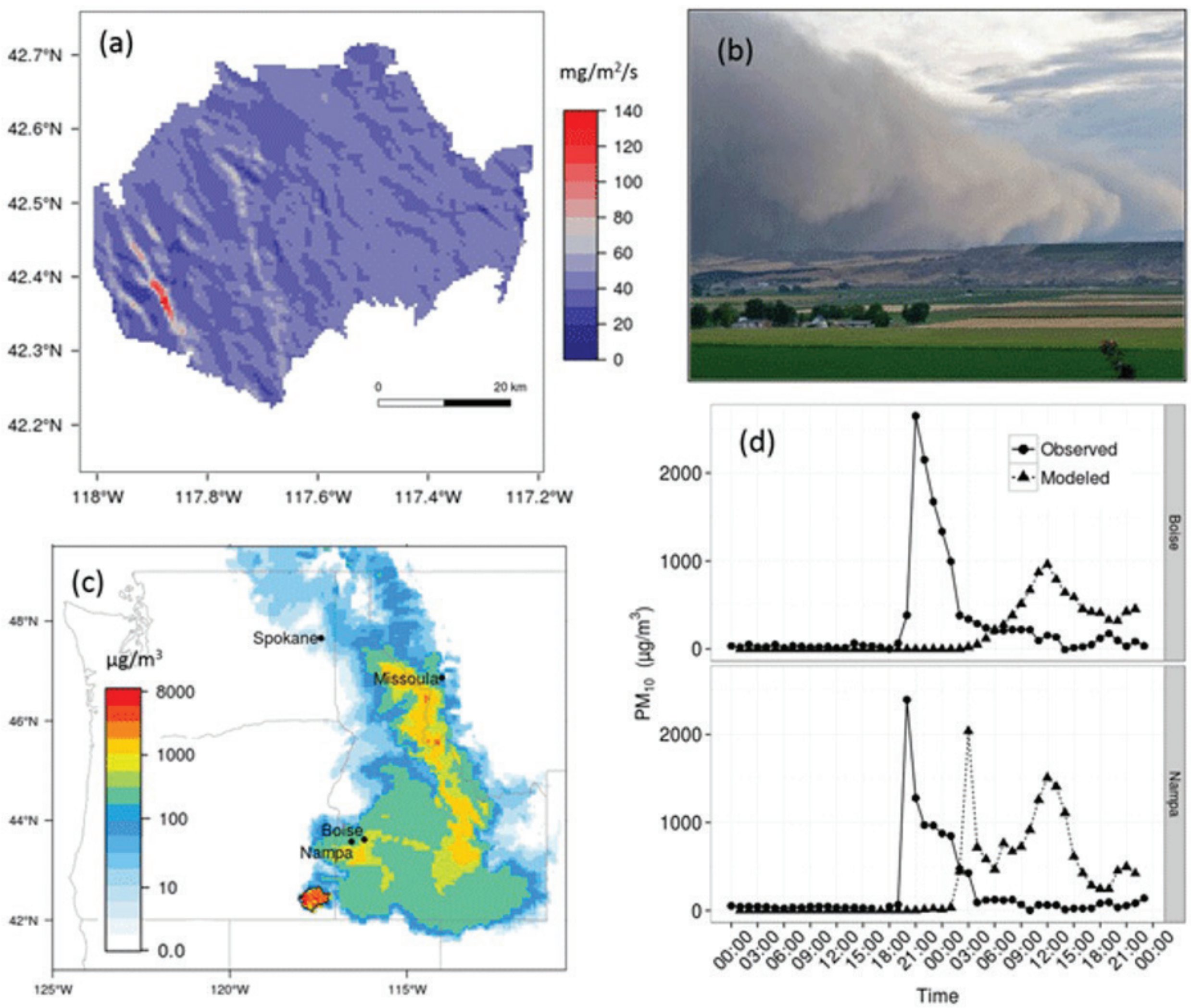

Figure 5.8. *(a) Modeled emissions from the Long Draw Fire. (b) A haboob originating from the Long Draw Fire and approaching Boise, Idaho, on August 5, 2012. Photo credit: ktvb.com. (c) Modeled PM_{10} concentrations during the August 5 haboob event. (d) Modeled and observed surface PM concentrations in Boise and Nampa (~ 34 km west of Boise), Idaho. Source: Waggenbrenner et al. (2017).*

> ***Finding:*** *Evidence suggests post-fire landscapes can emit significant quantities of fine particulate matter.*

> ***Conclusion:*** *Post-fire particulate matter emissions from the wind erosion of burned landscapes likely represent a significant and understudied health impact and consequence of wildfires.*

> ***Conclusion:*** *Other significant contributors to increased particulate matter levels beyond the immediate wildfire should be accounted for when estimating public health impacts.*

> ***Recommendation:*** *California should systematically monitor post-wildfire particulate matter emissions from burned landscapes.*

> ***Recommendation:*** *Incorporate post-fire dust exposure impacts into post-wildfire landscape rehabilitation (BAER and WERT) planning and activities.*

Contemporary Considerations: Viruses and Wildfire

Public Health: Virus and Wildfire Interactions

The COVID-19 global pandemic impacts many facets of life and policy in the State of California, including wildfire management. The major impacts of the interaction of wildfire smoke and COVID-19 are the combined health effects, the modification of fire management, and suppression strategies to protect firefighters and communities from infection, and the reduction in the firefighter workforce due to sickness. Wildfire smoke exposure alters immune function, increasing susceptibility to viral pathogens such as SARS-CoV-2. Further, inflammation of the respiratory system (due to smoke) may increase the risk of developing more severe outcomes of COVID-19. Those who have or have had COVID-19 may be at increased risk of health complications due to wildfire smoke exposure (CDC, 2020b).

COVID-19 and Wildfire Smoke

Areas with elevated air pollution are associated with increased viral outbreak rates. In Italy, regions with poor air quality were correlated with higher than average lethality of COVID-19 (Conticini et al., 2020). Preliminary evidence from a study in England found that on an individual level, exposure to particulate matter ($PM_{2.5}$, PM_{10}) increases the risk of COVID-19 infection (Travaglio et al., 2020). These findings are supported by prior studies during the SARs pandemic of 2002, where there were similar associations between outbreaks and increased pollution levels (Yan Cui, 2003). Overall, we know that air pollution increases susceptibility to viral infections such as SARS-CoV-2, and can exacerbate preexisting chronic lung disease such as asthma and COPD.

Modeled impacts of wildfire smoke on COVID-19 rates showed that a moderate smoke episode could increase both the number of COVID-19 cases and the deaths due to COVID-19 by approximately 10% depending on the current state of the outbreak (Henderson, 2020). These findings suggest that increases in particulate matter due to wildfire smoke, may lead to increases in the infection rate and/or lethality of COVID-19.

Additionally, evidence of SARS-CoV-2 virus was found on particulate matter (PM_{10}), which may indicate enhanced persistence of the virus in the outdoors in polluted areas. However, the longevity of the virus on particulate matter is still unknown (Setti et al., 2020).

Influenza and Wildfire Smoke

Increased influenza transmission is also associated with worse overall air pollution levels, especially on cooler days (Gongbo Chen, 2016). Wildfire seasons are also associated with increased influenza rates months later; an increase of average daily summer particulate matter ($PM_{2.5}$) by 1 μg/m3 led to a 16–22 percent increase in influenza cases the following winter (Landguth et al., 2020). Experiments on lab animals demonstrate that exposure to air pollutants, including particulate matter (Zhao et al., 2014; Zelikoff et al., 2003), nitrogen dioxide (Chauhan et al., 2003; Rose et al., 1989), and ozone (Olivieri et al., 2005; Schlesinger et al., 1987), increased susceptibility to both bacterial and viral lung infections by interfering with immune defenses.

> ***Finding:*** *Increased $PM_{2.5}$ from wildfires causes previously unrecognized downstream health impacts, rendering the immune system less capable of fighting off viral pathogens such as COVID-19 and influenza.*

> ***Conclusion:*** *Wildfire smoke may lead to increases in COVID-19 infection rates and influenza infection rates and may increase susceptibility to other viruses.*

5.5 Prevention and Loss Mitigation

5.5.1 Mitigating Smoke Exposure

Actions aimed at reducing the negative health consequences of wildfire events do so by reducing the risk of fires and limiting the number of people directly or indirectly exposed. Prevention and mitigation actions that reduce the population's exposure to wildfire smoke are effective at reducing health losses and are likely to be cost effective (Kochi et al., 2010; Fisk & Chan, 2017; CDPH, 2019).

One pathway for reducing exposure to wildfire smoke is through fire prevention and mitigation actions that reduce the occurrence of wildfires and smoke in populated areas (Chapter 3). A second pathway is through mitigation actions that allow individuals to reduce their personal exposure. Methods include educating to avoid exposure to high concentrations of smoke and reducing exposure through building alterations intended to create indoor clean air spaces (CDPH, 2019). Some of the available prevention and mitigation actions, such as Public Safety Power Shutoffs and prescribed burns, carry their own risks of negative consequences, but those can be largely mitigated with proper planning and institutional support (Shusterman et al., 1993; Jenkins et al., 2009; National Academies Press, 2019).

Studies that investigate the effectiveness of fuels management on reducing PM 2.5 levels of wildfire smoke are reviewed in Chapter 3. One such report on the 2007 Angora Fire reviewed the effect of fuel management treatments on the fire's behavior in the Tahoe Basin. Primarily based on post-fire field surveys and first-hand accounts from firefighters, the report found fuel treatments significantly changed fire behavior, reducing fire severity and increasing effectiveness of suppression efforts in protecting homes and aiding public safety evacuations (Murphy, 2007).

Suppressing fires to minimize smoke exposure may prevent some particulate matter from being released by limiting the combustion of organic material. Suppression, however, is not necessarily an effective long-term solution for reducing health losses. Importantly, fire suppression may ultimately result in larger fires with more severe health consequences as fuels build up and increase fire intensity (Kochi et al., 2010).

Decreasing exposure by altering people's behaviors may prove more effective at protecting health when accounting for both immediate and protracted benefits. At a minimum, exposure can be limited by keeping windows closed during the smoke event and limiting use of external doors. However, given that most wildfires occur during the hotter times of the year, reducing ventilation in spaces without alternative cooling methods such as air conditioning may increase the risk of heat stress (CDPH, 2019).

The use of personal protective equipment or modifications to work plans can help reduce wildfires and wildfire smoke exposure thereby preventing health losses in firefighters and frontline workers (Vos et al., 2006; Broyles, 2013; Nayak et al., 2014). We found no studies on the use or effectiveness of mitigation methods for frontline workers. Feasible respiratory protective equipment has not been developed for wildland firefighter use. Particle-filtering masks do not filter gases, including volatile organic compounds and carbon monoxide emitted from fires.

Examples of behaviors and actions that can reduce a population's exposure to smoke during an active smoke incident include (CDPH, 2019):

- Evacuating the area.
- School or business closures and event cancelations.

- Usage of N95 masks or respirators that filter particles.
- Staying indoors or seek out access to designated clean air shelters.
- Avoiding physical activity.
- Limiting length of shifts in outdoor work.
- Avoiding activities that make indoor air quality worse, such as smoking, burning candles or wood, frying, and cleaning that stirs up dust.

Building upgrades/alterations to reduce wildfire smoke exposure include (CDPH, 2019; Fisk & Chan, 2017):

- Improving building seals, like those around windows and doors to reduce smoke exposure.
- Upgrading mechanical ventilation systems to filter incoming air.
- Upgrading the HVAC filter to a new high efficiency filter (MERV 13 or higher).
- Acquiring a portable air purifier with a new high efficiency (HEPA) filter.
- Acquiring AC units or fans to aid in keeping windows closed without increasing risk of heat stress.

Usage of prevention and mitigation actions to reduce population exposure to wildfire smoke are not systematically tracked in California. Again, access to these mitigation methods is not equitably distributed among all parts of the population. Multiple factors affect people's ability to limit exposure, including the costs of masks or employment in outdoor occupations.

> ***Finding:*** *Effective mitigation strategies exist, but there are few studies estimating their implementation.*

> ***Finding:*** *Given smoke exposure and the lack of adequate availability of mitigation, many Californians still experience the unhealthy impacts of wildfire smoke exposure.*

> ***Conclusion:*** *Given the ongoing widespread health impacts from wildfire smoke exposure, existing mitigation measures are inadequate, especially for vulnerable populations.*

> ***Recommendation:*** *California should develop programs to increase availability of affordable mass-produced mitigation strategies (e.g. smoke-filtering window screens; widespread emergency N95 mask availability) or other community-based methods (e.g. widespread portable clean air mobile units) to minimize smoke exposure.*

5.5.2 Mitigating Water Contamination

Cities, counties, and water utilities issue “boil water” or “do not drink” public health advisories to prevent the public from using contaminated water and may increase water treatment and testing efforts to reduce contamination (Ragain, 2010). Studies analyzing the effectiveness of boil water advisories show they are at most 68% effective (Vedachalam et al., 2016). However, in instances with chemical or particulate contamination, “do not boil” advisories can help protect the public but have not been evaluated for effectiveness.

Treatment options include filtration, boiling, and chlorination (Waskom et al., 2013). The costs associated with these prevention efforts include those of additional treatment and testing, and of provisioning alternative water sources during these advisories. For example, following the Camp Fire in 2018 in Paradise, bottled water was provided to citizens whose water supply was contaminated with benzene. The cost of providing bottled water and replacing water lines was paid for by the Paradise Irrigation District (Paradise Irrigation District, 2019). Some residents incurred these costs themselves, paying for water tanks and water delivery, often totaling several thousand dollars (Peterson, 2019).

> ***Finding:*** *There appears to be no systematic tracking of the duration, number of customers impacted, and spatial extent of “do-not-drink” orders following wildfires.*

> ***Conclusion:*** *The costs of mitigating water contamination due to wildfire, though potentially significant, are unknown and represent an important research gap.*

5.5.3 Mitigating Direct Heat and Flame Exposure

Prevention and mitigation of health losses from wildfires include actions to reduce the risk of catastrophic wildfires that could threaten populations and actions to reduce exposure of the public when wildfires occur. Efforts to reduce the risk of catastrophic wildfire include actions to prevent spread into populated areas (see Chapter 3 for more discussion).

When wildfires do threaten populated areas, emergency evacuations or sheltering-in-place can reduce the risk of direct heat and flame exposure. The primary method used to prevent heat and flame exposure is emergency evacuation, which can affect large populations. The efficacy of evacuation in preventing injuries and fatalities depends partially on the ability and willingness of the general population to safely and quickly carry out an evacuation and partially on the ability to effectively disseminate the order and fulfill logistical challenges. Emergency evacuation, if improperly carried out or poorly planned, can cause additional injury or death, particularly resulting from disruption in health care for medically vulnerable populations (Shusterman et al., 1993; Jenkins et al., 2009; National Academies Press, 2019). Some downstream impacts include complications from evacuating critical care patients from hospitals, difficulty in replacing prescription medications left behind, or traffic fatalities related to emergency traffic diversion.

Effective evacuations depend largely on accessible, clear communication of directions to the public. Costs associated with emergency evacuation include those of temporarily sheltering large numbers of people, missed workdays, transportation, and other logistical challenges. There does not appear to be an inventory of past evacuation orders in the state and the costs associated with evacuation and mitigation efforts are unknown; we found no datasets or studies on the costs of emergency evacuation actions in California.

Additionally, the effectiveness of evacuations often depends upon the population being evacuated. People with mobility issues, like those with medical conditions or the elderly, or low-income communities lacking the resources to stay elsewhere will inevitably have more difficulty evacuating. Notably, CAL FIRE has been significantly investing in understanding, streamlining, and equalizing evacuation processes. New means of communication and investment in resources for those displaced can help diminish the risks of evacuation.

No datasets systematically track the occurrence of emergency evacuations or other exposure reduction actions for wildfires. One study estimated a combined 1.1 million people were ordered to evacuate from 11 California wildfires between 2017 and 2019 (Wong, 2020). Additional surveys of individuals from three wildfires estimated 3–13% of the population who received a mandatory evacuation order did not comply.

Contemporary Considerations: Protecting Firefighters and Communities in the COVID-19 Context

Clean air shelters—group spaces with filtered air such as gymnasiums, fairgrounds and auditoriums—provide refuge from wildfire smoke exposure to those that are unable to access clean air in their own home. Shelters such as these may provide a route of transmission of COVID-19 (CDC, 2020c). This is particularly problematic because many users of clean air shelters are those most vulnerable to COVID-19 (older adults with pre-existing respiratory and cardiovascular conditions). In order to reduce COVID-19 transmission in clean air shelters, new protocols are being proposed and the CDC has recommended consideration of utility assistance to reduce the need for clean air shelters (CDC, 2020c). In the event of a wildfire that prompts evacuations, public disaster shelters will also be vulnerable sites for spreading COVID-19 (CDC, 2020d). Alternatives to large group shelters have been proposed, including using hotels as evacuation sites (California Professional Firefighters, 2020).

New protocols and management strategies for fighting wildfire have also been implemented in response to the COVID-19 pandemic. Specific strategies include the use of personal protective equipment (face coverings), increased focus on hand hygiene, screenings of firefighters upon arrival for work, prioritization of COVID-19 testing for first responders (including wildland firefighters) and use of virtual communication where possible (CDC, 2020e). Additional strategies to protect wildland firefighters include social distancing for the first 14 days on a fire crew, isolating each fire crew/module, eliminating or reducing interchange of personnel between crews, and minimizing the number of people at each camp and command post (CDC, 2020a, 2020e; Fire Management Board, 2020).

5.5.4 Regulatory Impediments to Prevention

Some of the best practices in mitigating the health consequences of fires involves appropriate forest management. These strategies, however, face significant regulatory barriers related to public health that limit their implementation. Namely, overlapping state and federal jurisdictions can create logistical and coordination difficulties. $PM_{2.5}$ is regulated as a criteria pollutant under the U.S. Clean Air Act. State and local Air Quality Management Districts have responsibility for meeting the ambient air quality standards set by the U.S. EPA for $PM_{2.5}$. These state authorities can limit activities that degrade air quality or may lead to exceedances of the ambient air quality standards. Air quality regulations have long restricted prescribed burning because of the contribution of these emissions to air pollution. However, PM 2.5 created by wildfire is an "exceptional event" under the Clean Air Act (section CAA §319(b)), which absolves air regulators of responsibility for air pollution events related to natural disasters. In 2016, the regulations for the "exceptional events" policy were revised in part to allow for greater inclusion of prescribed fire impacts. Likewise, the California Air Resources Board and Air Quality Management Districts have facilitated permitting of prescribed fire since 2017. Nevertheless, significant barriers remain to the use of forest management due to the differential treatment it receives relative to wildfire under U.S. air pollution law. Some of these barriers are discussed in detail in Chapter 3.

5.6 Conclusion

The public health impacts of wildfires and wildfire-related events are profound but often overlooked. Many of these impacts have not been previously appreciated and represent an active area of research. The most important is smoke, the primary mechanism through which wildfires impact health for large portions of the population.

The health consequences of wildfire do not end when the flames are extinguished. Rather, wildfires should be understood as disasters whose lingering effects represent a significant public health threat. With wildfires in the United States costing an estimated $450 billion annually, proper forest management should be seen not only as a way to protect public health, but also as a public health investment with substantial returns (Fann et al., 2018). The devastating wildfires of the 2017, 2018, and 2020 seasons have prompted many to investigate the full consequences of wildfires and as such, this area of research is expanding rapidly. Substantial new research is being performed now and the results that will emerge in the next few years should improve our ability to identify and quantify the true scope of health impacts of wildfire and their associated costs. The public health stakes are extremely high and there is urgent need to deploy widespread mitigation measures.

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Chapter 6

Ecosystem Processes

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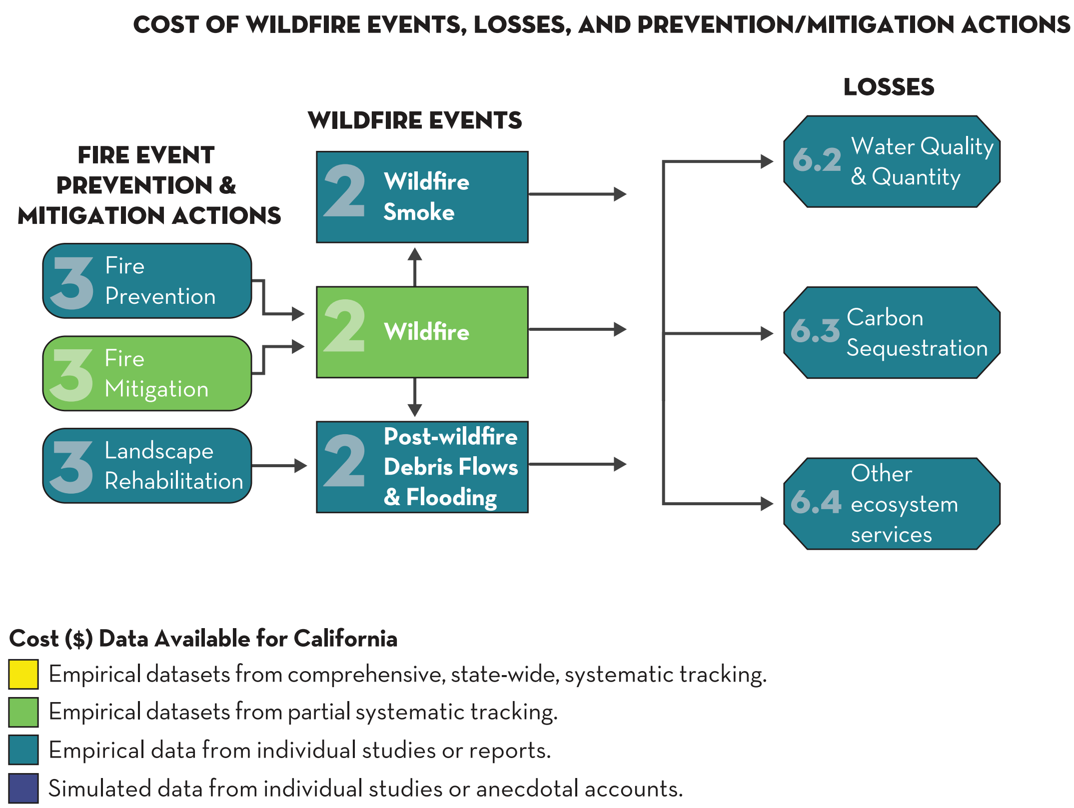

Figure 6.1. *The colors in the diagram indicate the category of California-specific datasets available to characterize the dollar value costs associated with wildfire losses. Large numbers in the filled shapes indicate the chapter where each topic is discussed. For Chapter 6 topics—water quality and quantity losses, carbon sequestration, and other ecosystem services—cost estimates of specific losses from specific wildfires in California are available in individual studies or reports (blue). Comprehensive, state-wide cost estimates of all ecosystem losses due to wildfire in California are currently unavailable in the research literature or other publicly available resources.*

6.1 Chapter Scope

Chapter 6 focuses on wildfire impacts to ecosystem processes that result in outcomes considered losses to society and/or the environment even if they do not currently have a direct market value (Figure 6.1). For wildfire losses to economic sectors that utilize natural resources and lands (e.g., timber, tourism, and recreation), see Chapter 7. Chapter 6 is not intended to be a general review of fire ecology, the robust academic field concerned with understanding the complex and myriad ways wildfires impact ecosystems. Nor does this chapter include a discussion of wildfire impacts to ecosystems that result in beneficial outcomes. Because the scope of our report focuses on wildfire losses and their associated costs, the topics covered in this chapter (water quality and quantity, carbon sequestration, and a handful of other examples) represent only a small subset of the many ways that wildfires impact ecosystems in California that may be especially policy-relevant. This limited scope is by no means a suggestion of a lack of importance of other wildfire outcomes or their potential to be valued as either benefits or losses. Instead, it underscores the need for additional work by researchers and policymakers to better determine the value of wildfire impacts to ecosystems.

6.1.1 California Ecosystems and Wildfire

California is home to a rich diversity of ecosystems that provide numerous ecosystem goods and services, including clean air, abundant clean water, economic and culturally important resources, mitigation of extreme weather consequences, groundwater recharge, soil generation, waste decomposition, carbon sequestration, biodiversity, maintenance of high-quality habitats, recreation, aesthetic value, and human physical and mental well-being (Batker et al., 2013; Hanson et al., 2013; Christin et al., 2017; Underwood et al., 2018). Each of these goods and services arises from a healthy, functioning ecosystem. Many of California's ecosystems, including mixed-conifer forests, oak woodlands, and chaparral shrublands, have evolved in concert with their own specific wildfire regime (see Chapter 2, Section 2.2.1 for a detailed discussion of wildfire regimes in California). Regime-appropriate wildfire, wildfire smoke, and post-wildfire landscape events are periodic, natural disturbances that cause short- and long-term impacts on the biological and physical processes that make up an ecosystem and are part of its healthy functioning (Figure 6.2).

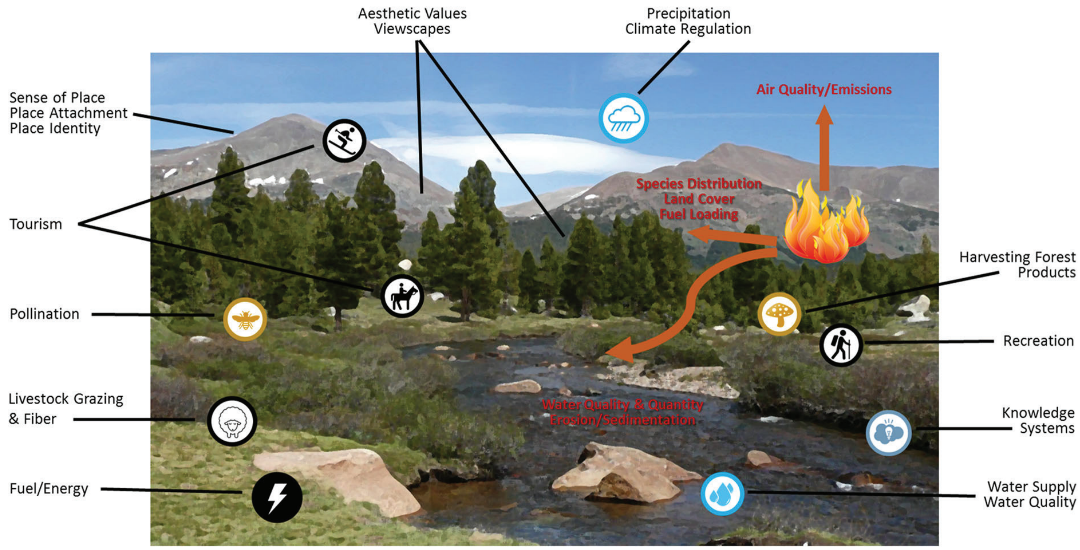

Figure 6.2. *An overview of ecosystem services impacted by fire. Depending on the context, some wildfire impacts may be considered benefits, whereas others may be considered losses. Source: Figure 1 from Vukomanovic & Steelman (2019).*

There is strong consensus among fire ecologists and many wildland managers that fire use is an important part of maintaining healthy ecosystems. Despite this agreement, long-standing fire suppression policies—and aligned public education campaigns—have until very recently shaped public opinion of wildfire impacts to ecosystems as ever-harmful losses regardless of context, in the same way that wildfire impacts to human health or the built environment are always considered a loss to society (Miller & Aplet, 2016). But some ecological outcomes of wildfire can be considered benefits (Table 6.1). As described in Chapter 1, wildfire impacts to California's ecosystems can not automatically be categorized as losses or benefits without considering their ecological and social contexts. Whether any given wildfire outcome should be valued as a negative loss or a positive benefit depends on the specific ecosystem, the current fire regime relative to its natural variability, and our own specified management goals (e.g., watershed function, critical habitat, or recreation) (Hanson et al., 2013). Moreover, the periodic nature of wildfire disturbances means that losses may be cumulative and better considered at the time scale of wildfire regimes than that of individual fires.

> ***Finding:*** *Healthy California ecosystems provide many goods and services and have evolved with their own specific wildfire regimes.*

> ***Finding:*** *There is strong scientific consensus that wildfire can be essential and beneficial to the healthy functioning of California ecosystems.*

> ***Conclusion:*** *Wildfire impacts to California's ecosystems may not automatically constitute losses and in fact can provide important benefits.*

> ***Recommendation:*** *Wildfire impacts to ecosystem functioning and related goods and services, and potential economic values thereof, must be considered in terms of specific ecosystems, their associated fire regimes, and specified ecosystem and fire management goals.*

The challenge of determining a sum cost of ecosystem losses due to wildfire throughout the state is immense, even without the obstacles presented in attempting systematic collection of relevant data. Not only must a researcher determine whether a particular outcome should be considered a loss or a benefit, but determining a dollar value for said ecosystem impact is nontrivial. Navigating this complex challenge requires a combination of ecological and socio-economic research (Venn & Calkin, 2009; Thompson et al., 2011). The latter is especially so, as many of the ecosystem services provided by natural lands do not have a direct market value. In cases where a direct market value for an ecosystem good does not exist, economists have developed a number of tools to estimate its economic value (Tietenberg & Lewis, 2019). A variety of **revealed** (inferred) and **stated-preference** (direct) approaches are available to approximate economic values for such non-market goods or services, including:

- Contingent valuation: A **stated-preference** survey approach where individuals are asked about their willingness to pay for a specific non-market outcome.

- Travel-cost: A **revealed** preference method for inferring the value of an environmental amenity by analyzing visitation expenditures (including travel to/from the site, park entry fees, the opportunity cost of the time, etc.)

- Hedonic pricing: A **revealed** preference method for estimating the implicit value of an environmental amenity by analyzing how the price of a market good changes when the environmental amenity changes.

- Avoided cost: A **revealed** preference approach that infers the value of a non-market good by quantifying expenditures to either mitigate or restore a negative environmental outcome.

- Benefit transfer: A common method for applying non-market values from one setting to another setting.

These various approaches require dedicated research to ascertain an estimated value of ecosystem benefits or losses. As a consequence, the values of only a small subset of the many ecosystem goods and services for each of the distinct ecosystems in California have been assessed. For example, of the ecosystem services likely impacted by the Rim Fire, only a handful have had their dollar value estimated by prior research, and even fewer have a dollar value estimate specific for California (Table 6.1). The small proportion of services with applied values demonstrates a fundamental challenge to comprehensive estimates of costs associated with ecosystem losses from wildfire in California: a lack of valuation estimates for many ecosystem services, generally. Moreover, if studies use different approaches to estimate values of ecosystem services, direct comparison between studies could be difficult because each approach might be expected to produce a different dollar value estimate. As a consequence of these limitations, economic analyses assessing the costs of wildfires are typically forced to exclude many of the wildfire ecosystem outcomes because they do not have readily available dollar value estimates (Batker et al., 2013; Buckley et al., 2014; Christin et al., 2017). Thus, a truly comprehensive accounting of the costs associated with wildfire losses to California's ecosystems is currently unknown.

Table 6.1. *The value of ecosystem services from the Rim Fire burn area. Source: Table 3 from Batker et al. (2013).*

	Grassland	Lake	River	Forest (Broad Leaf and Other)	Forest (Coniferous)	Shrub	Herbaceous Wetlands	Riparian
Food Provisioning	■	■	■	■		■	■	
Raw Materials		■			■	■	■	■
Medicinal Resources		■	■		■	■	■	■
Air Quality	X	■	■	X	X	X	■	■
Climate Stability (Carbon Sequestration)	**X**			**X**	**X**	**X**	**X**	■
Moderation of Extreme Events	■	■			X		X	X
Soil Retention	■	■	■	■	■	■	■	**X**
Biological Control	■	■	■	X	X	■	■	■
Water Regulation	■	■	■	X	X	■	■	■
Soil Formation	■	■	■	■		■	■	■
Pollination	X	■	■	■	X	X	X	■
Habitat and Biodiversity	■	■	X	■	X	X	**X**	X
Aesthetic Information	X		**X**	**X**	■	■	■	X
Recreation and Tourism	■	**X**	**X**	**X**	**X**	X	X	X
Science and Education	■	■	■	■	■	■	■	

Ecosystem service not produced by land cover	
Ecosystem service produced by land cover, no dollar value established	■
Ecosystem service produced by land cover and dollar value(s) provided	X
Ecosystem service produced by land cover and dollar value(s) provided from California	**X**

> ***Finding:*** *An estimate of the economic value of many of the ecosystem goods and services provided by the numerous habitats in California is currently unknown.*

> ***Conclusion:*** *A comprehensive accounting of the gains or costs associated with wildfire impacts to California's ecosystems is currently not possible with the existing data.*

> ***Recommendation:*** *California should support additional research to document and value the full range of wildfire impacts to ecosystems.*

Summarized in the following sections is the available literature that explicitly considers wildfire impacts to California ecosystem services as monetized losses. Though the ecosystem goods and services provided by California's ecosystems are numerous (as illustrated in Table 6.1), the vast majority of the information we found specific to wildfire losses and cost estimates concerns water quality and quantity (Section 6.2) and carbon sequestration (Section 6.3). A collection of other ecosystem services, discussed in the small number of studies that frame wildfire outcomes in terms of explicit losses in California, are briefly reviewed in Section 6.4. This chapter aims to give the reader an understanding of the evidence available (or still needed) to consider the balance between ecosystem costs, and effective mitigation and prevention measures. Accordingly, each following section begins with a description of the wildfire event's impact, what losses might arise from that impact, prevention and mitigation measures to avoid these losses, and the effectiveness of these actions.

6.2 Watersheds

6.2.1 Exposure

In order to discuss the scale of impacts to watersheds from wildfire events, one must first consider the scale of exposure to these events. Exposure to wildfires, wildfire smoke, and post-wildfire landscape events such as erosion, debris flow, and flooding can affect a watershed's functioning and its associated ecological goods and services, including water quantity and water quality (Moody & Martin, 2004; Hallema et al., 2018, 2019; Moody et al., 2013; Shakesby & Doerr, 2006). Data on which of the thousands of California watersheds have been exposed to wildfire is not systematically reported. Although not fully comprehensive for California's watersheds, Hallema et al. (2019) does provide a publicly available dataset of 168 watersheds in the U.S. that have been exposed to wildfire (Figure 6.3). According to this dataset, many of the watersheds in California have had more than 80% of their watershed area burned in wildfires. Additional data on individual watershed exposure to wildfire in California can be found in BAER, WERT, and other reports, as well as individual studies (Table 6.2), but these reports also do not represent a comprehensive collection of all watersheds impacted by wildfire over time.

> ***Finding:*** *Multiple studies cite specific California watersheds as being impacted by wildfire, but in this review we found no overarching studies or reports cataloging all wildfires in the state by impacted watershed.*

> ***Conclusion:*** *There does not appear to be comprehensive, systematic tracking of wildfire-impacted watersheds in California.*

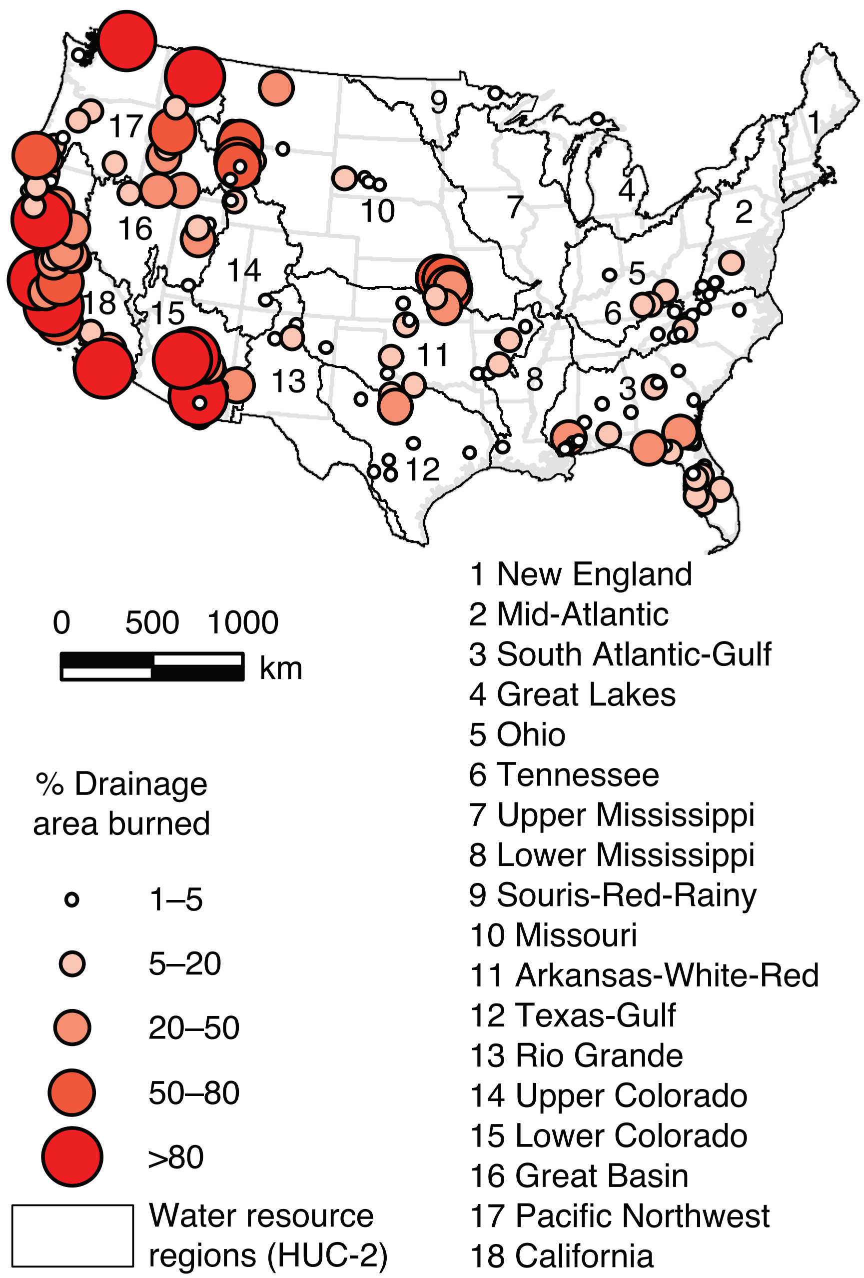

Figure 6.3. *The scale of wildfire impacts on watersheds. The map overlay shows that more than 80% of the drainage area of many watersheds in California have been burned by wildfire. Source: Figure 2 from Hallema et al. (2018).*

Figure 6.4. *Map of California's nine Regional Water Quality Control Boards. North Coast Regional Water Board (1); San Francisco Bay Regional Water Board (2); Central Coast Regional Water Board (3); Los Angeles Regional Water Board (4); Central Valley Regional Water Board (5); Lahontan Regional Water Board (6); Colorado River Basin Regional Water Board (R7); Santa Ana Regional Water Board (8); San Diego Regional Water Board (9). Source: California State Water Resources Control Board.*

6.2.2 Impacts

Wildfires can impact water quality, water quantity, and water movement within watersheds. Wildfires, wildfire ash and smoke, and post-wildfire landscape effects can decrease water quality by introducing and increasing concentrations of pollutants and toxic contaminants in watersheds that pose a health risk to humans and ecosystems (Smith et al., 2011; Stein et al., 2012; Rust et al., 2018). Additionally, wildfire can alter and mobilize soils and sediments, leading to changes in volume of runoff and sediment loading. Further, these changes can impact water quantity throughout the watershed via alterations to reservoir capacity, as well as impact water chemistry and clarity downstream, which has implications for suitable aquatic habitat—salmon, for example, require deep pools of clean gravel for spawning and rearing in California rivers (Neary et al., 2003; Boisramé et al., 2019; Hallema et al., 2018, 2019; Maina & Siirila-Woodburn, 2020; Madej and Ozaki, 2009). Wildfire impacts to watersheds have been found to persist for at least 5 years (Hallema et al., 2018, 2019; Rust et al., 2018).

Water quality and water quantity are systematically tracked at the national level by the USGS National Water Information System, and at the state level by the California State Water Resources Control Board Surface Water Ambient Monitoring Program and its regional water quality control boards (Figure 6.4). However, these datasets do not typically distinguish the specific impacts of wildfires from other potential causes for changes in water quality and quantity. Although the systematic tracking of these metrics does not distinguish wildfire-related impacts from other forces, numerous studies and reports do explicitly assess wildfire impacts on watersheds in California. The individual studies we found (Table 6.1) use a variety of methods and metrics to assess wildfire impacts in watersheds; often these studies measured changes in water quantity and chemistry, including trace metals, dissolved constituents, and sediments. (See Table 6.2 for an illustration of how varied the set of constituents may be for monitoring wildfire impacts via water samples.) Different methods and metrics each provide important insights about how wildfires impact watersheds. At the same time, the lack of standardization across case studies means that additional analyses and research would be required to allow direct comparisons of wildfire-caused impacts in watersheds between different fires or regions, or to assess trends over time.

> ***Finding:*** *Water quality and quantity in California watersheds are systematically tracked by multiple agencies, though changes in tracked metrics are not attributed directly to wildfire.*

> ***Finding:*** *Multiple case studies have assessed wildfire-caused watershed impacts (including water quantity and quality), but these metrics are not consistently defined between cases or watersheds.*

> ***Conclusion:*** *It is difficult to make meaningful comprehensive or comparative statements about California watershed losses due to wildfires over time without standardized metrics.*

> ***Recommendation:*** *Researchers and decision makers interested in wildfire impacts on watershed-based ecosystem services over time should identify important standardized metrics and collection resolution in order to allow for meaningful comparisons between watersheds and between fire events.*

Table 6.2. *List of monitoring analytes used in the San Francisco Bay Regional Water Quality Control Board (SFB Control Board) Fire Response Monitoring Plan. Included here as illustration is a subset of constituents and properties that can be measured before and after a fire to assess potential wildfire impacts on ecosystem goods and services. This is not an exhaustive list and its inclusion is merely intended to show an example of the set of analytes one organization chose from a wide array of constituents that* ***could*** *be measured to monitor change in water as a result of wildfire--each organization's list may vary significantly depending on their monitoring objectives. This table comes from the SFB Control Board's post-fire monitoring plan document. Source: San Francisco Bay Regional Water Quality Control Board Post-Fire Monitoring Plan.*

General	Nutrients	Metals	PAHs
Alkalinity	Ammonia	Aluminum[T,D]	Acenaphthene
Hardness	Nitrate	Arsenic[T,D]	Acenaphthylene
Sulfate	Total Nitrogen	Cadmium[T,D]	Anthracene
Total Organic Carbon	Orthophosphate	Chromium[T,D]	Benzo (a) anthracene
Total Dissolved Solids	Total Phosphorus	Copper[T,D]	Benzo (a) Pyrene
Total Suspended Solids		Iron[D]	Benzo (b) flouranthene
Dissolved Oxygen[F]		Lead[T,D]	Benzo (g,h,I,) Perylene
pH[F]		Manganese[D]	Benzo (k) Fluoranthene
Specific Conductance[F]		Mercury[T,D]	Chrysene
Temperature[F]		Nickel[T,D]	Dibenzo (a,h) anthracene
Turbidity[F]		Selenium[T,D]	Fluoranthene
		Zinc[T,D]	Fluorene
			Ideno(1,2,3-C,D)Pyrene
			Naphthalene
			Phenanthrene
			Pyrene

[F]Field Measurement
[T]Total
[D]Dissolved

6.2.3 Losses

Wildfires are natural disturbances in many of California's ecosystems, and subsequent watershed impacts caused by wildfire can be critical to maintaining healthy ecosystem function. Whether a specific impact from wildfire should be treated as a loss or a benefit depends upon the context and established goals. Wildfire impacts to watersheds are considered a loss only when they cause outcomes that fail to meet established standards or management goals. For example, a wildfire-caused alteration to water quality would be considered a loss if concentrations of toxic chemicals in drinking water sources were increased enough to exceed Maximum Contaminant Levels (MCL) set to protect public health (Smith et al., 2011; Stein et al., 2012). When this occurs, post-wildfire contamination of watersheds that serve as drinking water sources could lead to subsequent health losses

(Chapter 5). The costs associated with this type of watershed loss include increased testing and treatment to ensure the delivery of clean drinking water. Similarly, wildfire impacts to erosion are considered a loss when they cause increased sedimentation rates in reservoirs, debris basins and other water infrastructure—here, associated costs include dredging to maintain capacity of the water delivery and flood control system (Buckley, 2014; Christin et al., 2017; Loomis et al., 2003; SAWPA, 2003).

Watershed losses and costs are not systematically tracked in California but water quality data from select recent wildfires is available in individual reports from the state's Regional Water Quality Control Boards (NC RWQCB, 2018, 2019; SF RWQCB, 2018) and from other reports and studies (Table 6.2).

> ***Finding:*** *Some wildfire-caused, watershed-based ecosystem losses are reported in peer-reviewed studies and in reports from California agencies such as the California Regional Water Quality Control Boards.*

> ***Conclusion:*** *Watershed-based ecosystem losses from wildfire do not appear to be systematically tracked in California.*

> ***Conclusion:*** *Additional collation and analyses of existing information would be required to compare watershed-based losses broadly across the state or to track trends over time.*

> ***Recommendation:*** *California should undertake a synthesis of existing peer-reviewed studies, agency reports, and other available databases, to provide the understanding of wildfire effects on watershed-based ecosystem losses over time necessary for a comprehensive accounting of associated dollar costs.*

6.2.4 Prevention and Mitigation

Prevention and mitigation activities to reduce watershed-based losses from wildfire focus primarily on fuels management and post-fire landscape mitigation (Elliot et al., 2010; Wohlgemuth, 2001; Wohlgemuth & Robichaud, 2007). The links between fire and watershed dynamics have motivated California water agencies, federal agencies, tribal agencies, and other land managers to incorporate fire management efforts in their long-term strategic planning to manage healthy watersheds (Boisramé et al., 2019; Collins et al., 2017; Karuk Tribe, 2019). Specific cases of prevention efforts are documented in individual studies and reports (Table 6.2). The actual costs of prevention and mitigation actions deployed in California are generally unknown. In cases where BAER and WERT reports give estimates of costs associated with deploying various proposed mitigation actions, they include the caveat that these estimated values may differ from actual expenditures.

6.2.5 Effectiveness at Reducing Losses

The effectiveness of fire management and post-wildfire watershed rehabilitation at preventing watershed impacts is not systematically tracked in California. We found a handful of case studies that assess the effectiveness of prevention and mitigation efforts to specifically avoid watershed losses, and only two studies that assess the cost-effectiveness (Table 6.3). One of these studies, based on simulated wildfires, found the use of prescribed fire in Los Angeles County watersheds was predicted to be cost-effective at reducing debris basin clean out (Loomis et al., 2003). The other, a study by Buckley et al. (2014) that simulated fuel treatments in the Mokelumne watershed, found that treatments were cost-effective at avoiding a suite of losses including sedimentation costs to water utilities.

6.2.6 Conclusion

The impacts of wildfire on watersheds, and the use and effectiveness of prevention efforts, have been documented in individual case studies, but are not systematically tracked in California. The full economic value of watershed impacts and prevention efforts are generally unknown. We found no economic assessments of the cost-effectiveness of efforts to prevent watershed losses based on actual events and expenditures.

Table 6.3. California-specific literature relevant to watershed losses from wildfire and prevention and mitigation actions to reduce exposure, from this review. The table is not intended as an overview of literature discussing watershed impacts from wildfire more generally.

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Exposure	Losses		Prevention and Mitigation		Effectiveness at Reducing Losses	
Source	**Wildfire**	**Numeric**	**Numeric**	**Dollars**	**Numeric**	**Dollars**	**Numeric**	**Dollars**
BAER Burned Area Reports Database	Wildfires on federal land	2	2	2	2	2	0	0
Batker et al., 2013	2013 Rim Fire	0	1	1	0	0	0	0
Boisrame et al., 2019	Managed wildfires	2	0	0	2	0	2	0
Buckley et al., 2014	Simulated Wildfires	0	1	1	1	1	1	1
Burke et al., 2010	2005 Topanga Fire, 2006 Pines Fire, 2006 Day Fire	2	0	0	0	0	0	0
Burke et al., 2013	2009 Station Fire	2	0	0	0	0	0	0
Burton et al., 2016	2009 Station Fire	2	2	0	0	0	0	0
CA Watershed Emergency Response Team (WERT)	CA wildfires on non-federal land	2	2	2	2	2	0	0
Christin et al., 2017	2016 Loma Fire	0	1	1	0	0	0	0
Elliot et al., 2016	Simulated Wildfires	0	0	0	1	0	1	0
Hallema et al., 2018, 2019	Select California Wildfires	2	0	0	0	0	0	0
Kinoshita and Hogue 2011	2003 Old Fire	2	0	0	0	0	0	0
Kinoshita and Hogue 2015	2003 Old Fire	2	0	0	0	0	0	0
Loomis et al., 2003	Simulated Wildfires	0	1	1	1	1	1	1
Miles et al., 1989	1987 Shasta-Trinity Fires	0	0	0	2	2	0	0
NC RWQCB, 2018, 2019	2017 Tubbs Fire, 2017 Nuns Fire	2	2	0	0	0	0	0
Oliver et al., 2012	2007 Angora Fire	2	0	0	0	0	0	0
SAWPA, 2003	2003 Grand Prix, Old, and Padua Fires	2	2	2	2	2	0	0
SF RWQCB, 2018	2017 Atlas, 2017 Nuns, 2017 Tubbs	2	2	0	0	0	0	0
Sham et al., 2013	Select California Wildfires	0	2	0	0	0	0	0
Stein et al., 2012	Select California Wildfires	2	2	0	0	0	0	0
Wohlgemuth 2001	2003 Old Topanga Fire	0	0	0	2	0	2	0
Wohlgemuth & Robichaud, 2007	1999 Mixing Fire, 2002 Williams Fire, 2003 Cedar Fire	0	0	0	2	0	0	0

6.3 Carbon Sequestration

6.3.1 Impacts

California's ecosystems can act as major carbon sinks in the natural carbon cycle and can serve as a pathway for actively controlling atmospheric CO2 concentrations to meet the state's climate goals (Anderegg et al., 2012; Pan et al., 2011; Baker et al., 2020). Atmospheric carbon is continuously being captured by trees and other plants through photosynthesis and then stored in living and dead biomass (e.g., trunks, roots, leaves, etc.) or in soils (Figure 6.5). At the same time, carbon is emitted back to the atmosphere through various natural pathways, including as a result of wildfire. Wildfires cause the release of stored carbon through combustion of biomass (Campbell et al., 2007), decomposition of dead vegetation following the fire (Harmon, 2000; Campbell et al., 2016; Bonnicksen, 2008), or the burning of organic material in soils (Homann et al., 2011).

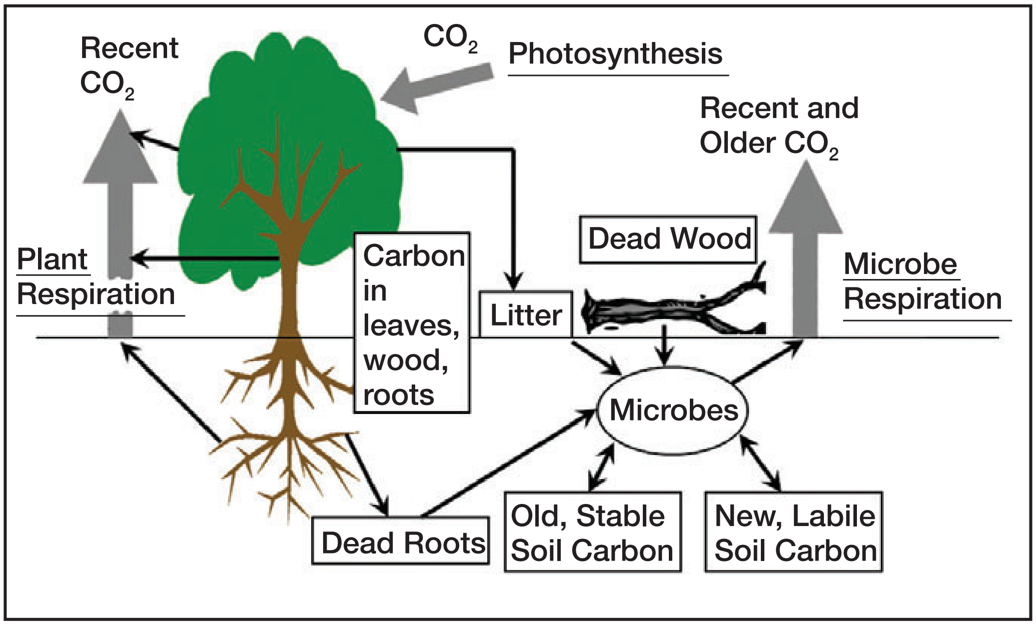

Figure 6.5. *Forest carbon cycle. Source: Figure 2 from Ryan et al. (2010).*

Figure 6.6 shows a simplified schematic for changes in forest carbon over time. Following the initial and sudden loss of stored carbon following a wildfire, total carbon stores will then begin to increase over time by future growth of trees and other vegetation. Wildfires could cause a net loss in sequestered carbon if the amount of carbon emitted by wildfires is consistently greater than the amount accumulated by the natural lands. A net loss could occur if the rate of emissions outpaces the rate of vegetation recovery (e.g., due to changes in the frequency or severity of fire), or if wildfires induce the ecosystem to undergo a habitat type conversion to a system with lower carbon storage potential (e.g., conversion from forestland to shrubland, or from shrubland to grassland).

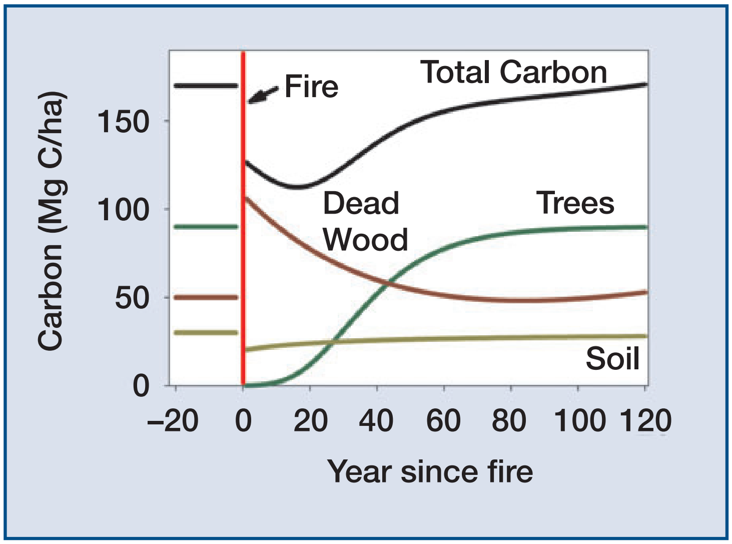

Figure 6.6. *Hypothetical change in total forest carbon after a wildfire disturbance based on a case study from Yellowstone National Park. Total amount of carbon sequestered (black line) in a forest at any given time is the sum of carbon stored in living trees (green line), dead trees (brown line), and in the organic component of soils (tan line). Wildfires can cause abrupt drops in the total amount of stored carbon (red vertical line) as combustion and decomposition of biomass emit carbon back to the atmosphere, but over time, total carbon stores can recover as trees regrow. Source: Ryan et al. (2010).*

There are many datasets and studies that report carbon emissions from wildfires, such as the annual estimates prepared by the California Air and Resources Board. These reports provide important insights into the role of wildfires in the carbon cycle and impacts on air quality. For example, we discuss the public health impacts and associated costs and losses related to air quality impacts of wildfire emissions in Chapter 5. However, emissions values alone are not sufficient to assess the net change in sequestered carbon from wildfire. A complete accounting of net sequestered carbon in California's ecosystems must take into account both the loss from emissions and the gains from vegetative growth.

Fire suppression, logging, and other land use decisions over the past few centuries have dramatically altered the ways in which carbon is stored in many of California's ecosystems, including mixed conifer forests and chaparral, by altering both the rate of emissions and vegetative regrowth. Fire suppression has created forests that are more densely packed with smaller trees and shrubs (McKelvey et al., 1996; Bouldin, 1999; Minnich et al., 1995). These denser forests are at greater risk of high-severity wildfires (Westerling et al., 2006). And it is unclear how these altered landscapes might impact long-term carbon storage capacity. Denser forests do not necessarily equate to more carbon storage: some studies have, in fact, shown that dense and shady forests may actually store less carbon than forests with natural fire regimes in which larger trees can grow (Fellows & Goulden, 2008). Of course, depending on the timescale considered and the extent to which carbon transfer to soils is incorporated into calculations, other studies have come to different conclusions (Tilman et al., 2000; Jandl et al., 2007).

Shifting wildfire regimes in California's extensive native woody shrublands such as chaparral has resulted in more frequent fires in these habitats, which is dramatically altering the carbon balance in the state. Shortening intervals between fires is preventing the re-establishment of woody shrublands that require long recovery times (Keeley et al., 2012; Syphard et al., 2019). In turn, weedy invasive grasses are establishing in place of the native shrubs, resulting in widely-distributed habitat type conversion and subsequent loss of carbon storage (Underwood et al., 2018). These weedy grasslands may even be resulting in type conversion of forests to grasslands (i.e., not just to shrublands)—and a larger potential loss of carbon storage capacity (Franklin, 2010; Lenihan et al., 2008).

> ***Finding:*** *The amount of carbon sequestered in the landscape depends on both the rate of carbon storage and the rate of emissions from wildfire or other causes, or removal via logging, vegetation management, habitat type conversion, and development.*

> ***Conclusion:*** *Carbon emissions values alone are not sufficient to assess the net change in sequestered carbon due to wildfire or other causes.*

6.3.2 Losses

The state of California has set a goal of a net 5 million metric tons of CO2 ($MMTCO_2$) annual sequestration rate of carbon by the state's forests (A.B. 1504, Skinner, 2010). The state produces annual reports of forest carbon stocks and includes systematic tracking of net change in stored carbon as a result of wildfire and vegetative regrowth.

The value of naturally sequestered carbon can be estimated using the concept of a "social cost of carbon" (SCC). The SCC is a modeled estimate of the monetary damages associated with an additional ton of CO_2 (tCO_2) emitted, or the avoided damages of sequestered CO_2 (Greenstone et al., 2013). Damages from agricultural loss, sea level rise, and human health are several categories of impacts included in the calculation. A 2017 National Academy of Sciences study reports an average SCC of \$12-\$62/tCO_2, depending on the discount rate, for a ton of CO_2 emitted in 2020 (NAS, 2017). The discount rate refers to a reduction (or 'discount') in value that a future cost or benefit is adjusted for each year in the future to be compared with a current cost or benefit. Forest carbon sequestration or loss is not currently covered under the state's cap-and-trade program, although landowners can be paid for sequestered carbon under the state's offset program.

There is no statewide data available on the estimated costs of carbon sequestration losses induced by wildfires. A complete accounting system should take into account both the loss and re-growth dynamics. Some wildfire cost studies calculate the carbon cost of wildfires as the value of the carbon lost in burned vegetation; however, these studies miss the offsetting value of tree re-growth (Christin et al., 2017). A handful of case studies have estimated the total value of carbon sequestration for areas pre- and post-wildfire to calculate the potential monetary losses due to carbon emissions driven by a wildfire (Table 6.4). For the reasons discussed above, measuring the change in carbon directly after a fire likely overstates the net loss in ecosystem carbon. This approach should be avoided when possible in favor of more comprehensive carbon accounting.

> ***Finding:*** *The state produces annual reports of forest carbon stocks and includes systematic statewide tracking of net change in stored carbon as a result of wildfire and vegetative regrowth.*

> ***Conclusion:*** *Current tracking of carbon sequestration appears to be sufficient to meet present needs for understanding the societal costs of wildfire in California.*

6.3.3 Prevention and Mitigation

Prevention and mitigation of net sequestered carbon losses in dry mixed-conifer forests could potentially be achieved through fuels management and habitat restoration activities (see Chapter 3). These activities promote increased carbon accumulation and storage through vegetative growth and/or decreased carbon emissions when wildfires do burn. The extent to which fuels management is deployed across the state, with the stated goal of preventing loss of sequestered carbon, is not currently systematically tracked. The costs of these prevention and mitigation efforts are generally unknown.

6.3.4 Effectiveness at reducing losses

By reducing the size and severity of wildfire (Campbell & Ager, 2013; North & Hurteau, 2011), fuel treatments are intended to reduce the amount of carbon emitted in a given wildfire event. However, the effect of fuel treatments on net amount of carbon sequestered depends on the timescale considered, the fuel treatment implemented, the contribution of other mitigation actions such as suppression, the vegetative composition, and the specific model used for analysis, among other variables. As a result, a number of studies present conflicting findings about the effectiveness of fuel treatments. Some studies find that fuel treatments can result in a net carbon savings relative to no fuel treatment (Hurteau et al., 2008; Finkral & Evans, 2008; Hurteau & North, 2009; Stephens et al., 2009; Wiedinmyer & Hurteau 2010), whereas others find that fuel treatments can result in a net loss of carbon (Campbell et al., 2013; Mitchell et al., 2009; Chiono 2017; Hurteau & North, 2009; Stephens et al., 2009).

Attempting a cost-benefit analysis of fuel treatments to defer carbon losses due to wildfires is far from straightforward, given the uncertainty in characterizing the actual effect of altered fire regimes on carbon storage. Net fuel treatment costs are a function of direct expenditures for implementing a treatment, the cost of periodic maintenance, and the potential revenues generated from the sale of marketable products like biomass, pulpwood, and timber (Thompson & Anderson, 2015). While the cost of a given fuel treatment may be relatively simple to estimate or record (e.g., mechanical fuel treatments under challenging conditions can cost thousands of dollars per hectare (USDA Forest Service, 2003), it is much more challenging to estimate how cost-effective those fuel treatments are as a function of the amount of carbon sequestration they preserve. The variability in assessing the amount of carbon sequestered by using fuel treatments and determining the price of carbon leads to highly variable estimates of monetary savings resulting from fuel treatments (Buckley, 2014).

6.3.5 Conclusion

The impacts of wildfire on carbon sequestration in California's forest lands is systematically tracked by the state. The economic value of net changes in sequestered carbon due to wildfire has not been assessed. Land management efforts including fuels management and prescribed fire have the potential to alter net changes in sequestered carbon. The extent to which prevention efforts have been implemented across the state—and the cost-effectiveness of those efforts with respect to carbon sequestration—is generally unknown.

Table 6.4. *California-specific literature from this review relevant to losses in net sequestered carbon from wildfire and prevention and mitigation actions to reduce losses.*

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Exposur e	Losses		Prevention and Mitigation Actions		Effectiveness at Reducing Losses	
Source	**Wildfire**	**Numeric**	**Numeric**	**Dollars**	**Numeric**	**Dollars**	**Numeric**	**Dollars**
Batker et al., 2013	2013 Rim Fire	0	2	2	0	0	0	0
Buckley et al., 2014	Simulations of Mokelumne Watershed	0	1	1	1	1	1	1
Christensen et al., 2018	California Wildfires	3	3	0	0	0	0	0
Christin et al., 2017	2016 Loma Fire	0	2	2	0	0	0	0
Stephens et al., 2009	Simulated Wildfires	0	0	0	2	0	0	0
Stephens et al., 2012	Simulated Wildfires	0	0	0	2	0	0	0
Vaillant et al., 2013	Simulated Wildfires	0	0	0	2	0	0	0
Wiedinmyer and Hurteau 2010	California Wildfires	0	0	0	1	0	0	0

6.4 Other Ecosystem Services

6.4.1 Impacts

In addition to watershed services and carbon sequestration, California's ecosystems provide numerous other ecosystem goods and services including recreation, habitat for species, air quality, natural and cultural resources, pollinators, and aesthetic value. Wildfires are a natural disturbance in many California ecosystems and there is a robust scientific literature on the ecological impacts of wildfires (Keeley, 2009; Newman et al., 2018; Reilly et al., 2020; Jennings et al., 2018). The U.S. Forest Service maintains an online collection of relevant papers that returns hundreds of results for California. As stated in the introduction, a full review of the fire ecology literature is outside the scope of this report. Here we highlight a small number of additional ecosystem goods and services because we found studies that specifically valued impacts to them as losses due to California wildfire events.

6.4.2 Losses

Whether any given outcome from a wildfire should be considered a gain or a loss depends on the management goals and values attributed to the specific land under consideration (Stephens et al., 2014). Examples of losses include negative impacts to populations of state- and federally-listed protected species, the loss of habitat or areas used for recreation, or the introduction or expansion of invasive species that outcompete native species (Franklin et al., 2006; Coffman et al., 2010; Keeley & Brennan, 2012; Halstead et al., 2019; Siegel et al., 2019). A full review of the literature discussing how wildfire impacts these goods and services is outside the scope of this report.

As discussed in the introduction to this chapter, valuing non-market ecosystem losses due to wildfire in California is difficult and generally not known, especially because many of these losses are cumulative and manifest ecologically over long time scales. Post-fire BAER and WERT reports may include assessment of potential ecological losses from wildfire such as degradation of critical habitat for endangered species. We found only a handful of individual studies in the literature that assess the value of ecological losses from wildfire (Table 6.5). Ecosystem services valued include: aesthetics (Batker et al., 2013); moderation of extreme events (Batker et al., 2013); air quality (Batker et al., 2013); soil retention (Batker et al., 2013; Christin et al., 2017); and critical habitat for Spotted Owl (Loomis, 1997). In general, the full economic costs of ecosystem losses are unknown.

6.4.3 Prevention and Mitigation and their Effectiveness

Prevention of ecosystem losses typically relies on landscape and fire management activities to promote beneficial wildfire regimes and resilient ecosystems. For instance, Yosemite National Park uses fire and vegetation management to achieve multiple benefits including ecosystem health and restoration of native flora and fauna. Similarly, the Karuk Tribe in northern California uses fire to promote the growth and quality of natural food, medicine, crafting, and cultural resources (Karuk Tribe, 2019). Post-fire BAER and WERT reports may include the cost of activities to mitigate impacts to critical species, protect culturally important resources, restore habitats, and prevent the spread of invasive species. The cost-effectiveness of these efforts is generally not known.

Table 6.5. *California-specific literature from this review relevant to costs associated with ecosystem services losses from wildfire.*

Legend: Availability of California-specific Data

- 0 No data for CA
- 1 Simulated data from individual studies or anecdotal accounts
- 2 Empirical data from individual studies or reports
- 3 Empirical datasets from partial systematic tracking
- 4 Empirical datasets from comprehensive, state-wide, systematic tracking

		Exposure	Losses		Prevention and Mitigation Actions		Effectiveness at Reducing Losses	
Source	**Wildfire**	**Numeric**	**Numeric**	**Dollars**	**Numeric**	**Dollars**	**Numeric**	**Dollars**
BAER Burned Area Reports Database	Wildfires on federal land	2	2	2	0	0	0	0
Batker et al., 2013	2013 Rim Fire	0	0	2	0	0	0	0
CA Watershed Emergency Response Teams (WERT)	CA wildfires on non-federal land	2	2	2	0	0	0	0
Christin et al., 2017	2016 Loma Fire	0	0	2	0	0	0	0
Loomis, 1997	NA	0	0	2	0	0	0	0
Schaaf et al., 2004	Simulated Wildfires	0	1	1	1	1	1	1
Thompson et al., 2017	SImulated Wildfires	0	1	1	1	1	1	1

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Chapter 7

Additional Economic Impacts of Wildfires

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7.1 Chapter Scope

Chapter 7 reviews literature on the economic effects of wildfires in a wide range of sectors and markets, as well as in the economy overall. These broader effects are important to account for when considering wildfire costs. However, the existing understanding of many of these impacts is limited. Ideally, we would like to measure the effects of wildfire on economic surplus—i.e., the benefits to consumers and businesses from consuming and producing goods and services, minus of the cost of supplying them. This notion of surplus or "welfare" is usually not directly observable in data. Nearly all of the studies reviewed in this section do not measure changes in welfare. Instead, they generally report overall economic and market impacts resulting from wildfire events. These include changes in prices, quantities, and other indicators of economic activity. Caution should be taken not to add up all of these impacts to obtain an estimate of total cost. Often, different indicators of broad economic activity are measuring the same impact from different perspectives. An important gap in the existing literature is the lack of studies that measure the full welfare impacts of changes in markets after wildfire events.

It is also important to keep in mind when discussing the economic impact of wildfires that repairing and rebuilding damaged assets may appear in data as an increase in economic activity. For example, rebuilding destroyed homes will boost economic activity in the construction sector in the short run. However, this increase in economic activity in certain sectors in the short-run, has an opportunity cost of foregone economic activity in other parts of the economy. A full economic welfare analysis of wildfires would ideally measure these opportunity costs when considering the broad economic losses associated with wildfires.

7.2 Impacts by Sector

Like other natural and human-caused disasters, destructive wildfires have the potential to affect economic activity. Economic impacts can either be direct, where losses are the direct consequence of the fire, or indirect, where changes in business and consumer demand affect specific sectors. We focus on three sectors of the economy: working lands, recreation and tourism, and construction. Electric power, which is another important sector that experiences direct market impacts from wildfires, is discussed in Chapters 3 and 4.

7.2.1 Recreation and Tourism

Wildfires have the potential to disrupt visitation and tourism in recreational areas throughout the state. Disruptions can occur during a wildfire event due to safety concerns, as well as after the wildfire due to changes in the natural landscape. Changes in recreational visitation also have indirect effects on the broader tourism industry surrounding an affected area, as well as supply chain and income multiplier effects due to changes in spending in the tourism industry. In fact, the tourism sector is more prone to disruption resulting from wildfire than other sectors of the economy (Nielsen-Pincus et al., 2014). Economic losses within the recreation/tourism sector can be felt for “many years” after significant wildfire events in the American West (Barrett, 2018). For example, the large wildfire bordering Yellowstone National Park in 1988 resulted in decreased visitations, costing an estimated $21 million in 1988, $13 million in 1989, and $26 million in 1990 (Barrett, 2018). There were losses between $2.7 and $4.5 million resulting from visitation decreases during and after wildfire in Utah’s national parks (Kim & Jakus, 2019). The length of the visitation decline can last for several seasons depending on the severity of the wildfire event (Hilger & Englin, 2009; Barrett, 2018).

Studies of California wildfires follow the general findings from this literature. After the 2008 wildfires in Trinity County, which burned across approximately 241,000 acres, there was decreased tourism and recreation spending in regional economies, including rafting and camping reservation cancellations (Davis et al., 2014). Survey data from the San Jacinto Wilderness, which covers 33,000 acres in the San Bernardino National Forest, indicates a welfare loss of $3.7 million if the wilderness area were to close due to significant wildfire, but a welfare gain of $1.2 million for changes in the viewscape of the park under low-intensity fire (Sanchez et al., 2016).

Other California wildfire case studies highlight the broad range in recreation losses attributable to wildfires. Christin et al. (2017) estimate recreation and tourism ecosystem services lost between $1,400 to $10,200 in the 2016 Loma Fire (4,474 acres) in Santa Clara County. Batker et al. (2013) estimate recreation and tourism losses from the 2013 Rim Fire (257,000 acres) in Yosemite National Park and Stanislaus National Forest ranging from $450,000 to $211,000,000. Both studies used a benefit transfer methodology to estimate losses.

It is difficult to compare tourism and recreation loss estimates across wildfires, because affected areas will vary in the size of the recreation area, the size of the fire, and baseline visitation levels. No studies were identified that analyzed the factors affecting the range in losses across different wildfire events. Further, no studies were identified that measured possible losses to everyday, outdoor recreation. Smoke events from large wildfire events are likely to also affect these recreational activities and further evidence is needed in order to understand the magnitude of these impacts.

7.2.2 Working Lands

Wildfires often occur in heterogeneous landscapes comprised of both natural and working lands. When fires encroach onto working lands, they have the capacity to cause substantial direct impacts to agricultural and forestry products. These effects are very specific to the behavior of a specific wildfire, suppression efforts, and weather conditions. This subsection outlines the research on the wildfire losses to working lands.

7.2.2.1 Agriculture

There is widespread anecdotal evidence that wildfires have caused substantial damage to various agricultural regions. For example, following the 2007 Southern California wildfires, an assessment team for San Diego County noted that the wildfires had burned nearly 1,000 acres of crops, with a damage estimate of approximately $42 million (EDD, 2007) . For reference, the cost of property loss from the 2007 San Diego County wildfires was estimated around $1.5 billion. Avocados and lemons were cited as the most affected crop. In the 2017 Sonoma County wildfires, there was news coverage suggesting substantial losses to the regions wine industry. However, a 2018 study by the Sonoma State University Wine Business Institute concluded that 99.8% of vineyard acreage and 93% of wineries in the region were unaffected by the wildfires. The report noted a substantial (71%) drop in tasting room visits during and immediately after the wildfires, which recovered by November 2017. The survey did not report any decline in grape quality from smoke-taint, although this has been cited as a concern to the industry (Caffrey et al., 2019). Anecdotal evidence suggests there was widespread testing of smoke taint during the 2020 wildfire season in Northern California (Klearman, 2020). Testing is now required by growers for insurance payouts.

Data on crop losses to wildfire do not seem to be systematically tracked across the state. There may be county agriculture departments that collect such data. The National Fire Incident Response System, maintained by the Department of Homeland Security may also collect fire incident data by land use type.

No studies were identified that analyzed the economic incidence, or who pays for, the loss in agricultural crops. Farmers who have federal or private crop insurance would be covered in case of crop losses to wildfire. However, the California Employment Development Department (EDD, 2007) claims that only 50% of agricultural producers in the state have insurance coverage. Most high value crops in California are not covered by federal crop insurance programs. There were no reports found on whether fire losses to agriculture are occurring at higher rates for insured or uninsured producers.

7.2.2.2 Range/Livestock

No studies were found that analyzed the economic impact of wildfires on California's ranching sector. Anecdotal evidence from a report on the economic costs of the 2013 Rim Fire noted that costs to the ranching sector were in the millions of dollars from lost grazing land and killed livestock (Barrett, 2018). This is a small fraction of the total economic cost of the Rim Fire ($388–$1,271 million) reported in Barret (2018). One academic modeling study was identified examining the effects of wildfires on a representative ranching operation in Southeast Oregon (Kim et al., 2012)

7.2.2.3 Timber

Timber losses to wildfire are tracked annually through a multi-agency process in AB 1504 California Forest Ecosystem and Harvest Wood Product Carbon Inventory reports (Christensen et al. 2019). While estimates are broken down by land status and ownership class, the estimates are reported as carbon losses and not as the value of merchantable timber. This information could potentially be used to make an inference of lost wood product revenue, however systematic analysis of the topic was not found.

In addition to merchantable timber lost on private land to wildfire, it is important to note that salvage logging on public and private land generally increases after a wildfire event. For example, the U.S. Forest Service allowed salvage logging in large swaths of forest following the 2013 Rim Fire. There have been several economic studies on this issue (Prestemon & Holmes, 2004; Prestemon & Holmes, 2008; Zhai & Kuusela, 2020). Salvage logging following wildfire events can have significant impacts on timber markets in both the short and long run, however, there do not appear to be any welfare estimates on the aggregate effects that would allow for a calculation of net losses or gains.

7.2.3 Construction

Anecdotal evidence suggests that wildfires can have significant impacts on the construction industry as communities attempt to rebuild lost structural assets after a wildfire event. The topic does not appear to have been systematically studied in the context of wildfires; however, analysis of other natural disasters has shown that employment in the construction sector can increase substantially after a disaster event (Strobl & Walsh, 2008). However, as Strobl and Walsh note, "any increase in construction employment from increased economic activity devoted to restoring damaged capital should not be thought of as offsetting the losses associated with the hurricane since this activity reflects resources being utilized to replace destroyed capital."

Anecdotal evidence in California, based largely on news reports, suggests rebuilding efforts and the response of the construction market often vary both between fires and between neighborhoods affected by a single fire. Responses also are likely to vary regionally based on local property markets. There is also anecdotal evidence to suggest that the rebuilding effort puts upward pressure on construction costs, particularly in areas with extensive property loss and damages, and in areas with already tight construction markets. However, no studies were found that studied these dynamics in detail and this appears to be an important area for future research.

7.2.4 Supply chain effects

Wildfires can have both direct sectoral impacts, such as those detailed above, but can also cause broader business interruptions due to damaged supply chains and lower consumer demand. California wildfires have disrupted supply chains by causing road closures along important trucking routes, loss of material inputs for manufacturing, and forcing closures of threatened distribution centers. Most of the recorded evidence for these disruptions has been for wildfires in Southern California, although other major wildfires are likely to have caused similar business disruptions in other parts of the state. A systematic analysis of these supply chain effects was not found, suggesting an important gap in our understanding of the economic impacts of wildfires.

Measuring direct losses from wildfires is relatively straightforward since such losses are largely observable. Measuring the supply chain and other indirect economic effects of wildfires is more challenging but these effects can be quite large in advanced, interconnected economies. Butry et al. (2019) propose a methodology for quantifying supply chain losses from wildfires that relies on computable general equilibrium (CGE) models of regional economies. CGE models depend on underlying input-output data tables to model the interconnectedness of economic sectors and consumer demand. Alternative approaches relying on firm-level data have been applied in other disaster settings (Inoue & Todo, 2019). While the methodologies and data appear to be available and have been applied to other natural disasters and electric power disruptions in California (e.g., Rose & Lim, 2002; Sue Wing & Rose, 2020), there appear to be no applications in the context of wildfires broadly, or California wildfires specifically.

> ***Finding:*** *Wildfires create economic impacts across a range of sectors beyond those typically considered. In addition to direct economic impacts on affected sectors, wildfires can create disruptions in supply chains that have broader economic multiplier effects.*

> ***Conclusion:*** *The magnitude of these supply chain losses in various sectors is highly localized and often poorly understood. Data to study these effects in not widely available for the research community.*

> ***Recommendation:*** *A long-term study of the sectoral impacts of wildfires, both direct and indirect, is needed. New data collection efforts, or a compiling of existing data sources, may be needed to support this effort.*

7.3 Economy-wide Impacts

In this section we review the literature analyzing the relationship between wildfires and broad macroeconomic indicators. These include indicators of economic growth and output (such as gross domestic product and total productive output), indicators of impacts in the labor market, indicators of household well-being (such as wealth and income), and indicators of household migration. While presumably economy-wide indicators are some reflection of the aggregation of impacts in different sectors, because much of the literature uses macroeconomic data, we felt it was important to separate these two categories of impact.

7.3.1 Labor Market Impacts

Local labor markets often experience changes after natural and human-caused disasters (Belasen & Polacheck, 2008, 2009; Ewing et al. 2003, 2009). In general, economic theory suggests that natural disasters cause reductions to both labor market supply and demand. Labor supply can drop if regional workers are forced to evacuate a region either temporarily or for an extended period of time. In the short run, theory suggests that both wages and unemployment would increase from a labor supply decrease. Business closures, supply chain disruptions, or a drop in consumer demand resulting from a natural disaster would decrease labor demand. These factors would reduce employment and depress local wages.

Several studies have focused on the labor market effects of wildfires. The first set of studies analyzes the impact of the wildfire event itself on local labor markets, while other studies have focused on the labor market effect of smoke exposure, often far from the wildfire event.

Nielson-Pincus et al. (2013) studied the effects of wildfire events in the western U.S. over a five-year time frame. Nearly 40% of the wildfires in their sample occurred in California. They found that when the wildfire was active, average employment and wage growth increased by a very small margin (approximately 1%). They attribute this to the direct and indirect economic stimulus provided by suppression efforts. Nielson-Pincus et al. (2014) broke down the employment effects by sector, finding that natural resource related sectors see a 2.7% increase in employment activity during wildfires, while leisure and hospitality sectors see a 2.5% decrease in employment activity during wildfire. In a follow-up report to the October 2007 wildfires in Southern California, the California Employment Development Department analyzed fire-related unemployment insurance claims in seven Southern California counties. The agency documented 6,427 fire-related unemployment insurance claims, including 755 Disaster Unemployment Assistance claims. According to EDD, there were 3,135 firms within the fire perimeters, employing 41,394 individuals.

Wildfire impacts on labor market outcomes may differ from other types of natural disasters because of the adverse effects of smoke exposure and the ability of smoke to affect communities far away from the actual wildfire. A large body of economics research has established that pollution can decrease both labor market participation and labor productivity (Graff Zivin & Neidel, 2013; Aragon et al., 2017). Borgshulte et al. (2020)

measured the labor market effects of smoke exposure, finding that wildfire smoke can reduce earnings for up to two years after the smoke event. The authors suggest that the welfare loss of these lower earnings may be even larger than the mortality cost of the smoke exposure. This is an important preliminary finding, suggesting that welfare losses in labor markets are substantial and occurring far from the source of the wildfire.

Wildfire prevention and mitigation efforts also provide labor market benefits in California. For example, vegetation management, whether through hand and mechanical thinning or prescribed fire, requires a dedicated workforce of foresters, burn operators, and other specialized occupations. No systematic analysis of the prevention and mitigation workforce was identified, although many of the issues associated with workforce development are outlined in Collier (2020).

Data for studying these relationships is available from a variety of sources. County-level employment and wage data by economic sector is available for all counties in California. Several datasets collected by the Federal government report employment and wage data.

> ***Finding:*** *Wildfires and associated smoke exposure appear to impact local labor markets. Limited evidence suggests that wildfire smoke exposure reduces employment and earnings.*

Contemporary Considerations: COVID-19 and the Firefighting Workforce

Reduction in firefighting workforce

In addition to implementing new safety guidelines and management strategies for fighting wildland fire, the COVID-19 pandemic caused a reduction in the firefighting workforce. A COVID-19 special study by the U.S. Fire Administration found that 265,764 fire service personnel had confirmed or suspected COVID-19 cases out of the 1,249,265 responses collected January–July 2020 (NFIRS, 2020). While these infections are largely acquired by responses to emergency medical response calls, rather than wildland fire, they still have an impact on the available firefighting force (NFIRS, 2020). In California in particular, the State relies heavily on incarcerated firefighters to combat wildland fires, yet due to the disproportionate impact of COVID-19 on incarcerated people, only 94 of 192 inmate fire crews from the California Department of Corrections and Rehabilitation are available (CBS Bay Area, 2020).

In order to increase the number of firefighters available to fight wildland fire, CAL FIRE is hiring an additional 858 seasonal firefighters and six California Conservation Corps crews. Further, the state budgeted $85.6 million to fund permanent firefighting positions and increased the size and technological capacity of the CAL FIRE air fleet (Office of the Governor, 2020).

7.3.2 Economic Growth and Wildfires

There is substantial evidence that natural and human-caused disasters can affect economic growth, especially locally. This is due to a range of factors including labor supply disruptions, business interruptions, destroyed capital stocks, and reduced consumer demand. Much of the peer-reviewed literature in the United States on the economic growth effects of natural disasters has focused on hurricanes and flooding. For example, coastal counties experience a half percentage point decrease in economic growth directly following a hurricane (Strobl, 2011). Low-intensity hurricanes caused business interruptions equivalent to approximately 1% of total business output (Burras et al., 2002). Repeated low- or moderate-intensity disasters could therefore potentially have larger cumulative effects on short-term economic growth. In most cases, it appears that these growth effects are limited to the counties experiencing the disaster event and have little impact at the state or national level. The evidence also appears to suggest that in the case of moderate disaster events, adverse economic growth effects do not last particularly long.

It is not clear whether this finding applies more specifically to wildfires. In particular, no systematic studies were identified on the relationship on the economic growth effects of California's wildfires. Mu & Chen (2016) use the SHELDUS database, which tracks all natural disasters, including wildfires, to quantify the relationship between natural disasters and economic activity. Their results suggest a $112–$267/person reduction in economic activity in counties that experience a natural disaster. While county level data on economic activity is available, it does not appear to have been analyzed in the context of either wildfire or smoke effects.

Case study approaches that do simple before and after comparisons of county economic activity indicators have generally found that wildfires have no discernible impact on economic activity at the county level. For example, Thornberg (2018) reported county and state personal income (an aggregate indicator of economic activity) before and after four California wildfires. Except for the 2007 wildfires, which occurred at the beginning of the Great Recession, economic activity remained relatively unchanged, or in the case of the 2015 Valley Fire, increased substantially in the years at the fire. Many other factors that vary over time affect these measures of economic activity and simple before/after comparisons do not imply any sort of causal relationship. In fact, for broad macroeconomic indicators, these comparisons can be potentially misleading. More rigorous statistical analysis, controlling for other potential confounding factors, is needed on the relationship between wildfire events and economic activity.

While the current literature on natural disasters and economic growth is informative, one important limitation is that they do not consider the economic growth impacts of wildfire smoke that has the potential to travel long distances and potentially disrupt economic activity far from the wildfire event. No studies were found that documented the economic growth effects of wildfire smoke exposure.

There is considerable need for additional research on the relationship between wildfire events, including resulting smoke exposure, and economic growth indicators. Additional research could also broaden the set of indicators beyond traditional metrics of economic activity like income and aggregate production. For example, what effects do wildfire and smoke exposure have on educational outcomes? Do school closures from wildfires have lasting economic effects? No studies were identified that examined the impact of wildfire events on educational metrics.

> ***Finding:*** *The impact of wildfires on economic growth in California is unclear. Broader studies of natural disasters and economic growth suggest that there could be an adverse short-term, regional effect but the topic has not been well-studied in the context of wildfires specifically.*

> ***Finding:*** *No studies were identified that examined the economic growth impacts of wildfire smoke exposure.*

> ***Conclusion:*** *Additional research is needed to understand the effect of wildfires and wildfire smoke on economic growth. Research should focus on identifying short-run vs. long-run effects and differences across economic sectors.*

7.3.3 Household Well-Being

The disruptive nature of wildfires can affect the well-being of households by destroying physical assets, disrupting employment opportunities and income, and causing dislocation. There appears to be no systematic research on the relationship between wildfires and indicators of household financial well-being. The most relevant study, by Boustan et al. (2020), examined the impacts of natural disasters on county poverty levels in the U.S. The study reports that in the decade following a fire, poverty rates drop by 0.4% for each additional large fire in a county. There is not a strong explanation for why this occurs. Plausibly, if less affluent households are forced to relocate outside of an affected county, this could result in lower poverty rates. There is some evidence from the 2018 Camp Fire of this type of out-migration for less affluent households, but the topic has not been analyzed in depth.

7.3.4 Migration

Wildfires appear to cause a reasonably large (3.1%) level of out-migration from a county in the decade following a large wildfire event (Boustan et al., 2020). Recent work by researchers at California State University, Chico, has provided case study evidence from the Camp Fire supporting this broad out-migration finding. The researchers analyzed official change of address forms for approximately one-third of the 37,198 individuals living in the Camp Fire footprint. Several interesting results have emerged from their analysis, showing socio-demographic differences in out-migration patterns. First, more than 50% of the elderly population (65 or older) that changed their address moved more than 30 miles away from their previous address. The rates were much lower for other age groups (Figure 7.1). Second, less affluent households with new addresses appear more likely to move further away from their prior residence than more affluent households (Figure 7.1).

The effect of wildfires on household economic well-being could likely be studied in depth given currently available data. For example, in the context of other natural disasters, researchers have tracked the financial situation of households using individual tax returns (Deryugina et al., 2018), mortgage financing data (Gallagher & Hartley, 2017; Bleemer & van der Klaauw, 2019). Research has also found that natural disasters can have unequal impacts on household finances based on pre-disaster financial status (Billings et al., 2019). Detailed household-level migration data may be more difficult to acquire, although may be collected by the state Franchise Tax Board with tax filings. County-to-county migration flows are tracked as part of the U.S. Census Bureau's American Community Survey and there is a rich literature on methodologies and data sources for tracking migration flows.

Figure 7.1. *Migration patterns following the 2018 Camp Fire. Source: Hansen (2019)*

7.4 Housing Markets

Chapter 4 documented the direct losses to physical structures, including residential properties, associated with wildfire events. There are also indirect impacts of wildfires on residential property markets. We consider indirect impacts to be changes to the broader housing market after a wildfire affects a community. These studies generally use "hedonic pricing" models to determine the change in economic value associated with a wildfire, measured as the assessed value or sales price of a home,. In addition to capturing information about how housing markets change after wildfire events, the hedonic pricing approach can plausibly reflect amenity values, risk perceptions, and other conceptual variables of economic interest. This approach has been widely used to measure the impacts of natural disasters on home prices, including for floods (e.g., Bin & Polasky, 2004; Bin & Landry, 2013; Zhang &Leonard, 2019;); hurricanes (Carbone et al., 2006); and earthquakes (Beron et al., 1997). A national study analyzed 80 years of data, and found that severe disasters cause an average reduction in home price and rents by 5.2% and 2.5%, respectively (Boustan et al., 2020).

There is a fairly robust literature on the effects of wildfires on housing markets. Studies of single wildfire events have shown that nearby homes prices can fall quite precipitously following a major wildfire. For example, home prices fell by 15% for a Colorado community located two miles away from a large wildfire (Loomis, 2004). Homes within 5 kilometers (3.1 miles) of the 2010 Schultz Fire near Flagstaff, Arizona, fell by 31% (Mueller et al., 2018). The authors also document some price decline associated with the post-wildfire flood risk on steep slopes. Using a dataset of 256 wildfires in Montana, Stetler et al. (2010) found that home prices within 5 km (3.1 mi) of a wildfire were 14% lower than similar homes not near a wildfire. Proposed mechanisms include reductions in amenity value, which presumably drops after a damaging fire effects viewscapes, and increased risk perceptions (Loomis, 2004; Donovan et al., 2007; McCoy a& Walsh, 2018; Kiel & Matheson, 2018). Most studies outside of California have focused on regions that were relatively low-population density.

Most work on the relationship between housing markets and wildfires in higher-density California communities is in Southern California. Mueller et al. (2009) analyzed five fires in Los Angeles County during the 1990s. They found that average home prices dropped by approximately 10% after exposure to a single nearby fire and 23% if the home was exposed to a second nearby fire.

These decreases in value post-fire are well-documented but difficult to interpret. Do these changes reflect learning about local risk, so that buyers are not willing to pay quite so much to live there? And if so, are these changes in attitude permanent or is there “forgetting” over time? Or perhaps they reflect changes in amenity value due to disrupted views? Or do they reflect some other factor, such as changes in local homeowner’s insurance prices as insurance companies change rates? More research is needed to untangle these potential explanations.

As a start in this direction, recent work by Garnache & Guilfoos (2018) attempts to disentangle these amenity and risk perceptions effects. The authors analyzed the impact of 15 years of wildfires on housing markets in counties in the Los Angeles and San Diego basins, and found that nearby home prices dropped by an average of 4.5% due to impaired viewscapes (the amenity effect) and 3–4% reduction due to heightened risk perceptions. In a separate study focusing on wildfire risk perception, the authors found that changes in 2008 wildfire risk designations by CAL FIRE were associated with a drop in sales price of nearby homes of 10–11% (Garnache & Guilfoos, 2019). The authors suggest this drop in home price could be due to updated risk beliefs and higher insurance premiums, both which would lower the price of an affected home.

One recent working paper analyzed the relationship between wildfires and mortgage delinquencies and foreclosures (Issler et al., 2020). Using 18 years of data for California residents, the authors found that both mortgage delinquency and foreclosures increase after a fire event.

Because homes are such an important asset to many Californians, it is useful to understand market-related welfare changes resulting from wildfires. The current body of work is a good start, but several gaps remain. As mentioned above, a deep understanding of the drivers of property value changes is needed. Also, most research to date has focused primarily on Southern California, where the wildfire regime and population/market characteristics are quite different from other parts of the state. Another important gap is that the published research in this field does not include the most recent wildfire seasons, which included the Camp (2018) and Tubbs (2017) Fires. These fires destroyed 18,804 and 5,643 buildings, respectively. From a property loss perspective, these two fires were by far the most damaging in recent history in the state. The impacts of the events on local and regional property markets is not yet well understood. A final gap that should be addressed in this area of research is how the effects of wildfire on property markets are complicated by California's existing housing crisis. For example, to what extent does the inelastic housing supply in communities like Santa Rosa amplify any potential housing market impacts from wildfire?

> ***Finding:*** *A growing body of research highlights the impacts of wildfires on housing markets in California, focusing primarily on markets in Southern California.*

> ***Conclusion:*** *Several important gaps in this literature exist. These include a more comprehensive geographic understanding of housing market impacts and the impacts from the last several years of wildfires, which are outliers in the extent and severity of housing destruction and resident displacement.*

Data are widely available to track property values and home sales in the state. Most recent studies that utilize the hedonic pricing method generally rely on datasets from county assessors' offices. These local government agencies collect parcel-level transaction and characteristic data. These data are generally available to the public, although often must be purchased. Private firms, such as Zillow and CoreLogic, aggregate county assessor data into regional datasets that can be used for analyzing broader geographical housing market trends.

7.5 Fiscal Impacts

Federal, state, and local governments are critical actors before, during, and after wildfire events. Governments provide resources to reduce the likelihood of fire and mitigate the impacts of fire on livelihoods, property, and well-being. Government revenue is also affected by fire, as the tax base potentially changes, and even population reductions due to temporary or permanent out migration from an affected region.

Previous sections noted that wildfires, and natural disasters more broadly, can reduce home values, cause business interruptions, and reduce consumer demand in various ways. All three of these economic impacts have the potential to reduce government revenue at all levels through reduced property, sales, and business tax collections. However, this topic has not been studied in depth in the case of wildfires. There also appears to be no database or central accounting framework for collecting information on the impact of wildfires on tax revenues.

One case study was identified on the fiscal impacts of the 2017 wildfires in Sonoma County. The authors found that local tax revenues did not decline immediately after the wildfire season. They suggest that this may be due the rise in economic activity from the rebuilding efforts. The report also notes that assessed property values do not appear to decline after wildfire events, even in areas where significant property loss is recorded. They suggest that this may be due to the fact that the vast majority of a property's assessed value is tied to the land and not the structural assets.

Although not discussed in depth in the literature, the effect of wildfires on property taxes is complicated by California's Proposition 13, which limits the increase in a property's assessed value. If wildfires lead to more property sales, this could trigger re-assessments and much higher taxable assessments. California has other property tax protections for homeowners. For example, homeowners who decide to move or rebuild can transfer their Proposition 13 assessments to the new properties and construction. Additional taxes are only paid if the value of the new property or construction is substantially higher than the home that was damaged. State law also allows homeowners to defer their property taxes after a wildfire, which decrease tax revenues in the short run.

> ***Finding:*** *No systematic research was identified that analyzed the effects of the relationship between property tax revenues and Proposition 13 in the context of California wildfires.*

The Sonoma County case study is consistent with the limited academic research on the impacts of natural disasters on government fiscal status. For example, Miao et al. (2018) used the Spatial Hazard Events and Losses Database for the United States (SHELDUS), which includes wildfires, to estimate the impact of disasters on state-level expenditures, revenues, and federal transfers. While state expenditures and federal transfers increase after a disaster event, overall state revenues do not change much. However, the authors note that examining revenue by source (sales tax, property tax, and personal and corporate income tax) reveals both short and long run differences. For example, sales tax increases immediately after the disaster even but falls below the counterfactual after five years. Property taxes fall immediately but recover after several years. California's unique property tax laws make it difficult to make inferences from this national-study.

> ***Finding:*** *No studies were found that systematically analyzed the impact of wildfires on local government tax revenue, which is where you would most expect to observe an impact.*

> ***Conclusion:*** *The large turnover in housing stock from wildfire damage, and associated resident displacement, suggests that an understanding of the revenue implications from tax adjustments is highly consequential.*

> ***Recommendation:*** *Further study is needed to understand the implications of Proposition 13 and housing markets in communities that rebuild after wildfires.*

Federal and state disaster aid are often triggered by major wildfire events. An overview of direct assistance and prevention expenditures are covered in prior chapters. However, there are possibly other indirect expenditures from federal and state governments in response to wildfires, particularly if social safety net program expenditures increase due to long term displacement or unemployment. Deryugina (2017), studying 50 years of hurricanes in the U.S., found that non-disaster government transfers attributable to the hurricane were actually larger than direct state and federal disaster assistance. It is not clear whether this finding holds for wildfires in California. It likely depends on the severity of the disaster and the degree to which individuals are displaced and their physical assets destroyed.

Detailed government revenue data is publicly available for all levels of government. For example, the Census Bureau report states finance information in their State Government Finances Survey. However, local government revenue data does not appear to be centralized in order to systematically study the effects of wildfires on local government revenue streams.

> ***Finding:*** *Governments at all levels respond to wildfires with increased fiscal spending. The effects of wildfires on government revenues are not well established.*

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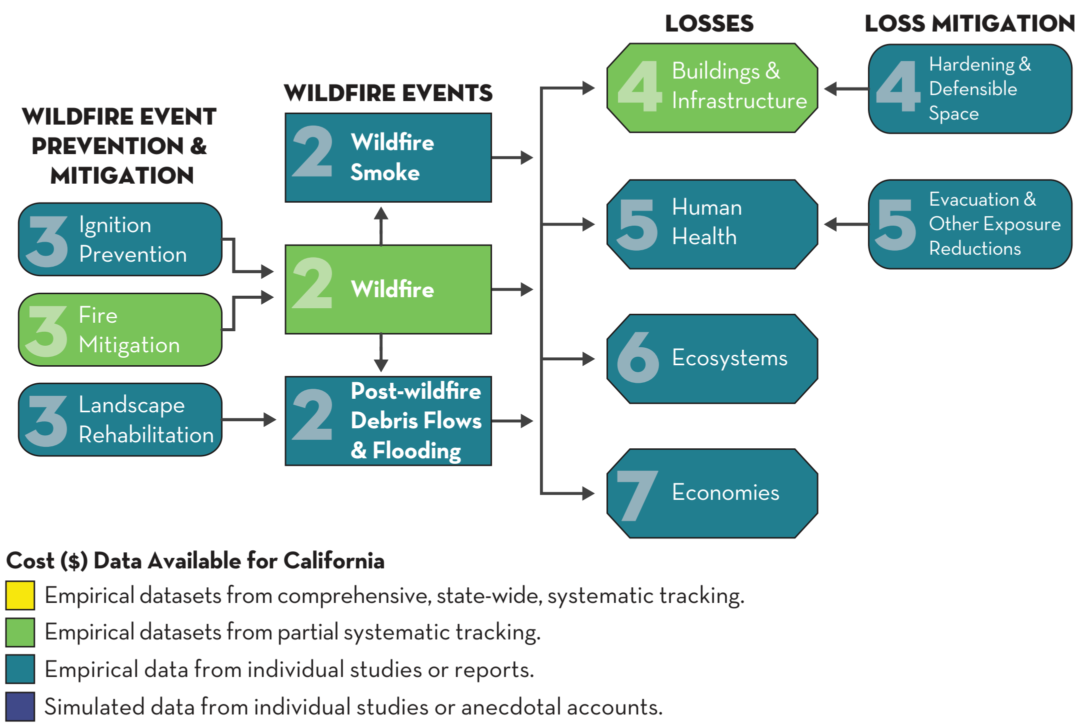
Chapter 8

Conclusion

The past three years of wildfire in California have imposed truly catastrophic costs on the State. Although wildfire is not new, and wildland-urban interface fires have been a particular concern with direct policy impacts for California since the Malibu Canyon Fire in 1970, the scale of human suffering and destruction wrought by recent fire seasons has refocused concern on the problem of fire management in California. Identifying the most beneficial changes to policy or new investments in improved wildfire management requires knowing the total societal costs of wildfire for the state. This CCST report summarized the current state of the science on what is known about these costs.

COST OF WILDFIRE EVENTS, LOSSES, AND PREVENTION/MITIGATION ACTIONS



Report Summary Diagram. *Figure colors identify the types of databases and studies available to assess the costs (dollar value) estimates of each overall topic addressed in this report. Lines indicate the interactions across multiple topics, illustrating the complexity of interrelated wildfire-relevant issues. Note that no shapes are colored yellow, indicating very few or no topics are tracked in a comprehensive, systematic way for the state as a whole.*

Below are listed the Findings, Conclusions, and Recommendations (FCRs) from each chapter of the report, followed by several cross-cutting themes that emerged from the report overall. The FCRs are listed in the same order as they appear in the report and their order here is not meant to reflect the importance of a specific Finding, Conclusion, or Recommendation. Also please note that not all sections include FCR's, but section headings are included for easy reference. Highlighting the existing data gaps and opportunities for improved understanding was a goal of this report and is an important first step in advancing needed public policy discussions. With these insights, relevant stakeholders can proceed to prioritizing the most effective and actionable next research and policy steps.

Chapter 1: Introduction and Conceptual Framework

1.4 What is a Catastrophic Wildfire?

Finding: Though the term "catastrophic" wildfire is used widely in public discourse, there is no commonly-accepted technical definition of "catastrophic" wildfire.

Conclusion: Policy discussions about wildfires would benefit from a consistent focus on the losses or benefits caused by wildfire rather than the traits that characterize wildfire.

Recommendation: We recommend that the term "catastrophic" wildfire refer not to the characteristics of a specific wildfire, but to the substantial undesired losses that these events impose on society and the environment. Further, any set of loss metrics used to designate a fire as "catastrophic" should be designed for its particular social and environmental contexts.

Chapter 2: Background—California Wildfires

2.2 Brief History of Wildfire in California

Finding: Fuel management strategies in the West's dry, mixed-conifer, ponderosa pine-dominated forests changed significantly over the twentieth century to protect economic interests including timber and grazing land, among other commodities and services, with a stated goal of fewer wildfires.

Conclusion: This management strategy has led to far higher fuel loads in many of the West's mixed-conifer forests compared to pre-European settlement.

Finding: Human population growth and urban expansion have increased ignitions in California shrubland ecosystems.

Finding: These increased ignitions have resulted in uncharacteristically high wildfire frequency that is detrimental to the native shrublands in those areas.

Conclusion: Increased fire frequency contributes to expansion of invasive flammable grasslands that further increase fire frequency and pose additional threats to human assets and reduction of ecological services that the native shrubland provide.

Finding: Wildfire suppression policy in California is determined by multiple agencies and driven by a complex set of jurisdictional stakeholder factors, such as local development patterns and politics.

Conclusion: The evolution of this multi-stakeholder system has led to varied philosophies on suppression needs, which has in turn made coordinating a statewide approach to wildfire management challenging.

Conclusion: The varied strategies, policies, and cultures of the many fire suppression organizations often translates to no clear leadership on a comprehensive strategy for maximizing the benefits from fire and mitigating its losses.

Recommendation: The state should consider how the multiple agencies currently responsible for or affected by wildfire could better coordinate to manage fire to maximize benefits and minimize costs and losses for California.

2.3 Recent Trends in Wildfire Regime

2.3.1 Wildfire Trends Across Regions of the State

Finding: Wildfire trends vary across regions of the state. While some areas of the state have been experiencing changes in fire regime over time, not all have. Where fire regime has changed, the trends are variable.

Finding: Climate-driven increases in wildfire occurrence, area burned, size, and severity are most pronounced in the Sierra Nevada and southern Cascades. The number of large wildfires and burned areas have also increased since the 1970s in some of the state's chaparral and woodland ecosystems.

Finding: Wildfire trends vary between forested and non-forested ecosystems.

Conclusion: Policy and planning should focus on variations in wildfire regimes across the state rather than the state-wide trends. Management and policy is most effective when specific to the local wildfire context.

2.3.2 Wildfire Season Length

Finding: The length of wildfire season is increasing.

Finding: Wildfire regimes in California are the outcome of multiple processes, including both natural and anthropogenic drivers, that operate differently in different parts of the state.

Conclusion: Successful strategy to reduce the costs of wildfire requires addressing this regional context.

Recommendation: While state-wide goals are important, management and planning strategies should be tailored to address local and regional fire regimes for greatest success.

Recommendation: Statewide wildfire trends are usually averaged across a very simple set of metrics (acres burned, number of fires, structures destroyed) but need to be bench-marked against relevant factors such as per capita values, population or housing densities, fire policies, staffing and other influential drivers of fire occurrence and consequences.

2.3.3 Drivers of Past Wildfire Activity

Finding: Human-caused changes in land use and land cover have significantly altered natural fire regimes across the state.

Conclusion: Increases in fire occurrence, area burned, size, and severity in mixed conifer forests are largely the result of climate change and a legacy of fire suppression that has dramatically increased fuel loads, making many forests more susceptible to burning.

Conclusion: Given the drivers and variability of fire regimes in the state, and increasing wildfire activity due to past management strategy, successful strategies for reducing the cost of wildfire must consider strategies beyond exclusion or suppression.

Recommendation: To successfully reduce the cost of wildland fire, agencies should embrace a strategy of contextually-appropriate fire management, rather than relying on exclusion or suppression in all cases.

2.4 Projections of Future Wildfire Regime

Finding: Projections of future wildfire activity largely predict a continuation of past trends of increased wildfire incidence, severity, and size, with the forested regions of the Sierra Nevada especially at risk.

Conclusion: Given the role of anthropogenic drivers such as fire suppression and land use in influencing fire regime, wildfire activity in California may continue to increase without changes in management approach.

Recommendation: California should evaluate fire management strategies based on their ability to address not just the status quo but also the degree to which they can stabilize or even reverse trends in wildfire activity and consequences.

Chapter 3: Fire Prevention, Mitigation, and Suppression

3.2 Ignition Prevention

3.2.1 Public Education Programs

Finding: Fire prevention educational campaigns are spread across a wide range of local, state, and federal governments, and private organizations, with limited coordination among the entities.

Conclusion: Greater coordination among fire prevention educational campaigns may improve the effectiveness and efficiency of these activities.

Recommendation: Detailed analysis is needed to understand the budgetary scope of the different educational programs and their effectiveness at preventing wildfires and mitigating impacts.

3.2.2 Electrical Infrastructure Ignition Prevention Programs

3.2.2.1 Public Safety Power Shutoffs

Finding: PSPS events, utilized as a wildfire prevention measure, impose a large opportunity cost to society.

Conclusion: Current data sources and methods are insufficient to adequately measure the costs and safety impacts of PSPS events.

Recommendation: The state should support research into the behavior of utility customers before, during, and after PSPS events as well the costs of these interruptions, especially in cases where advance notice was given by the utility.

3.3 Mitigation

3.3.1 Hazard vs. Risk and the Role of Mitigation

Finding: The state has multiple agencies statutorily tasked with reducing losses from wildfire through a variety of plans, programs, and assessments.

Conclusion: To date, there is only a statewide hazard assessment of wildfire, but not a correlating statewide risk assessment that reflects the many mitigation programs actively pursued in California.

Conclusion: Without a statewide model for assessing wildfire risk, there will be many independent approaches which will lead to confusion about the impacts of mitigation investments.

Recommendation: The state should direct the appropriate agency to develop a statewide Fire Risk Map that mirrors the Fire Hazard Severity Map and accurately reflects the reduced wildfire risk created by public and private investment. All risk assessments should always clearly articulate the risk that is being assessed and the core variables calculated in that risk assessment.

3.3.3 Natural Environment

3.3.3.1 Fuels Management

Finding: Data on select California fuel treatment projects and costs can be found interspersed across multiple datasets, including inventories maintained by federal and state entities and those compiled for individual reports and research papers.

Finding: It is not clear from our review whether all fuels management projects in the state—and their associated costs—are represented by the datasets and inventories described above.

Conclusion: There is no comprehensive state-wide database tracking California fuel management projects or their associated costs.

Conclusion: An estimate of total state-wide costs of fuel treatments conducted in California for the purpose of fire management would require compiling existing data from multiple sources, and possibly collection of new data, to produce the necessary dataset for analysis.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track the dates, locations, and impacts of all fuel treatment projects across all jurisdictions (including state, federal, tribal, and private lands) that are relevant for meeting the state's fire management goals.

3.3.3.2 Effectiveness of Fuel Treatments in California

Finding: Empirical research has found fuel treatments can be effective at modifying wildfire events and reducing select losses of wildfire in California's forests.

Finding: Case studies in non-forested ecosystems have found that fuels management is most effective in strategic locations around communities where firefighters can access them for defensive actions.

3.3.3.3 Cost-Effectiveness of Fuel Treatments in California

Finding: We found no California-based studies that evaluate the cost-effectiveness of real-world fuel treatments at reducing the losses of real-world wildfires.

Finding: Models of simulated fuel treatments and simulated wildfires predict fuels treatments can be cost-effective at avoiding select losses from wildfires in California forests.

Conclusion: Comprehensive, state-wide estimates of the total cost-effectiveness of real-world fuel treatments at avoiding wildfire losses would require additional research on benefits and losses in a representative diversity of habitats to produce the necessary datasets.

Recommendation: California should consider supporting research into economic and ecological outcomes to evaluate the cost-effectiveness of different fuel treatments in different ecosystems to reduce losses from wildfire.

Recommendation: The State should consider developing a method for valuing and verifying fuel treatment losses and benefits within a larger framework to value and monetize ecosystem services, resource sustainability, and impacts to local, statewide, and global climate management.

3.3.3.4 Landscape Management

Finding: Data on select California post-wildfire landscape management projects and costs can be found in BAER and WERT reports and in datasets that have been compiled for analysis in individual reports and research papers.

Finding: It is not clear from our review whether all post-wildfire landscape management projects in the state—and their associated costs—are represented by the reports and studies mentioned above.

Conclusion: There is no comprehensive state-wide database tracking California post-wildfire landscape management projects or their associated costs with the goal of reducing losses from catastrophic wildfires.

Conclusion: An estimate of total state-wide costs of post-wildfire landscape management projects conducted in California would require compiling existing data from multiple sources, and possibly new data collection or research.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track all post-wildfire landscape management projects across all jurisdictions (including state, federal, tribal, and private lands).

3.3.4 Social Environment

Finding: The social environment has a fundamental influence on perceptions of and willingness to take action to mitigate wildfire risk at the individual- and the policymaking-level.

Conclusion: The social environment is very influential in determining future wildfire consequences, especially in terms of fire survivability of communities and infrastructure.

Recommendation: A statewide systematic review, definition, development, and dissemination of the social component of mitigation could serve as the foundation for a comprehensive wildfire mitigation plan for California.

3.3.5 Response Environment

Finding: The vast majority of CAL FIRE's budget goes to wildfire suppression. Suppression expenditures also far exceed prevention and mitigation expenditures in the state budget.

Finding: Though suppression cost data is well-tracked across federal and state government agencies, it is stored in a format that does not allow for an accessible, detailed understanding of suppression expenditures in California. Local suppression expenditures are not reported in a centralized location.

3.4 California State Budget: Prevention and Mitigation

Finding: State spending on wildfire mitigation is a small fraction of state spending on wildfire suppression.

Finding: Funding for prevention and mitigation is unstable and not sustainably funded.

Conclusion: Without defined mitigation funding that includes both direct and indirect costs and benefits, California will systematically underinvest in risk reduction and as a result be compelled to overinvest in suppression.

Conclusion: California currently lacks a cost-benefit framework in which to evaluate prevention and mitigation investments against suppression investments.

Recommendation: The state should consider establishing a process to determine an optimal budget for prevention and mitigation spending that includes both direct and indirect costs and benefits, with a goal of minimizing total costs.

Recommendation: Because of the long history of underinvestment in prevention and mitigation, the state should consider establishing an accountability mechanism such as a defined ratio of mitigation to suppression spending similar to FEMA requirements for post-disaster spending.

Chapter 4: Buildings and Infrastructure

4.2 Building Losses from Wildfire

4.2.1 Exposure

Finding: State-wide data on building exposure to wildfires is systematically tracked by the CAL FIRE DINS program for wildfires that cause at least some damage in California.

Finding: Although the DINS program records data for select unburned structures close to ones that were damaged or destroyed, the number is relatively small, although the DINS program grows and improves every year.

Finding: Thorough assessment of building characteristics can be challenging because the level of destruction was so complete.

Finding: Better identification of structures exposed but not damaged will enable better identification of effective mitigation actions.

Conclusion: Developing a standardized working definition of structure exposure and a systematic approach for increasing the number of exposed, surviving structures surveyed via DINS could improve the robustness of statistical comparison and analysis of destroyed and unburned structures.

Recommendation: California should consider systematically reporting summary statistics on the buildings that have been exposed to wildfires.

4.2.2 Losses—the physical buildings

Finding: State-wide data on building losses caused by wildfires is systematically tracked by the CAL FIRE DINS program for buildings worth at least $10,000 in California.

Finding: The costs associated with the actual repair or replacement of buildings damaged or destroyed by wildfires is not systematically tracked for California.

Finding: Summary statistics on the estimated costs associated with physical building losses for wildfires are available from several entities including CAL FIRE, CDOI, and the III.

Conclusion: Published estimates of property losses are likely an underestimate of total costs associated with building damages.

4.2.3 Losses—the clean up

Finding: Data on post-wildfire clean up of building losses and associated costs have been compiled in individual reports and studies for select California wildfires.

Finding: It is not clear from our review whether the available data is comprehensive of all clean up efforts and costs in the state.

Conclusion: There is no single, comprehensive database systematically tracking data on post-wildfire clean up of building losses or their associated costs for wildfires in California.

Conclusion: An estimate of the total state-wide costs of post-wildfire clean up of building losses in California would require compiling existing data from multiple sources, and possibly new data collection.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track all post-wildfire clean-up efforts and their associated costs.

4.2.5 Mitigation

Finding: Data on select building hardening and defensible space actions to reduce building losses can be found in the CAL FIRE DINS database, and in datasets that have been compiled for analysis in individual reports and research papers.

Finding: We found no California-based studies that estimate the costs associated with building hardening and defensible space actions that have been implemented in the state to reduce building losses from wildfire.

Conclusion: There is no single, comprehensive, state-wide database tracking building hardening and defensible space actions or their associated costs.

Conclusion: An estimate of the total state-wide costs of building hardening and defensible space conducted in California for the purpose of reducing building losses from wildfire would require compiling existing data and collection of new data.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track all building hardening and defensible space actions conducted in California.

4.2.6 Effectiveness at reducing losses

Finding: Case studies based on empirical evidence have found building hardening and defensible space can be effective at reducing building losses from wildfire in California.

Finding: We found no studies that establish the cost-effectiveness of building hardening or defensible space at reducing losses from wildfires.

Conclusion: Comprehensive estimates of the total cost-effectiveness of building hardening and defensible space at avoiding losses from wildfire in California would require additional research.

Recommendation: California should consider supporting research to evaluate the cost-effectiveness of different building hardening and defensible space treatments to reduce the costs of wildfire in California.

4.3 Water Infrastructure

Finding: Data on water infrastructure exposure to wildfire, losses due to wildfire, mitigation actions to reduce losses have been compiled in individual reports and studies for select California wildfires.

Conclusion: There is no single, comprehensive database systematically tracking data on water infrastructure losses or their associated costs for wildfires in California.

Conclusion: An estimate of the total state-wide costs of water infrastructure losses in California would require compiling existing data from multiple sources and new data collection.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track all water infrastructure losses and their associated costs for wildfires in California.

4.4 Electric, Gas, and Telecommunications

4.4.1 Exposure

Finding: State-wide data on utility infrastructure exposure to wildfires in California have been compiled for individual reports and research papers.

Conclusion: There is no comprehensive state-wide database tracking utility infrastructure exposure to wildfires in California.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track utility infrastructure exposure to wildfires.

4.4.2 Losses

Finding: Data on select utility infrastructure losses caused by wildfires and their associated costs can be found in individual regulatory filings submitted to the CPUC and in datasets that have been compiled for analysis in individual reports and research papers.

Conclusion: There is no comprehensive state-wide database tracking utility infrastructure losses caused by wildfires or their associated costs in California.

Conclusion: An estimate of total state-wide costs of utility infrastructure losses in California would require compiling existing data from multiple sources, and possibly collection of new data.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track utility infrastructure losses caused by wildfires.

4.4.3 Mitigation

Finding: Data on select infrastructure mitigation actions and associated costs to reduce wildfire losses can be found in wildfire mitigation plans submitted to the CPUC.

Conclusion: There is no single, comprehensive, state-wide database tracking infrastructure mitigation actions or their associated costs.

Conclusion: An estimate of the total state-wide costs of infrastructure hardening, defensible space, and temporary service replacement conducted in California for the purpose of reducing infrastructure losses from wildfire would require compiling existing data and collection of new data.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track all mitigation actions to reduce utility infrastructure losses from wildfires in California.

4.4.4 Effectiveness at reducing losses

Finding: We found no California-based empirical studies that evaluate the effectiveness or cost-effectiveness of mitigation actions to reduce infrastructure losses of wildfires.

Finding: Models of simulated mitigation actions predict that infrastructure hardening and defensible space could be effective at avoiding select losses from wildfire.

Conclusion: Comprehensive estimates of the total cost-effectiveness of infrastructure hardening and defensible space at avoiding losses from wildfire in California would require additional research.

Recommendation: California should consider supporting research to evaluate the cost-effectiveness of different infrastructure hardening and defensible space treatments to reduce the costs of wildfire in California.

4.5 Transportation Infrastructure

Finding: We found no databases or studies on the exposure of transportation infrastructure to California wildfires.

Conclusion: An estimate of the total transportation infrastructure that has been exposed to wildfires in California could be calculated with existing datasets of wildfire perimeters and road networks.

Finding: Select data on transportation infrastructure losses and mitigation actions to reduce losses is collected by CalTrans and can be found in BAER and WERT reports.

Conclusion: There is no single, comprehensive database systematically tracking data on transportation infrastructure losses or their associated costs for wildfires in California.

Conclusion: An estimate of the total state-wide costs of transportation infrastructure losses, and mitigation actions to reduce losses in California, would require compiling existing data from multiple sources, and possibly new data collection.

Recommendation: California should consider creating and maintaining a comprehensive state-wide database to track all transportation infrastructure losses and their associated costs for wildfires in California.

4.6 Losses from Wildfire Smoke and Post-wildfire Landslides

Finding: We found no datasets that systematically track building and infrastructure losses and costs from wildfire smoke or post-wildfire landslides in California.

Conclusion: An estimate of the total state-wide costs of building and infrastructure losses and costs in California would require compiling existing data from multiple sources, and possibly new data collection.

Recommendation: California should consider including losses from wildfire smoke and post-wildfire landslides in state-wide datasets tracking the losses and associated costs of wildfires.

Chapter 5: Health Impacts

5.2 Health Impacts of Wildfire Smoke

Finding: Wildfire smoke consists primarily of $PM_{2.5}$, which can enter the bloodstream and trigger dysfunction throughout the body.

Finding: Widespread health impacts of wildfire smoke exposure range from mild illness to death. Both respiratory and cardiovascular emergency room visits and hospital admissions are associated with wildfire smoke exposure.

Finding: Health outcome data is not easily accessible or available in real time, hindering the association with the health impacts of wildfire smoke exposure.

Conclusion: Wildfire smoke exposure has both short-term and long-term health impacts. New discoveries regarding smoke impacts on health are ongoing and the field remains an active area of investigation.

Conclusion: Additional research to address gaps in both acute and chronic health impacts is needed.

Conclusion: Because the composition of the particulate matter and the composition of the smoke varies depending on the source, research is needed to determine the toxicity of various sources of wildfire smoke on health.

Recommendation: California should create a centralized mechanism to track real-time association of acute health outcomes (emergency room visits, hospital admissions, outpatient appointments, cardiac arrests) with wildfire smoke exposure to fully account for smoke impacts.

5.2.1 Vulnerable Populations

Finding: Vulnerable populations are more susceptible to the health impacts of wildfire smoke exposure.

Conclusion: The impacts of smoke on vulnerable populations, as well as which additional populations are also at higher risk, is poorly understood. However, the body of evidence on these topics is rapidly advancing.

Recommendation: The State should consider supporting research to determine if additional previously unaccounted vulnerable populations exist and to target resources to mitigate their exposure.

5.2.2 Special Consideration: Firefighters

Finding: Chronic exposure to wildfire smoke in firefighters is associated with increased risk of acute and chronic adverse health outcomes, including cancer and mental health disorders.

Finding: No research was identified that estimates the cost of health losses to wildland firefighters as a result of exposure to wildfires or wildfire smoke in California.

Conclusion: Overall, large gaps in knowledge exist regarding the long-term health impacts from smoke exposure.

Conclusion: Additional research is needed to understand the long-term health impacts of chronic smoke exposure, especially in firefighters.

Recommendation: The State should monitor individual cumulative smoke exposure history for firefighters and others chronically exposed to wildfires.

5.2.3 Smoke from Prescribed Fire

Finding: There is limited research on the health impacts of exposure to smoke from prescribed fire.

Finding: Retrospective studies find that exposure to smoke from prescribed fires is associated with public health consequences, but given the strict regulations required for prescribed burning, the health impacts are expected to be less than uncontrolled wildfires.

Conclusion: The balance in health impact tradeoffs between a significant scaling up of prescribed fire and uncontrolled wildfires is not fully realized.

Recommendation: California should support research to better quantify the health-related impacts of exposure to smoke from prescribed fire.

5.2.4 Wildfire Smoke Plume Spread

Finding: Wildfire smoke plumes can travel thousands of miles from the source and impact the health of those within and outside of California.

5.2.5 Smoke Plume Tracking

Finding: Centralized tracking of pollutant exposures due to wildfire smoke does not exist at the state level.

5.2.5.1 Quantifying Social Burdens and Health Impacts from Smoke Exposure

Finding: The immediate and long-term economic consequences from wildfire smoke health impacts are estimated to approach $100 billion per year nationally.

Finding: The health impacts from wildfire smoke are likely much greater than health impacts from heat or flame exposure.

Finding: The full public health impact of wildfire smoke is systematically undercounted due to its difficulty to measure, and is not systematically tracked in California.

Conclusion: There are large gaps in our understanding of the health impacts of wildfire smoke exposure and associated costs.

Recommendation: The State should track healthcare costs and lost productivity associated with wildfires to more accurately account for the social and health burdens.

5.3 Health Losses from Heat and Flame Exposure

5.3.2 Injuries and Fatalities from Heat and Flames

Finding: We found no studies that reported the costs of health losses in California from heat and flame exposure, though FEMA databases may contain relevant data for further analysis.

Finding: Counts of injury and fatalities due to direct heat and flame exposure are systematically tracked by CAL FIRE, but counts may not include wildfires in federal or local jurisdictions, and may undercount especially those deaths which occur later.

5.3.3 Mental Health Impacts

Finding: There is no research that estimates the costs associated with mental health impacts from wildfires in California.

Conclusion: Understanding the prevalence, severity, and associated healthcare and productivity costs of the mental health impacts of wildfire exposure represents an important gap in the literature.

5.4 Post-Fire and Secondary Health Consequences

5.4.3 Water Contamination

Finding: We did not find studies on the short- or long-term impact of post-fire water contamination on health.

5.4.4 Particulates and Dust

Finding: Evidence suggests post-fire landscapes can emit significant quantities of fine particulate matter.

Conclusion: Post-fire particulate matter emissions from the wind erosion of burned landscapes likely represent a significant and understudied health impact and consequence of wildfires.

Conclusion: Other significant contributors to increased particulate matter levels beyond the immediate wildfire should be accounted for when estimating public health impacts.

Recommendation: California should systematically monitor post-wildfire particulate matter emissions from burned landscapes.

Recommendation: Incorporate post-fire dust exposure impacts into post-wildfire landscape rehabilitation (BAER and WERT) planning and activities.

Finding: Increased $PM_{2.5}$ from wildfires causes previously unrecognized downstream health impacts, rendering the immune system less capable of fighting off viral pathogens such as COVID-19 and influenza.

Conclusion: Wildfire smoke may lead to increases in COVID-19 infection rates and influenza infection rates and may increase susceptibility to other viruses.

5.5 Prevention and Loss Mitigation

5.5.1 Mitigating Smoke Exposure

Finding: Effective mitigation strategies exist, but there are few studies estimating their implementation.

Finding: Given smoke exposure and the lack of adequate availability of mitigation, many Californians still experience the unhealthy impacts of wildfire smoke exposure.

Conclusion: Given the ongoing widespread health impacts from wildfire smoke exposure, existing mitigation measures are inadequate, especially for vulnerable populations.

Recommendation: California should develop programs to increase availability of affordable mass-produced mitigation strategies (e.g. smoke-filtering window screens; widespread emergency N95 mask availability) or other community-based methods (e.g. widespread portable clean air mobile units) to minimize smoke exposure.

5.5.2 Mitigating Water Contamination

Finding: There appears to be no systematic tracking of the duration, number of customers impacted, and spatial extent of “do-not-drink” orders following wildfires.

Conclusion: The costs of mitigating water contamination due to wildfire, though potentially significant, are unknown and represent an important research gap.

Chapter 6 – Ecosystem Processes

6.1.1 California Ecosystems and Wildfire

Finding: Healthy California ecosystems provide many goods and services and have evolved with their own specific wildfire regimes.

Finding: There is strong scientific consensus that wildfire can be essential and beneficial to the healthy functioning of California ecosystems.

Conclusion: Wildfire impacts to California's ecosystems may not automatically constitute losses and in fact can provide important benefits.

Recommendation: Wildfire impacts to ecosystem functioning and related goods and services, and potential economic values thereof, must be considered in terms of specific ecosystems, their associated fire regimes, and specified ecosystem and fire management goals.

Finding: An estimate of the economic value of many of the ecosystem goods and services provided by the numerous habitats in California is currently unknown.

Conclusion: A comprehensive accounting of the gains or costs associated with wildfire impacts to California's ecosystems is currently not possible with the existing data.

Recommendation: California should support additional research to document and value the full range of wildfire impacts to ecosystems.

6.2 Watersheds

6.2.1 Exposure

Finding: Multiple studies cite specific California watersheds as being impacted by wildfire, but in this review we found no overarching studies or reports cataloging all wildfires in the state by impacted watershed.

Conclusion: There does not appear to be comprehensive, systematic tracking of wildfire-impacted watersheds in California.

6.2.2 Impacts

Finding: Water quality and quantity in California watersheds are systematically tracked by multiple agencies, though changes in tracked metrics are not attributed directly to wildfire.

Finding: Multiple case studies have assessed wildfire-caused watershed impacts (including water quantity and quality), but these metrics are not consistently defined between cases or watersheds.

Conclusion: It is difficult to make meaningful comprehensive or comparative statements about California watershed losses due to wildfires over time without standardized metrics.

Recommendation: Researchers and decision makers interested in wildfire impacts on watershed-based ecosystem services over time should identify important standardized metrics and collection resolution in order to allow for meaningful comparisons between watersheds and between fire events.

6.2.3 Losses

Finding: Some wildfire-caused, watershed-based ecosystem losses are reported in peer-reviewed studies and in reports from California agencies such as the California Regional Water Quality Control Boards.

Conclusion: Watershed-based ecosystem losses from wildfire do not appear to be systematically tracked in California.

Conclusion: Additional collation and analyses of existing information would be required to compare watershed-based losses broadly across the state or to track trends over time.

Recommendation: California should undertake a synthesis of existing peer-reviewed studies, agency reports, and other available databases, to provide the understanding of wildfire effects on watershed-based ecosystem losses over time necessary for a comprehensive accounting of associated dollar costs.

6.3 Carbon Sequestration

6.3.1 Impacts

Finding: The amount of carbon sequestered in the landscape depends on both the rate of carbon storage and the rate of emissions from wildfire or other causes, or removal via logging, vegetation management, habitat type conversion, and development.

Conclusion: Carbon emissions values alone are not sufficient to assess the net change in sequestered carbon due to wildfire or other causes.

6.3.2 Losses

Finding: The state produces annual reports of forest carbon stocks and includes systematic statewide tracking of net change in stored carbon as a result of wildfire and vegetative regrowth.

Conclusion: Current tracking of carbon sequestration appears to be sufficient to meet present needs for understanding the societal costs of wildfire in California.

Chapter 7: Additional Economic Impacts of Wildfires

7.2 Impacts by Sector

7.2.4 Supply chain effects

Finding: Wildfires create economic impacts across a range of sectors beyond those typically considered. In addition to direct economic impacts on affected sectors, wildfires can create disruptions in supply chains that have broader economic multiplier effects.

Conclusion: The magnitude of these supply chain losses in various sectors is highly localized and often poorly understood. Data to study these effects in not widely available for the research community.

Recommendation: A long-term study of the sectoral impacts of wildfires, both direct and indirect, is needed. New data collection efforts, or a compiling of existing data sources, may be needed to support this effort.

7.3 Economy-wide Impacts

7.3.1 Labor Market Impacts

Finding: Wildfires and associated smoke exposure appear to impact local labor markets. Limited evidence suggests that wildfire smoke exposure reduces employment and earnings.

7.3.2 Economic Growth and Wildfires

Finding: The impact of wildfires on economic growth in California is unclear. Broader studies of natural disasters and economic growth suggest that there could be an adverse short-term, regional effect but the topic has not been well-studied in the context of wildfires specifically.

Finding: No studies were identified that examined the economic growth impacts of wildfire smoke exposure.

Conclusion: Additional research is needed to understand the effect of wildfires and wildfire smoke on economic growth. Research should focus on identifying short-run vs. long-run effects and differences across economic sectors.

7.4 Housing Markets

Finding: A growing body of research highlights the impacts of wildfires on housing markets in California, focusing primarily on markets in Southern California.

Conclusion: Several important gaps in this literature exist. These include a more comprehensive geographic understanding of housing market impacts and the impacts from the last several years of wildfires, which are outliers in the extent and severity of housing destruction and resident displacement.

7.5 Fiscal Impacts

Finding: No systematic research was identified that analyzed the effects of the relationship between property tax revenues and Proposition 13 in the context of California wildfires.

Finding: No studies were found that systematically analyzed the impact of wildfires on local government tax revenue, which is where you would most expect to observe an impact.

Conclusion: The large turnover in housing stock from wildfire damage, and associated resident displacement, suggests that an understanding of the revenue implications from tax adjustments is highly consequential.

Recommendation: Further study is needed to understand the implications of Proposition 13 and housing markets in communities that rebuild after wildfires.

Finding: Governments at all levels respond to wildfires with increased fiscal spending. The effects of wildfires on government revenues is not well established.

Cross-Cutting Themes

Based on the report's comprehensive review of the literature on the costs and losses associated with wildfires in California, several broad, cross-cutting conclusions are drawn and corresponding recommendations proposed:

Conclusion ES.1. Wildfire in California presents a complex management challenge, as natural fire regimes—long-term spatial and temporal characteristics of wildfires—are increasingly altered by population growth and the growth of the developed footprint.

Recommendation ES.1. To design contextually appropriate wildfire policy, policymakers must remain attuned to how climate change, land use change, and other human impacts may impact wildfire differently across the diverse regions of the State.

Conclusion ES.2. While wildfire suppression, utility investments, and structure losses are well quantified, understanding the scale of other losses and the cost—and cost effectiveness—of other mitigation and prevention activities will require the measurement of impacts that may range well beyond the geographic boundaries of fire events.

Recommendation ES.2. The State should create a comprehensive public accounting of relevant programs in order to better understand the costs of wildfire mitigation activities.

Recommendation ES.3. The State should consider supporting necessary research to fully assess the cost effectiveness of prevention and mitigation activities. The research will provide an opportunity to compare these investments to costs of suppression and the losses incurred as a result of wildfire. This accounting should explicitly consider ecosystem and natural resource values as well as structure values.

Conclusion ES.3. The location and pattern of housing development is one of the most important factors explaining structure loss in wildfires.

Recommendation ES.4. The State should evaluate land use planning and urban development as an alternative strategy for preventing structure loss and increased ignitions in wildland areas.

Conclusion ES.4. Public health impacts from wildfire are substantial and likely to be significantly underestimated. Aside from injuries or deaths due to heat exposure from fires, these impacts are not systematically tracked in the State. Available evidence suggests that pulmonary and cardiovascular outcomes from wildfire smoke are the most significant cause of morbidity and mortality and may have both acute and long-term consequences.

Recommendation ES.5. In order to understand the full costs of wildfire and the potential public health benefits of mitigation activities, as well as the tradeoffs associated with prescribed fire, the State should create a program to systematically track public health impacts from wildfire smoke, especially for vulnerable populations.

Recommendation ES.6. California should create and manage a systematic, comprehensive data clearinghouse for wildfire events including wildfire smoke, prevention and mitigation, losses including health, societal and ecological impacts, and associated costs. Models exist for this type of clearinghouse in the CalEnviroScreen and the California Open and Transparent Water Data Platform. Such a clearinghouse could be established via an extension and expansion of the recently established Wildfire Forecast and Threat Integration Center.

Appendix A

CCST Steering Committee Members

The Steering Committee (SC) oversees the report authors, reaches conclusions based on the findings of the authors, drafts recommendations and writes an executive summary.

Full *curricula vitae* for the SC members are available upon request. Please contact CCST (916) 492-0996.

Steering Committee Members

- **Michael Wara, Stanford University (Chair)**
- **Judson Boomhower, University of California, San Diego**
- **Kate Dargan, Intterra; former California State Fire Marshal**
- **Peter Larsen, Lawrence Berkeley National Laboratory**
- **Mary Prunicki, Stanford University**
- **Alexandra Syphard, San Diego State University and Sage Insurance**

Steering Committee Members

Michael Wara

Steering Committee Chair
Director of the Climate and Energy Policy Program & Senior Research Scholar
Stanford Woods Institute for the Environment

Michael Wara is a lawyer and scholar focused on climate and energy policy. Wara is Director of the Climate and Energy Policy Program and a senior research scholar at the Stanford Woods Institute for the Environment, where he provides fact-based, bipartisan, technical and legal assistance to policymakers engaged in the development of novel climate and energy law and regulation. He also facilitates the connection of Stanford faculty with cutting edge policy debates on climate and energy, leveraging Stanford's energy and climate expertise to craft real world solutions to these challenges.

Wara's legal and policy scholarship focuses on carbon pricing, energy innovation, and regulated industries. He collaborates with economists, engineers and scientists in research on the design and evaluation of technical and regulatory solutions to climate and energy challenges. He is also an expert on international environmental law with a particular focus on the ozone and climate treaty regimes.

Wara conducts research, advises and has testified before California and US Congressional legislative committees on issues related to wildfire and utilities. Wara served as a Commissioner on the Commission on Catastrophic Wildfire Cost and Recovery that proposed creation of a Wildfire Insurance Fund. He currently serves on the California Catastrophe Response Council, which oversees the Wildfire Fund created by AB 1054.

Prior to joining Woods, Wara was an associate professor at Stanford Law School and an associate in Holland & Knight's government practice. He received his J.D. from Stanford Law School and his Ph.D. in Ocean Sciences from the University of California at Santa Cruz.

Judson Boomhower

Assistant Professor, Department of Economics
University of California, San Diego

Judson Boomhower is an assistant professor in the Department of Economics at the University of California San Diego and a Faculty Research Fellow at the National Bureau of Economic Research. He is an applied microeconomist who studies environmental and energy economics and policy. He received his PhD in Agricultural and Resource Economics from the University of California, Berkeley. He earned his bachelor's and master's degrees from Stanford.

Current work in progress includes:

Mitigating and Managing Extreme Wildfire Risk in California

A multi-campus research effort focused on understanding and managing wildfire risk and electricity infrastructure.

Moral Hazard, Wildfires, and the Economic Incidence of Natural Disasters (2019)

This study measures the degree to which large public expenditures on wildfire protection subsidize development in harm's way. Using administrative firefighting data, we calculate geographically-differentiated implicit subsidies to homeowners throughout the western USA. We first examine how the presence of homes affects firefighting expenditures. These results are used to reconstruct the implied historical cost of protecting each home and to perform an actuarial calculation of expected future protection cost. The expected net present value of this subsidy increases with fire risk and decreases surprisingly steeply with development density. A simple conceptual model is used to explore effects on expansion of developed areas, density, and private risk-reducing investments.

Kate Dargan

Co-Founder, Chair of the Board, and Chief Strategist
Intterra
Former California State Fire Marshal

Kate Dargan began her career as a firefighter at age 18 and worked her way up, becoming a fire chief and State Fire Marshal (CAL FIRE), the first woman to serve California in that capacity. She has responded to emergencies and disasters around the state and worked on boards, committees, councils, and task forces to advance wildland-urban interface fire safety. Dargan is widely recognized for her consensus-building style and innovative approaches to old problems.

In 2010 Dargan co-founded Intterra, a successful situational awareness and analytics software company for firefighters, holding the position of CEO until 2016. She currently serves as Chief Strategist and Chair of the Board.

She is currently a Board Member of the California Firesafe Council (CFSC), a nonprofit formed as a project of the California Department of Forestry and Fire Protection (CAL FIRE) in 1993.

Peter Larsen

Staff Scientist and Deputy Leader
Electricity Markets & Policy Department
Energy Analysis & Environmental Impacts Division
Lawrence Berkeley National Laboratory

Peter Larsen is a Research Scientist and Deputy Group Leader in the Electricity Markets and Policy Group at the Lawrence Berkeley National Laboratory. He conducts research and analysis on electricity reliability and resiliency, energy efficiency, and regional electric system planning including: Energy Services Company Industry and Market Trends; Utility Resource Planning Practices and Trends; Western Electricity and Natural Gas Markets; Societal Impacts from Abnormal Weather; and the Reliability of the U.S. Power System.

Larsen's work includes Project Lead for Berkeley Lab's Interruption Cost Estimate Calculator, and he is interested in the economic impact of past and future Public Safety Power Shutoffs.

Larsen has published his research in a number of reports, book chapters, and peer-reviewed journals including the Proceedings of the National Academy of Sciences, Global Environmental Change, Annual Review of Environment and Resources, Energy Policy, and Energy Economics. Previously, he worked at the Institute of Social and Economic Research in Anchorage, Alaska, the Societal Impacts Program at the National Center for Atmospheric Research, and Stratus Consulting (now Abt Associates).

Larsen holds a Ph.D. in Management Science and Engineering from Stanford University; M.S. degrees from Stanford University (Management Science and Engineering) and Cornell University (Natural Resource Economics); and a B.A. in Economics from the University of Montana at Missoula

Mary Prunicki

Director of Air Pollution and Health Research
Sean N Parker Center for Allergy & Asthma Research, Stanford University

Since coming to the Nadeau immunology laboratory at Stanford University in 2014, Dr. Prunicki has designed and executed numerous innovative air pollution and wildfire projects. Lab studies have primarily focused on Fresno, CA, a city always in the top four in the nation for ozone and particle pollution and also exposed to the wildfire smoke from forest fires in Yosemite. Research findings have resulted in publication in high-impact journals, shaping of public policy and extensive media exposure. Dr. Prunicki is especially passionate about helping at-risk populations, such as children and the underserved, who disproportionately share the burden of air pollution exposure. Prunicki received her PhD from Northwestern University and her MD from Southern Illinois University.

Dr. Prunicki's research involves the investigation of the impact of environmental exposures on the immune system. Overall findings indicate that ambient air pollution exposures to CO, NO2, and PM2.5 mediate epigenetic alterations of Foxp3 and IL-10, key genes known to be associated with T cells and atopic disease. Similar epigenetic associations have been found with wildfire smoke exposure, in addition to increases in inflammatory cytokines.

Recent publications include:

Prunicki M, Kelsey R, Lee J, …, Nadeau K. (2019) The Impact of Prescribed Fire versus Wildfire on the Immune and Cardiovascular Systems of Children. *Allergy* 74(10):1989-1991.

Prunicki M, Dant CC, Cao S, …, Nadeau K. (2020) Immunologic effects of forest fire exposure show increases in IL-1β and CRP. *Allergy*. [Epub ahead of print]

Prunicki, M, Miller, S, Hopkins, A, Poulin, M, Movassagh, H, Yan, L and Nadeau, K. (2020) Wildfire smoke exposure is associated with decreased methylation of the PDL2 gene. *J Immunol*, 204 (1 Supplement) 146.17.

Alexandra Syphard

Chief Scientist, Vertus Wildfire Insurance Services
Adjunct Professor, San Diego State University
Associate, Conservation Biology Institute

Alexandra D. Syphard, Ph.D. is chief scientist at Vertus Wildfire Insurance Services, an associate at the Conservation Biology Institute, and an adjunct professor at San Diego State University. As a researcher, she has spent more than two decades analyzing the ecological and social drivers and impacts of landscape change, particularly focusing on wildfires in California, USA and other Mediterranean-climate ecosystems. Syphard uses a variety of geospatial, statistical, and modeling approaches to investigate how and why change has occurred in the past, how it is likely to occur in the future, and how different policy or management decisions may impact ecological and social well-being. Her extensive research on wildfire risk to communities forms the scientific basis for underwriting homeowners' insurance in fire-prone ecosystems. Dr. Syphard's work also focuses on the interactions among wildfire patterns, land use change and urban growth, climate change, vegetation dynamics and biodiversity, invasive species, and plant species' range shifts.

Syphard earned her PhD in Geography from San Diego State University and the University of California, Santa Barbara in 2005. She also received a B.A. in English from the University of Mary Washington, a Masters of Public Health at the Medical College of Virginia, and a Masters in Environmental Studies at Virginia Commonwealth University. Syphard also completed a postdoctoral research fellowship in the Department of Forest Ecology & Management at the University of Wisconsin, Madison and a postdoctoral fellowship in the Department of Biology at San Diego State.

Appendix B

Report Author Biosketches

Report Authors

Teresa Feo from CCST and Samuel Evans from Mills College, the report's lead authors, primarily researched and wrote the body of the report. In addition, the following individuals assisted in writing the report:

- Cade Cannedy, Bill Lane Center for the American West, Stanford University
- Brynn Cook, California Council on Science and Technology
- Hannah Palmer, University of California, Davis; University of California Center of Sacramento

TERESA J. FEO

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EDUCATION

2015	Ph.D., Ecology and Evolutionary Biology Yale University, New Haven, CT
2007	B.A., Integrative Biology University of California, Berkeley, CA

CURRENT AND PAST POSITIONS

Since 2018	Senior Science Officer California Council on Science and Technology, Sacramento, CA
Since 2017	Research Associate Smithsonian Institution, National Museum of Natural History Department of Vertebrate Zoology, Division of Birds, Washington, D.C.
2017 – 2018	California Council on Science and Technology Science Policy Fellow California State Senate Office of Research, Sacramento, CA
2015 – 2017	NSF Postdoctoral Research Fellow in Biology Smithsonian Institution, National Museum of Natural History Department of Vertebrate Zoology, Washington, D.C.
2008 – 2009	Laboratory Assistant Museum of Vertebrate Zoology University of California, Berkeley, Berkeley, CA
2008	Field Technician Museum of Vertebrate Zoology University of California, Berkeley, Berkeley, CA
2007 – 2008	Biological Technician Condor Country Consulting, Martinez, CA

HONORS AND AWARDS

2015	George Gaylord Simpson Prize, Yale Peabody Museum; $3,000
2007	Phi Beta Kappa

SAMUEL G. EVANS

Mills College
214B Lokey School of Business and Public Policy
5000 MacArthur Blvd
Oakland, CA 94613
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EDUCATION

2012	Ph.D., Agricultural and Resource Economics Colorado State University, Fort Collins, CO
2009	M.A., Economics, Colorado State University, Fort Collins, CO
2004	B.A., Economics Grinnell College, Grinnell, IA

CURRENT AND PAST POSITIONS

Since 2018	Adjunct Assistant Professor Department of Public Policy and Political Science, Mills College, Oakland, CA
Since 2019	Visiting Professor Department of Environmental Science, Policy & Management, University of California, Berkeley, Berkeley, CA
2015 – 2020	Principal Economist Berkeley Economic Advising and Research, LLC , Berkeley, CA
2015 – 2018	Postdoctoral Scholar College of Natural Resources University of California, Berkeley, Berkeley, CA
2012 – 2015	Principle Investigator and Postdoctoral Scholar Energy Biosciences Institute University of California, Berkeley, Berkeley, CA
2011	Instructor Department of Agricultural & Resource Economics Colorado State University, Fort Collins, CO

2010 – 2011	Research Intern USDA Economic Research Service
2009	Graduate Research Assistant Department of Agricultural & Resource Economics Colorado State University, Fort Collins, CO
2005 – 2007	Research Coordinator Numark Associates Energy and Environmental Consulting, Washington, D.C.

HONORS AND AWARDS

2008 – 2012	IGERT Fellow, National Science Foundation
2010	Outstanding Graduate Summer Intern, USDA Economic Research Service
2003 – 2004	Garrett O. Wyckoff Scholarship in Economics, Grinnell College

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EDUCATION

In Progress	M.A., Journalism (expected 2021) Stanford University, Palo Alto, CA
2020	B.A., Political Science Stanford University, Palo Alto, CA

CURRENT AND PAST POSITIONS

Since 2019	Policy Analyst, Study Coordinator Sean Parker Center for Asthma Research Stanford University, Palo Alto, CA
2018 – 2019	Research Assistant Bill Lane Center for the American West Stanford University, Palo Alto, CA
2015 – 2016	Intern Alan Maestas Law Office, Taos, NM

HONORS AND AWARDS

2020	Firestone Medal for Excellence in Undergraduate Research Advised by Dr. Bruce Cain, Stanford University

BRYNN COOK

CCST Science Fellow
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EDUCATION

2019	Ph.D., Environmental Sciences: Ecology University of Virginia
2013	B.S., Environmental Sciences UC Berkeley
2011	A.A., Liberal Arts Moorpark College

CURRENT AND PAST POSITIONS

2019-2020	CCST Science Fellow Placement in the office of CA State Senator Lena Gonzalez California Council of Science and Technology, Sacramento, CA
2013-2019	Graduate Student Researcher Department of Environmental Sciences, University of Virginia University of Virginia, Charlottesville VA
2013 – 2019	Graduate Student Teacher Department of Environmental Sciences, University of Virginia University of Virginia, Charlottesville VA
2018 – 2019	Graduate Student Research Associate University of Virginia Center for Teaching Excellence University of Virginia, Charlottesville VA

HONORS AND AWARDS

2018	Jefferson Conservation Award
2018	Garden Club of Virginia Fellowship
2017	University of Virginia Student Achievement Raven Award
2011	UC Berkeley Leadership Award

HANNAH PALMER

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EDUCATION

In Progress	Ph.D., Geology (Expected 2021) University of California, Davis, Davis, CA
2013	B.S., Marine Biology University of California, Los Angeles, Los Angeles, CA

CURRENT AND PAST POSITIONS

Since 2016	Graduate Student Researcher Earth and Planetary Sciences Department University of California, Davis, Davis, CA
2019	Research Assistant Invertebrate Zoology and Geology Department California Academy of Sciences, San Francisco, CA
2015 – 2016	Research Assistant Oceans and Climate Lab University of Colorado, Boulder, CO
2016	Education and Training Coordinator The Global Learning and Observations to Benefit the Environment Program, Boulder, CO

HONORS AND AWARDS

2020	UC Davis Dissertation Year Fellowship
2020	UC Center of Sacramento Presidential Graduate Opportunities for Leadership Development Fellowship
2018	Russell J. and Dorothy S. Bilinski Bodega Marine Lab Fellowship
2017	National Science Foundation Graduate Student Fellowship Honorable Mention

Appendix C

Scope of Work

CCST has received funding from the Gordon and Betty Moore Foundation to produce a peer-reviewed report on the costs and losses of wildfires in California. The report aims to frame the large issue in a manner useful to decisionmakers; it will identify key questions of interest and will include a literature review of existing datasets and studies that enumerate costs of wildfire management and wildfire-related losses in the state. A productive next step after the completion of this report would be to perform new analyses using the existing resources to address key questions this report identifies, and to fill the remaining significant data gaps also identified in this report.

The economic burden of wildfires on the State of California and its residents is a wide-ranging topic, so correctly framing the scope of work is a crucial step in the study process

Proposed Report Organization:

The overarching question for the report is:

What are the key considerations concerning costs and losses from California wildfires, and what information already exists to answer them?

Topics to be reviewed[1], by chapter:

Executive Summary – authored by the Steering Committee, based on the findings and conclusions of the report

Chapter 1: Introduction and Charge – Balancing the Costs and Losses of Wildfires in California

- Charge and goals of CCST for this report
- Approach, framing the conversation
- General discussion of data, economic modeling, limitations

1.Topics listed per chapter will be addressed to the best of the study team's ability, given time and resource constraints.

Chapter 2: Background – California Wildfires and Economic Impacts

- Brief history of wildfires in California
- Recent trends in severity
- Shifts in management practices/needs/philosophies

Chapter 3: Prevention and Suppression

- Prevention of catastrophic wildfire:
  - Education/training (public and fire department)
  - Ignition Detection
  - Monitoring and Forecasting of conditions (e.g. wind events, fuel loads)
  - Public Safety Power Shutoffs (plus discuss economic impacts of using)
  - Fuels management (e.g. mechanical thinning, prescribed burns)
- Suppression

Chapter 4: Human life and health losses

- Direct deaths and injuries from wildfire
- Public Health Impacts of wildfire smoke

Chapter 5: Infrastructure and structural losses

- Loss of:
  - Buildings
  - Infrastructure

Chapter 6: Natural and working land losses

- Loss of natural resources
- Loss of agriculture

- Environmental impacts (vegetation loss, watershed and soil impacts, etc.)
- Water quality/quantity impacts – also part of Chapter 4

Chapter 7: General economic losses

- General economic impacts (business interruption, population decline)
- Supply chain impacts
- Interruption of services (utilities, transportation, government)
- Housing market impacts
- Decrease in Tax Base
- Closures (Schools, Hospitals, Roads, work stoppages, etc.)

Chapter 8: Conclusion

- Summary of Key Questions
- Summary of Databases
- Summary of Gaps
- Summary of Conclusions and Recommendations

Appendix D

California Council on Science and Technology Study Process

For 30 years, The California Council on Science and Technology (CCST) has been advising California on issues of science and technology by leveraging exceptional talent and expertise. CCST studies are viewed as valuable and credible because of the organization's reputation for providing independent, objective, and nonpartisan advice with high standards of scientific and technical quality. Checks and balances are applied at every step in the study process to protect the integrity of the studies and to maintain public confidence in them.

CCST Entities Involved in the Study Process

The study process, including accepting and defining projects and building the teams to carry them out, involves a number of entities that are a part of CCST.

CCST Leadership – Consisting of the CCST Executive Director and the CCST Deputy Director, these positions are generally involved in interfacing with the sponsor and working through the initial ideation of the project and securing the contract. They work with the Board on all steps after ideation.

CCST Board of Directors ("Board") – Consisting of directors from CCST's academic and research partner institutions as well as independent directors often from industry, philanthropy or with a policy background. The Board gives final approval to take on a peer-reviewed report.

Program Committee – A subcommittee of the CCST Board, the Program Committee oversees and advises the programs by which CCST fulfills its mission to provide science advice to inform decision-making in the State of California. The Program Committee provides oversight throughout the study process.

Study Process Overview—Ensuring Independent, Objective Advice

CCST enlists the state's foremost scientists, engineers, health professionals, and other experts to address the scientific and technical aspects of society's most pressing problems.

CCST studies are funded by state agencies, foundations, and other private sponsors. CCST provides independent advice; external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. Authors and the Steering Committee gather information from many sources in public and private meetings, but they carry out their deliberations in private in order to avoid political, special interest, and sponsor influence. After the report has been drafted, it undergoes a rigorous peer review process, overseen by an independent Report Monitor who ensures all Peer Reviewer comments are sufficiently considered.

Stage 1: Defining the Study

Before the author(s) and Steering Committee selection process begins, CCST staff, and other CCST experts as needed and informed by the CCST Program Committee work with the study sponsors to determine the specific set of questions to be addressed by the study in a formal "statement of task," as well as the duration and cost of the study. In line with CCST's dedication to supporting diversity, equity, and inclusion (DEI) through its work, CCST intentionally integrates the social sciences and questions of equity. The statement of task defines and bounds the scope of the study, and it serves as the basis for determining the expertise and the balance of perspectives needed for the study authors, Steering Committee members, and peer reviewers.

The statement of task, work plan, and budget must be approved by CCST leadership in consultation with CCST's Project Director. This review sometimes results in changes to the proposed task and work plan. On occasion, it results in turning down studies that CCST believes are inappropriately framed or not within its purview.

Stage 2: Study Author(s) and Steering Committee (SC) Selection and Approval

Selection of appropriate authors and SC members, individually and collectively, is essential for the success of a study. CCST intentionally recruits a diverse team of experts. All authors and SC members serve as individual experts, not as representatives of organizations or interest groups. Each expert is expected to contribute to the project on the basis of his or her own expertise and good judgment.

To build the SC and Author teams, CCST staff solicit an extensive number of suggestions for potential SC members and authors from a wide range of sources, then recommend a slate of nominees, and send invitations to each provisional SC member and author to complete a non-disclosure agreement (NDA), a conflict of interest (COI) form and submit their current Curriculum Vitaes (CVs). The NDA is essential for ensuring an environment which supports frank and open discussion among study participants, both in establishing the team and as the study is ongoing. CCST staff send the COIs and current CVs to outside counsel for a thorough COI review and then organize all results and recommendations from the outside counsel. CCST organizes an in-person meeting for the provisional SC and lead authors to discuss the balance of the committee and evaluate each person for any potential COIs based on the outside counsel feedback. Any issues raised in this discussion are investigated and addressed. CCST sends the proposed study participant list and associated COI information, including any recommendations or concerns noted at the in-person meeting, to the Program Committee of the CCST Board for final approval. In some cases, the Program Committee is asked to review potential COIs ahead of the in-person SC meeting at the discretion of CCST Leadership. While the lead authors attend the in-person meeting for the discussion of their own potential COIs, they do not contribute to the discussion of the provisional SC Members' COIs. Members of a SC and the lead author(s) are anonymous until this process is completed.

Careful steps are taken to convene SCs that meet the following criteria:

An appropriate range of expertise for the task. The SC must include experts with the specific expertise and experience needed to address the study's statement of task. A major strength of CCST is the ability to bring together recognized experts from diverse disciplines and backgrounds who might not otherwise collaborate. These diverse groups are encouraged to conceive new ways of thinking about a problem.

A balance of perspectives. Having content expertise is not sufficient for success. It is also essential to evaluate the overall composition of the SC in terms of different experiences and perspectives. The goal is to ensure that the relevant points of view are, in CCST's and the Program Committee's judgment, reasonably balanced so that the SC can carry out its charge objectively and credibly.

Screened for conflicts of interest. All provisional SC members are screened in writing and in a confidential group discussion about possible conflicts of interest. For this purpose, a "conflict of interest" means any financial or other interest which conflicts with the individual's service because it could significantly impair the individual's objectivity or could create an unfair competitive advantage for any person or organization. The term "conflict of interest" is beyond individual bias. There must be an interest, ordinarily financial, that could influence the work of the SC or that could be directly affected by the work of the SC, for an individual to be disqualified from serving. Except for a rare situation in which CCST and the Program Committee determine that a conflict of interest is unavoidable and promptly and publicly disclose the conflict of interest, no individual will be appointed to serve (or continue to serve) on a SC used in the development of studies while having a conflict of interest relevant to the required functions.

SC members and authors continue to be screened for conflict of interest at regular intervals throughout the life of the committee. (In addition to the SC and Authors, co-authors, peer reviewers and CCST staff working on each project are also screened for COI.)

Point of View is different from Conflict of Interest. A point of view or bias is not necessarily a conflict of interest. SC members are expected to have points of view, and CCST attempts to balance these points of view in a way deemed appropriate for the task. SC members are asked to consider respectfully the viewpoints of other members, to reflect their own views rather than be a representative of any organization, and to base their scientific findings and conclusions on the evidence. Each SC member has the right to issue a dissenting opinion to the study if he or she disagrees with the consensus of the other members. COIs are updated throughout the study process to capture any new or updated information and to ensure a continued lack of conflicts.

Diversity. CCST members are often asked to serve on an SC, though membership in CCST is not a requirement SC selection. CCST seeks a diverse SC in all dimensions, including women, minorities, and professionals in varying career stages where available.

Stage 3: Author and Steering Committee Meetings, Information Gathering, Deliberations, and Drafting the Study

Authors and the Steering Committee typically gather information through:

meetings;

submission of information by outside parties;

reviews of the scientific literature; and

investigations by the study authors and/or SC members and CCST staff.

In all cases, efforts are made to solicit input from individuals who have been directly involved in, or who have special knowledge of, the problem under consideration.

The lead author(s) maintain continued communication with the SC as the study progresses through frequent updates and background meetings.

For larger reports, lead authors may request additional authors to ensure the appropriate expertise is included. Every author must be approved by the SC Chair(s) and CCST staff. Some of the additional authors may become section leads. The lead author reviews and approves the work of all other chapter authors, including section leads.

During the course of a report, authors' duties may shift which may change the lead author or section lead designations. Any such changes must be made in conjunction with CCST staff and the SC Chair(s). If the reorganization of author responsibilities or the addition of a new author raises conflict of interest concerns, they are presented to and resolved by the Program Committee.

The authors shall draft the study and the SC shall draft the Executive Summary which includes findings, conclusions, and recommendations (FCRs). The SC deliberates in meetings closed to the public in order to develop FCRs free from outside influences. All interim analyses and drafts of the study remain confidential.

Stage 4: Report Review

As a final check on the quality and objectivity of the study, all CCST full commissioned reports must undergo a rigorous, independent external peer review by experts whose comments are provided anonymously to the authors and SC members. CCST recruits independent experts with a range of views and perspectives to review and comment on the draft report prepared by the authors and the SC. The proposed list of peer reviewers is approved by the Program Committee to ensure all report sections are adequately reviewed.

The review process is structured to ensure that each report addresses its approved study charge, that the findings are supported by the scientific evidence and arguments presented, that the exposition and organization are effective, and that the report is impartial and objective. Peer Reviewers will be made aware of any COIs that have been disclosed on the website by CCST.

The authors and the SC must respond to, but need not agree with, reviewer comments in a detailed "response to review" that is examined by one or more independent "report monitor(s)" responsible for ensuring that the report review criteria have been satisfied. After all SC members and appropriate CCST officials have signed off on the final report, it is transmitted to the sponsor of the study and the sponsor or CCST can release it to the public. Sponsors are not given an opportunity to suggest changes to the content of the reports though may ask clarifying questions about findings, conclusions, and recommendations. All reviewer comments and SC deliberations remain confidential. The names and affiliations of the report reviewers are made public when the report is released.

Appendix E

Review of Information Sources

This study was conducted as a review of existing publicly available data including the results of many currently ongoing or recently-completed relevant studies, protocols, and proposed regulations. The quality of the assessment depended on the quality of the information and time available for the study.

Our scientists cited a given reference in the report if it met all three of the following criteria:

1. Fit into one of the eight categories of admissible literature (described in a-h below).

    a. Published, peer-reviewed scientific papers.

    b. Government data and reports.

    c. Academic studies that are reviewed through a university process, textbooks, and papers from technical conferences.

    d. Studies generated by non-government organizations that are based on data, and draw traceable conclusions clearly supported by the data.

    e. Voluntary reporting from industry. This data is cited with the caveat that, as voluntary, there is no quality control on the accuracy or completeness of the data.

    f. Other relevant publications including reports and theses. We state the qualifications of the information used in the report.

    g. Additional authoritative sources including the expert opinion of the committee and scientific community.

    h. News articles (only when the discussion centered on anecdotal information being the only publicly-available information).

2. Was relevant to the scope of the report.

3. Added substantive information to the report.

For this report, the authors reviewed many sources of public information, including some that are not easily accessible to all citizens, such as fee-based scientific journals. If a member of the public wishes to view a document referenced in the report, they may contact CCST directly.

Appendix F

Expert Oversight and Review

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- **David Shew,** Wildfire DefenseWorks; National Fire Protection Association
- **Kerri Timmer,** Sierra Business Council
- **Krista West,** San Diego State University

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