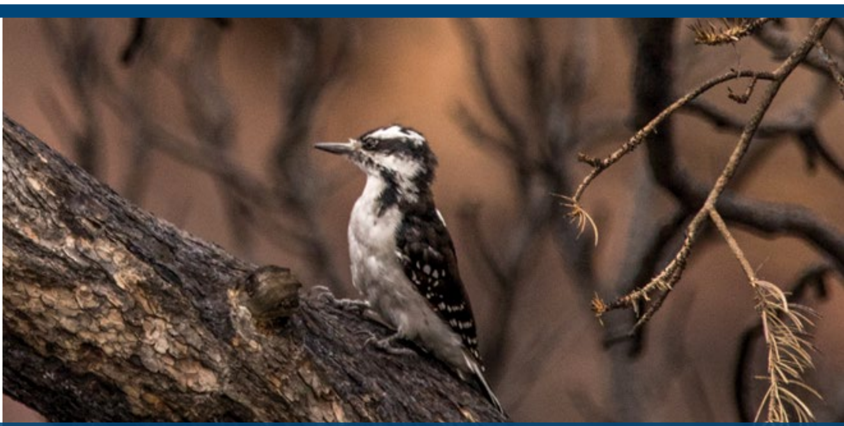
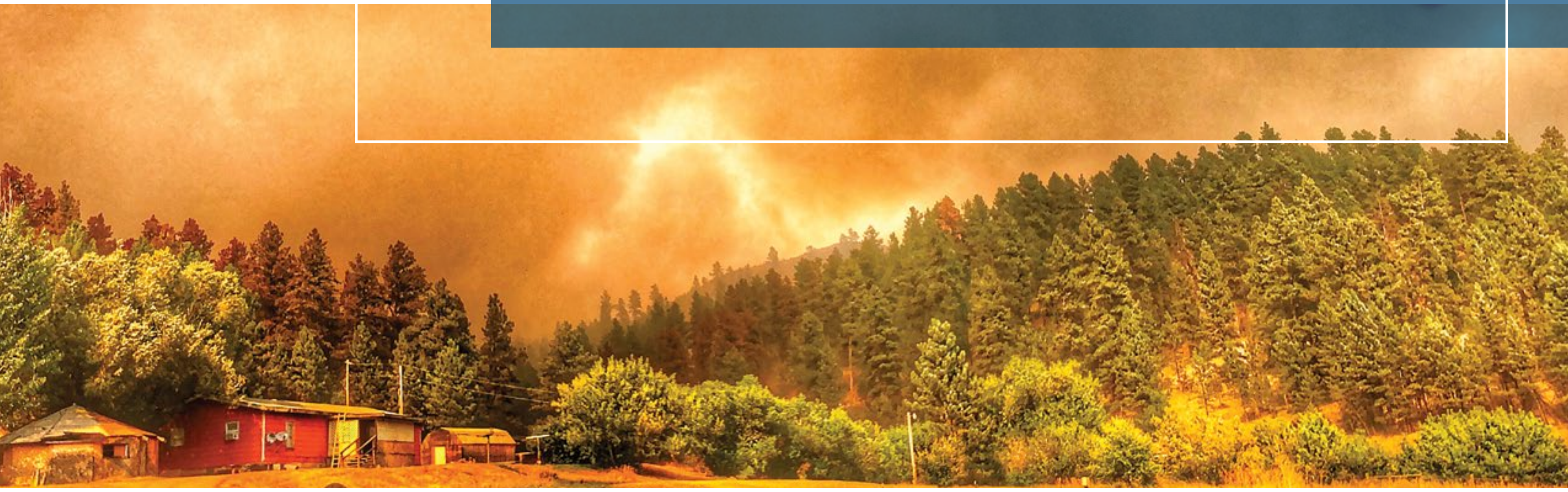
WESTERN FORESTRY LEADERSHIP COALITION



The True Cost of WILDFIRE in the Western U.S.

2022 REPORT



COVER, clockwise from top left: 1) A high-severity wildfire can scorch the landscape and leave ground primed for erosion. Photo: Jason Moghaddas/Spatial Informatics Group; 2) A woodpecker in the Peekaboo Fire burn area in Colorado. Photo: Rachel Portwood/U.S. Fish and Wildlife Service; 3) A residence under smoke-filled skies near the Richard Spring Fire in Montana. Photo: Phil Millette/U.S. Fish and Wildlife Service; 4) A mudslide closed Interstate 70 through Glenwood Canyon in Colorado. Photo: Glenwood Springs Fire Department; 5) Grandview Drive in Flagstaff, Arizona, floods after the Museum Fire. Photo: Jennifer Beltz/for the Southwest Fire Science Consortium

BACK COVER: Incident Commander Riley Rhoades watches the 2020 Trap Creek Fire cross Highway 21 in Idaho. Photo: Jace James/USDA Forest Service

THIS PAGE: Wildfire conditions can create weather anomalies such as this fire whirl seen during Colorado's Pine Gulch Fire in 2020.
Photo: Eric Coulter/BLM

TABLE of contents

The True Cost of Wildfire in the Western U.S., 2022

FIVE POINTS TO KNOW

1

This report describes the full range of costs associated with wildland fire in the Western United States (U.S.) to help inform leaders and policymakers working to improve wildfire response and mitigation. Wildfire cost information has, in the past, primarily focused on suppression costs and structure losses; however, as this report shows, there are many other types of costs relating to values such as human health, water supply, transportation, the labor market, and local economics, among others. These less-recognized costs are massive in aggregate.

2

This report breaks down costs into three high-level categories: Direct Costs, which are incurred directly during an incident; Indirect Costs — Losses, which are incurred after an incident but attributable to it; and Indirect Costs — Mitigation Investments, which represent expenditures that would reduce the incidence of and damage from future catastrophic fire. Under each of these three categories, subcategories of costs are given. A detailed discussion outlines why each matters, how it is quantified, how researchers have addressed it, and what types of data exist, if any, to track it. As this section makes clear, data availability is highly inconsistent and/or lacking for many cost categories. Case studies of eight major western wildfires are used to illustrate the variety of wildfire cost types.

3

This report presents a framework that could be used in the future to approximate full costs of a wildfire in a more systematic manner. It also provides recommendations for addressing information gaps through additional research. The report does not attempt to generate a single number representing the total cost of wildfire in the Western U.S. Such an undertaking is functionally impossible today given the limits of available data.

4

In the near term, several steps can be taken to begin the process of more systematically tracking wildfire costs to better inform public policy and investment decisions. These same steps could also help facilitate the development of a national system of wildfire cost accounting in the long term. First, a more holistic and granular assessment of data gaps and inconsistencies is needed. Second, more research is needed to develop better modeling approaches to assist in cost estimation and disentangle the amounts directly attributable to fire, versus other confounding factors. Third, more complete and accurate estimates are needed to understand the costs of mitigation investments, from fuel treatments, to home hardening, to defensible space, to fire-safe land planning. Finally, more data needs to be collected and analyzed about disparities in the distribution of wildfire costs among different socioeconomic, demographic, racial, and geographic groups. If, as research suggests, wildfire cost burdens are disproportionately borne by those who can least afford them, such as rural, elderly, and lower-income communities, getting a more complete picture of these costs is critical to ensuring aid and compensation are both equitably distributed and based on need.

5

This report raises the question of how knowing more about the true cost of wildfire might inform these and other future policies, legislation, or best practices. This is impossible to predict with certainty but given the jaw-dropping magnitude of these numbers, such information is likely, at a minimum, to prove a highly powerful motivator to the public and legislators. More importantly, it will provide the information needed to take a data-driven approach to wildfire management and mitigation planning; one that improves targeting of investments, that directs aid and compensation equitably to groups and areas with the highest need, and that enables funders to track returns on investment.

At night, from the Spot Mountain Lookout, the Indian Ridge Fire in Idaho can be seen burning in the Selway-Bitterroot Wilderness. The wildfire started from a lightning strike in July 2022 in rugged, remote terrain. Photo: Mark Moak, fire lookout, Bitterroot National Forest/for InciWeb

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A large air tanker dropped retardant near a neighborhood in the wildland-urban interface to help stop the spread of the 2015 Eyrie Fire in the Boise Foothills of Idaho. Photo: Austin Catlin/Bureau of Land Management

PURPOSE & history

Purpose of Report

This report aims to convey information on the full range of costs associated with wildland fire in the Western United States (U.S.) in order to inform leaders and policymakers as they work to improve wildfire response and mitigation. Information on the costs of wildfires is commonly reduced to the sum of suppression costs and structure losses; however, many other costs are commonly incurred, including compromised water supply, flood damage, lost economic opportunity, and declines in public health, among others. These costs are often overlooked because they are more difficult to quantify and their linkage to a wildfire event may be indirect.

This report seeks to highlight and categorize these often-overlooked costs in a systematic way so as to facilitate improved decision making and resource allocation. The report also shows how targeted investments in mitigation produce ancillary benefits, such as healthier and more resilient forests and rangelands, which can potentially lead to a reduction in catastrophic wildfire event costs later. It concludes with a roadmap of subsequent steps that would be needed in order to advance a consistent and comprehensive system of wildfire cost accounting, including research, data collection, and information management.

This report does not generate a single number representing the total cost of wildfire in the Western U.S. Such an undertaking is functionally impossible today given the limits of information available. In the eight case study incidents in this report, cost estimates are provided for notable categories of impact, where data exists. "Total costs" cannot be feasibly provided for these, however, because each case study has different levels of data availability and cost categories. Instead, this report presents a framework for use in understanding types of incident costs in a consistent and systematic manner. It also provides recommendations for addressing information gaps through additional research.

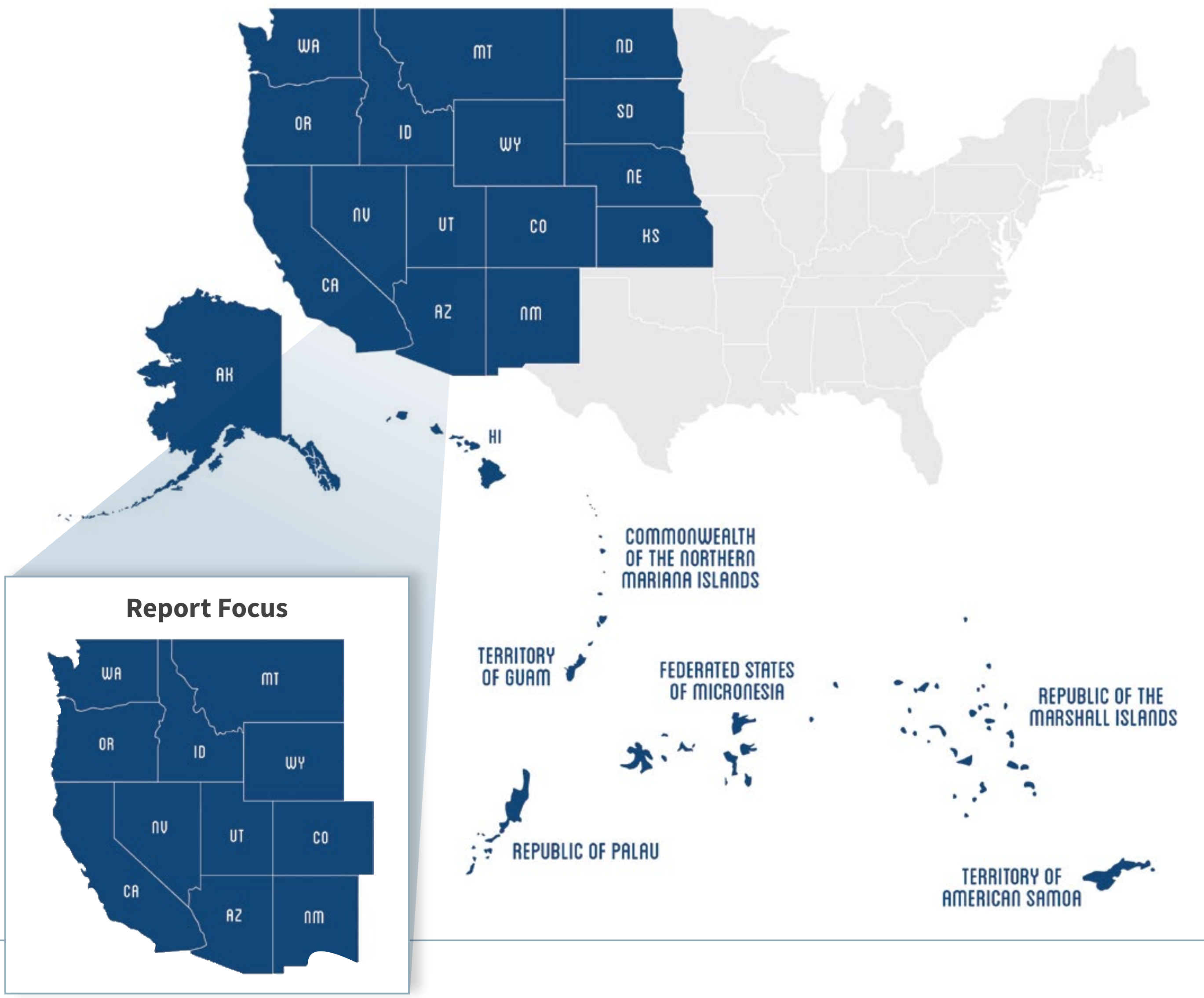
This report expands on the original *The True Cost of Wildfire in Western U.S.* (Dale 2010), that was published 12 years ago and also commissioned by the Western Forestry Leadership Coalition. The update includes new categories of costs and approaches to valuation, as well as a new set of eight case studies representative of more recent wildfire history. Further, it takes advantage of the large body of academic and professional literature written over the intervening years, which adds significantly to the understanding of wildfire behavior, vulnerability of assets, downstream effects on the economy and environment, and costs associated with wildfire mitigation practices.

South Lake Tahoe residents cheer, yell, and blow horns to thank firefighters for protecting their homes from the Caldor Fire in 2021. The locals gathered for several days near the Incident Command Post in South Lake Tahoe. Photo: Cecilio Ricardo/USDA Forest Service

Although this report covers the geographic area of the entire Western U.S., California is mentioned more than other states for several reasons: it has sustained the largest amount of property destruction from wildfire (59,000+ structures destroyed between 2005 and 2020, compared to 5,000+ in Texas, the next highest amount); it accounts for all 10 of the top 10 most costly wildfires in terms of insured losses between 2007 and 2020 (Aon Insurance and Zesty.ai, 2021); and it contains six out of 10 of the counties across the nation that have the highest property values at risk from wildfire.

Additionally, California's extensive and costly history with wildfire has led to more plentiful wildfire cost-related data and reporting than exists for other geographies. The frequency of information related to California is in no way designed to de-emphasize or draw attention away from the wildfire experiences of other western states. Rather, it is hoped that the lessons learned through California's investment in data collection related to wildfire cost may prove useful for other areas.

Western Forestry Leadership Coalition Represents the Western U.S. and Pacific Islands



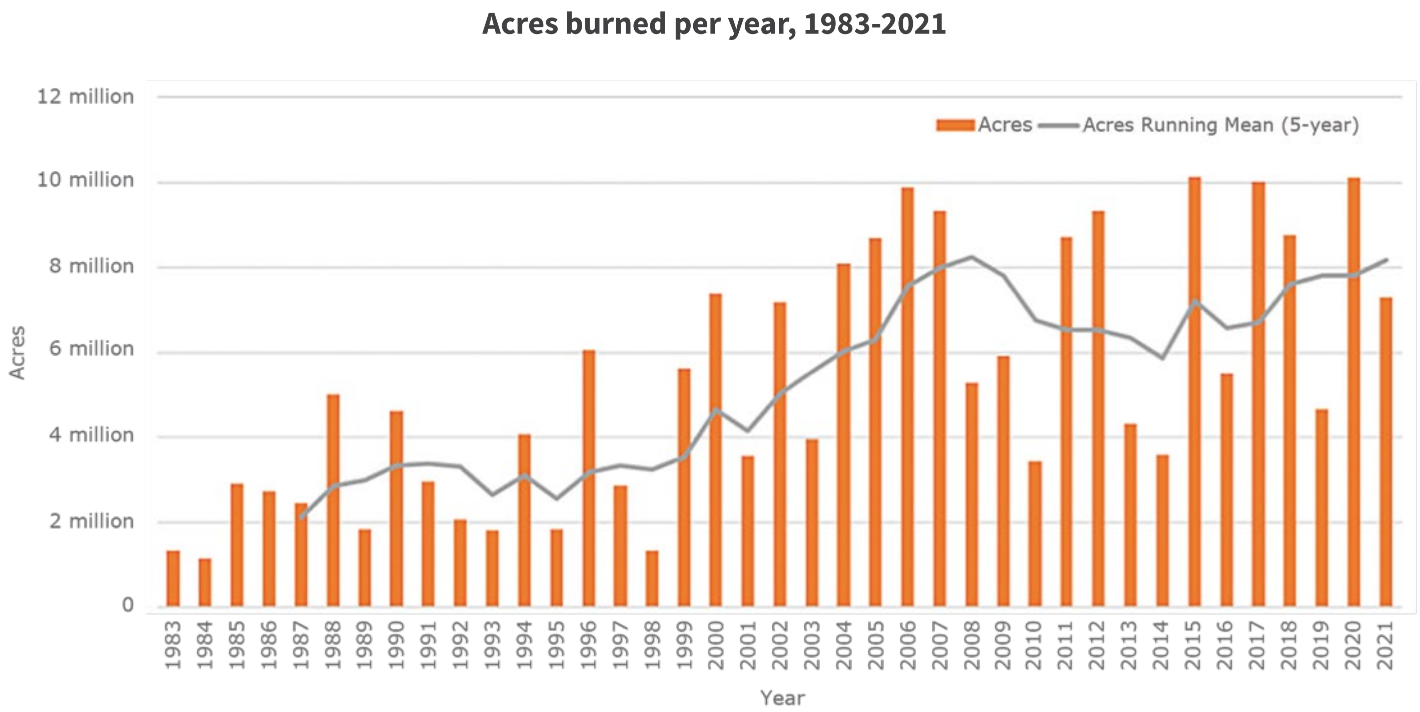


FIGURE 1 Acres burned per year from 1983 to 2021, indicating a steady increase in the 5-year running mean.
Source: National Interagency Fire Center, https://www.nifc.gov/fire-information/statistics

State of the Problem

The historic pattern of frequently occurring, low-intensity wildland fire has been significantly disrupted through intentional wildland fire suppression over the past century or more. In turn, both dead and living fuels and vegetation have accumulated. Exacerbated by a warming and drying climate that has yielded more combustible fuels, this hazardous accumulation of fuels has resulted in larger and more frequent, intense, and destructive fires in recent years (J. D. Miller & Safford, 2012). While fuel treatments can mitigate these trends, forest and rangeland management activities have not been able to keep pace.

The result has been a pattern of growth in large and highly catastrophic fires. According to the National Interagency Fire Center (NIFC), over the last several decades there has been a gradual increase in the moving averages of the acreage burned (Figure 1), as well as in the acreage per fire, although the number of individual wildfires has not increased significantly in the last three decades. Over 10 million acres were burned annually three times from 2015 to 2021, an amount that had not been exceeded prior to 2015 since modern record keeping began.

The increase in acreage burned is compounded by the rapid growth of the wildland-urban interface (WUI), exposing ever-increasing numbers of residents and homes to extreme wildfire risks (USDA Forest Service, 2022). This trend shows no signs of abating (Radeloff et al., 2018; Theobald & Romme, 2007) and has intensified with the COVID-19 pandemic. A 2021 study found that migration from large metropolitan areas to smaller metros, towns, exurbs, and rural areas increased by 9.3% in the last three quarters of 2020 (Whitaker, 2021). The result is a consistently increasing toll of destroyed and damaged structures (Figure 2).

More than 97,196 structures were destroyed by wildfires across the country between 2005 and 2022, according to the *Structures Destroyed by Wildfire* data site[1] compiled by Headwaters Economics. The majority of losses — 28,000 structures — occurred in just three California wildfires: the Camp Fire, LNU Complex, and North Complex. The second most

1 Headwaters Economics' *Structures Destroyed by Wildfire* database: https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire/

The wildland-urban interface (WUI) — where development intersects with natural vegetation — is increasing across the West. Though these areas offer desirable living conditions, they also expose more residents and homes to extreme wildfire risk. Photo: Austin Troy/ Spatial Informatics Group

impacted state is Texas, with more than 5,200 structures lost in that time. An additional 3,629 structures were destroyed in California alone from January to November 2021.

Headwaters Economics' data analysis shows 2018 (the year of the Camp Fire) as the most destructive wildfire year in history, followed by 2020. During the 15 years between 2005 and 2020, 62% of structure loss occurred in just three years: 2017, 2018, and 2020. These property losses track the geography of properties designated as "at high to extreme risk" by the insurance industry. According to Verisk's FireLine® product, California and Texas have the highest number of properties at risk from wildfire, with 2,040,600 and 717,800, respectively (Verisk, 2021). Montana and Idaho have the highest percentage of properties at risk, with 29% and 26%, respectively.

Structures destroyed by wildfire, 2005-2021

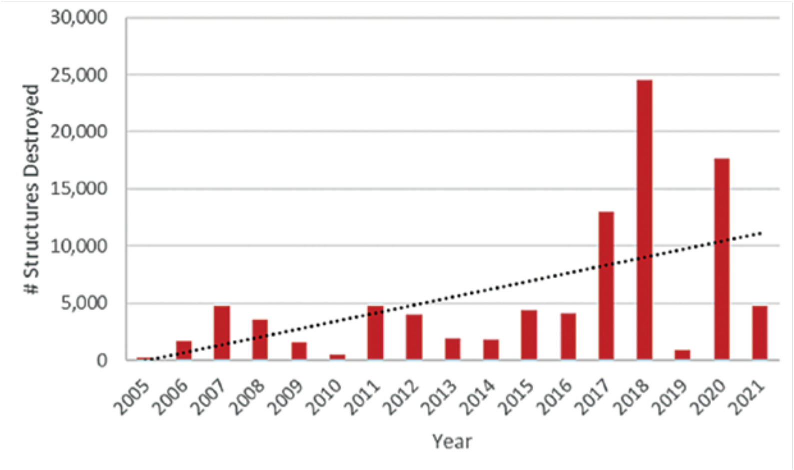


FIGURE 2 Trend in number of structures lost to wildfire from 2005 to 2021.

Sources:
- Headwaters Economics, https://headwaterseconomics.org/natural-hazards/structures- destroyed-by-wildfire/;
- National Fire and Aviation Management (FAMWEB) https://famit.nwcg.gov/;
- National Large Incident Year-to-Date Report (as of Nov. 9, 2021) https://gacc.nifc.gov/sacc/predictive/intelligence/NationalLargeIncidentYTDReport.pdf

Incident Commander Joe Williams, left, Bureau of Indian Affairs Forest Supervisor Chris Secakuku, center, and Operations Chief Mike Bertagnolli talk at the Boulder Ridge Fire on Aug. 14, 2022. The lightning-caused fire began on Ute tribal land near Neola, Utah. Photo: Geoff Liesik/ Bureau of Land Management

State of the Problem

In addition to structure loss, the most commonly quantified cost of wildfire is suppression, whose running mean has increased (Table 1, Figure 3). Federal suppression costs are well documented and, as a result, have garnered considerable attention. As of fiscal year (FY) 2020, total federal appropriations for suppression stood at $3.65 billion (Congressional Research Service, 2020). A considerable share of suppression costs are also borne by state and local agencies (see Figures 4 and 5 for Montana and Idaho examples). For instance, in FY 2020, California spent about $1.3 billion in suppression (Boxall, 2020).

Federal suppression costs are tracked consistently and are readily available from NIFC. Non-federal, state, local government and private sector suppression costs were neither consistently tracked nor easily obtainable (except California/CAL FIRE).

State costs (excluding private) were derived primarily from the University of Idaho *Policy Analysis Group (PAG) Report #37*, the State of Montana Fiscal Division (Figure 4) and Idaho Department of Lands (Figure 5). California has detailed numbers through 2021 (Figure 6). Colorado has some recent numbers as well. For instance, in 2020, one of the state's most expensive and destructive fire years, Colorado's suppression expenditures totaled $278 million and covered 16 wildfires in state responsibility areas (https://leg.colorado.gov/sites/default/files/fy2021-22_wildfirehrg.pdf).

PAG report data sources indicate inconsistencies. For example, Arizona, California, New Mexico, and Washington include federal reimbursements and Arizona includes tribal land. California, Colorado, and Oregon all include NIFC data. Oregon costs are unique and only include emergency fire suppression costs, not suppression costs paid through fire protection districts by "base layer" funding from the General Fund, Forest Patrol Assessments, and Forest Urban Interface Lands Assessment. Costs include additional state obligations for fire insurance premiums. And in Washington, acres are not differentiated by ownership.

Wildland firefighters watch an air tanker drop retardant on the Horse Park Fire in Colorado in 2018. Photo: Jerrod Fast/Bureau of Land Management

WESTERN STATES' SUPPRESSION COSTS, 2005-2015

STATE WILDFIRE ACRES AND COSTS

	Arizona*		California*		Colorado*		New Mexico*		Oregon*		Washington*	
Year	Acres Burned	Cost	Acres Burned	Cost	Acres Burned	Cost	Acres Burned	Cost	Acres Burned	Cost	Acres Burned	Cost
2005	147,746	no data	75,890	$543,605,579	6,195	no data	32,665	$3,889,750	99,610	no data	60,280	$18,166,527
2006	28,576	no data	206,787	$654,430,087	81,313	no data	422,640	$15,966,267	11,270	$10,590,626	48,803	$22,324,200
2007	27,365	no data	412,627	$873,489,764	12,539	no data	104,661	$7,960,976	54,733	$15,181,510	23,835	$47,968,257
2008	16,911	no data	404,954	$1,097,499,731	70,022	no data	314,519	$5,535,096	7,487	$9,907,966	32,680	$25,010,760
2009	74,015	$10,936,508	80,810	$839,976,900	17,815	no data	246,944	$12,484,068	7,034	$6,307,972	13,671	$30,167,656
2010	7,625	$9,698,203	27,240	$780,807,722	24,515	no data	73,751	$5,999,528	6,121	$5,860,776	25,440	$25,874,213
2011	68,343	$30,649,841	52,518	$749,844,212	98,239	no data	667,329	$13,501,508	2,637	$3,611,590	6,952	$16,361,855
2012	46,829	$12,158,582	61,249	$857,222,696	109,271	$7,906,426	26,266	$18,851,224	17,547	$6,354,926	22,716	$13,281,564
2013	63,789	$12,308,053	127,532	$786,510,564	33,408	$5,666,056	7,196	$9,911,616	104,167	$50,923,318	93,656	$47,220,775
2014	119,440	$7,689,263	103,211	$1,179,940,421	15,356	$54,016	12,450	$3,939,504	53,387	$24,712,041	197,705	$30,894,933
2015	61,032	$4,037,115	316,217	$1,443,785,926	15,999	no data	13,549	$3,625,726	86,629	$33,932,915	315,119	$89,227,713

TABLE 1 Western states' wildfire suppression costs from 2005 to 2015.[2]

Source: University of Idaho *Policy Analysis Group Report #37, State Funding For Wildfire Suppression in the Western United States*, 2017

2 **Arizona:** Acres include state, tribal and private lands. 2009-2014 costs include federal reimbursements.
California: Acres from NIFC/NICC, historical year-end fire statistics by state. Costs include state obligations and federal reimbursements.
Colorado: Acres are state and county, as reported by NIFC 2016a. Costs are from SIT 209 summaries.
New Mexico: Acres are state and private. Years shown are on a July 1-June 30 fiscal year. 2007-2015 costs include reimbursement from federal sources and other state agencies.
Oregon: Acres not differentiated by ownership, 2016 acres from NIFC 2016a. Only Emergency Fire suppression costs are reported, not suppression costs paid through fire protection districts by "base layer" funding from the General Fund, Forest Patrol Assessments, and Forest Urban Interface Lands Assessment. Costs include additional state obligations for fire insurance premiums. State costs not including fire insurance premiums rounded to the nearest $0.1 million by Oregon Department of Forestry. Years 2012-2015 include some estimated state obligation and reimbursement costs.
Washington: Acres not differentiated by ownership. State suppression costs are based on a July 1-June 30 fiscal year. Costs include federal, Clarke-McNary account and local general fund reimbursements.

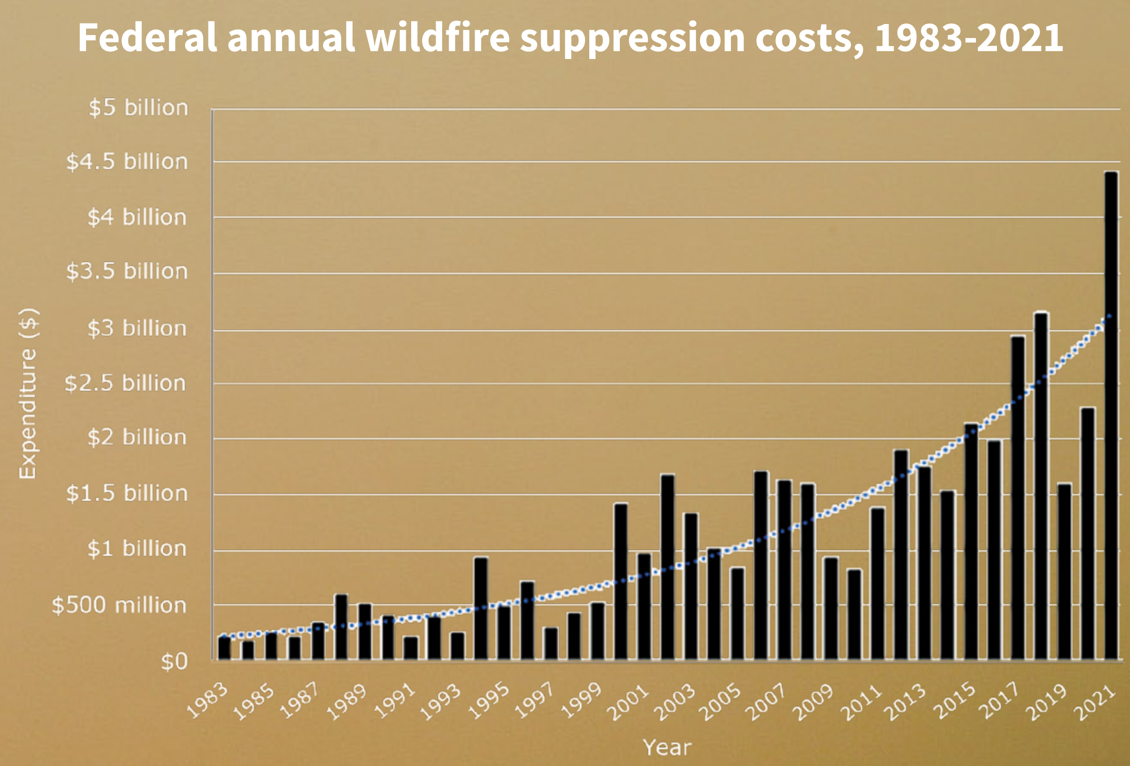
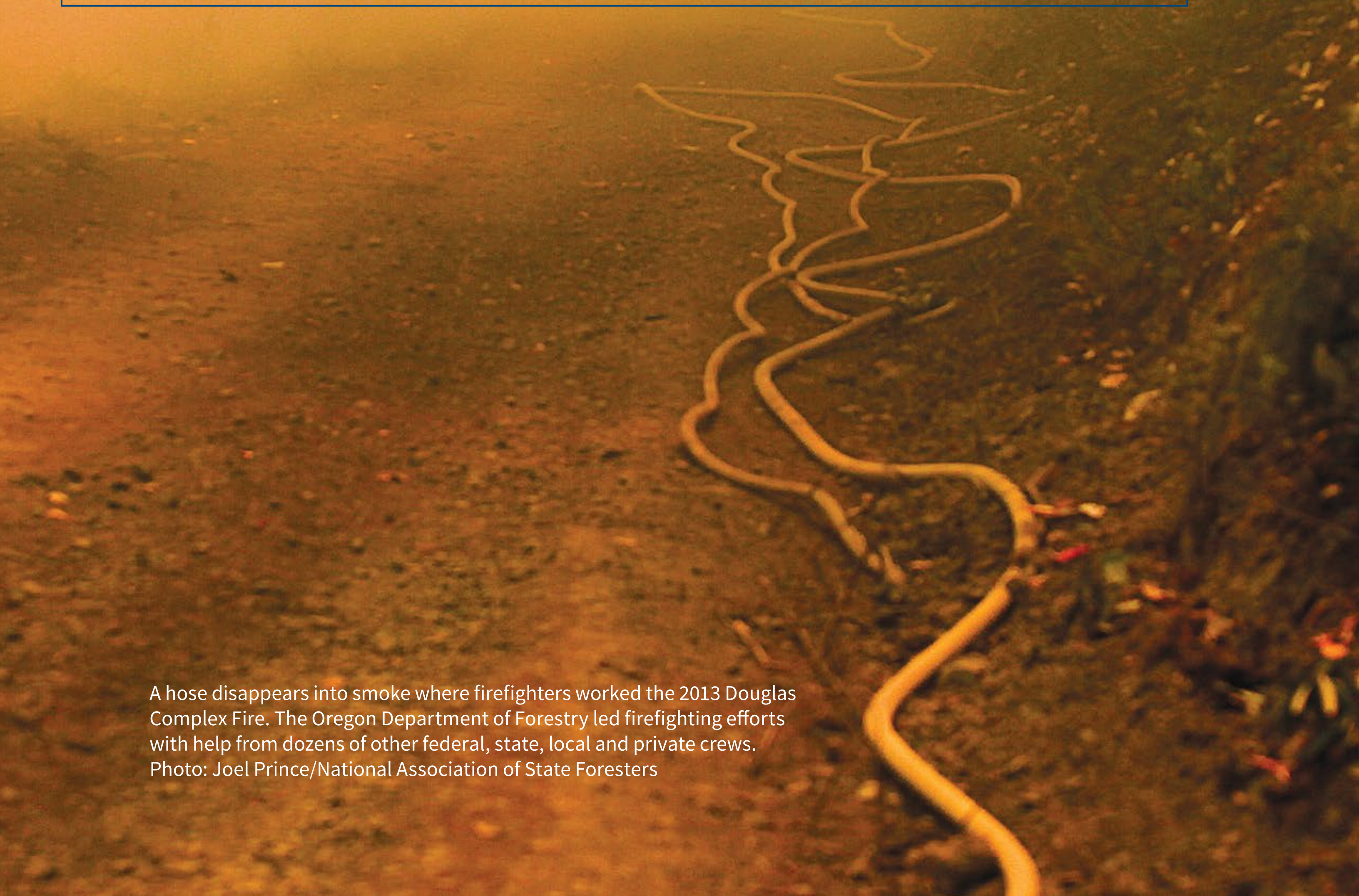


FIGURE 3 Total annual federal suppression costs from 1983 to 2021 (as of Nov. 7, 2021)

Source: National Interagency Fire Center, **https://www.nifc.gov/fire-information/statistics**



A hose disappears into smoke where firefighters worked the 2013 Douglas Complex Fire. The Oregon Department of Forestry led firefighting efforts with help from dozens of other federal, state, local and private crews. Photo: Joel Prince/National Association of State Foresters

STATE SUPPRESSION COSTS

Montana fire suppression costs, 2002-2020

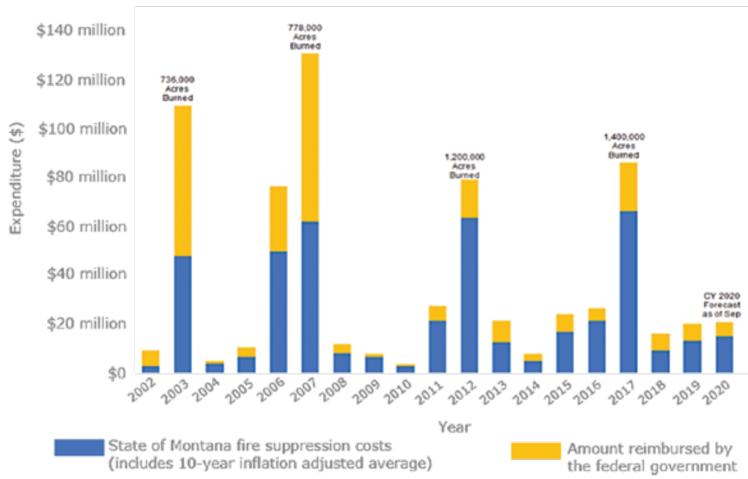


FIGURE 4 Montana state fire suppression costs from 2002 to 2020.

Source: Montana Legislative Fiscal Division, Wildfire Suppression Funding, 2020

Idaho trends in fire management expenditures, 2008-2017

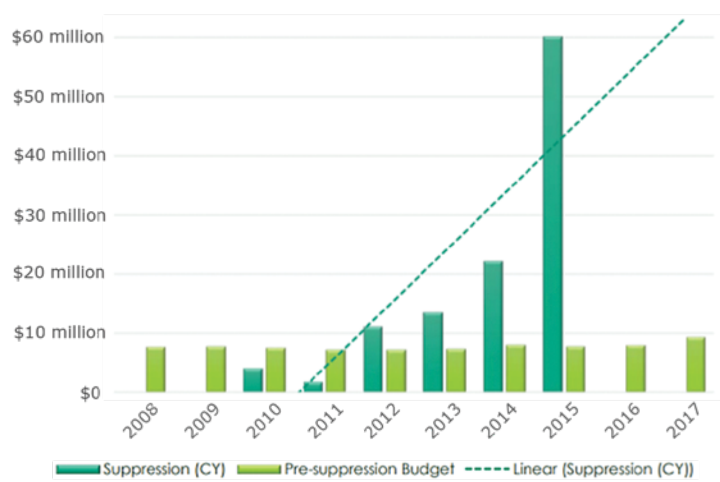


FIGURE 5 Idaho state trends in fire management expenditures from 2008 to 2017.

Source: Wildland Fire Associates, Idaho Department of Lands Fire Program Review, 2017

California wildfire suppression expenditures, 1979-2021

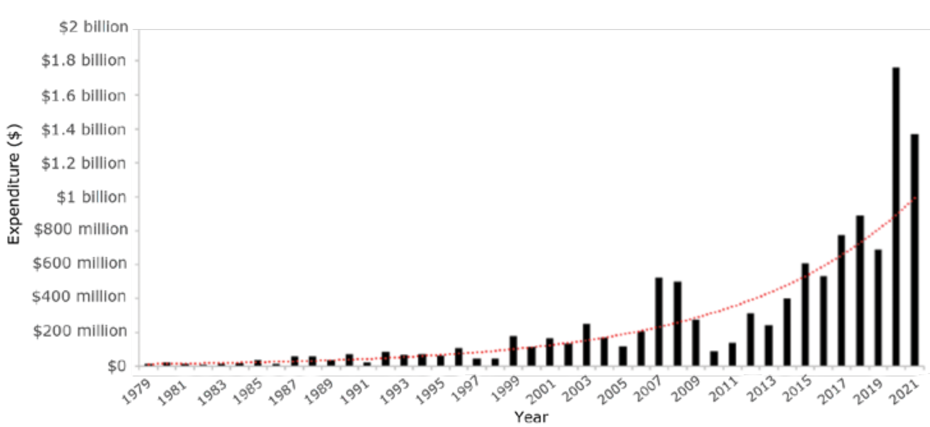


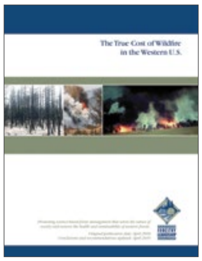
FIGURE 6 California wildfire suppression expenditures from 1979 to 2021.

Source: CAL FIRE **https://www.fire.ca.gov/media/px5lnaaw/suppressioncostsonepage1.pdf**

Previous Works on Wildfire Costs

This report is not the first attempt to summarize the costs of wildfire. The first edition of *The True Cost of Wildfire in the Western U.S.* was developed in 2010 (Dale, 2010). Additionally, other authors and organizations have tackled this issue both in broad overviews and for specific places or fire events. Table 2 summarizes highlights from some of the major previous studies. While they cover significant ground, there is still a clear need for an updated and holistic study that includes a comprehensive typology of costs — a need that this report fills.

NATIONAL STUDIES



THE TRUE COST OF WILDFIRE IN THE WESTERN U.S.

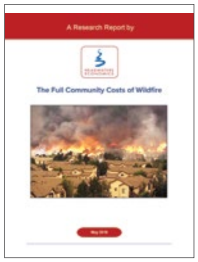
(Dale, 2010)

FINDINGS: The ratio of suppression costs to other costs varied greatly, from 3% in the Cerro Grande Fire (NM) to 53% in the Canyon Ferry Complex (MT).

This report conducts a follow-up to the original study, which separated the costs of wildfire into:

1) suppression;
2) direct costs;
3) rehabilitation;
4) indirect costs; and
5) additional categories

It looked at six case studies in five states and summarized costs by the five categories.



THE FULL COMMUNITY COSTS OF WILDFIRE

(Barrett, 2018)

FINDINGS: Suppression costs comprise only about 9% of total wildfire costs, and nearly half of wildfire costs are borne at the local level, most of them being the result of long-term damage.

The report showed the largest cost category was "degraded ecosystem services," accounting for 34% of all costs, followed by home and property loss (21%), long-term landscape rehabilitation (16%), suppression costs (8%), depreciated property values (8%) and immediate road and landscape stabilization (3%), among others. A key finding was how small suppression costs were in relative terms, at less than 7% of the total.

U.S. WILDFIRE COST-PLUS-LOSS ECONOMICS PROJECT

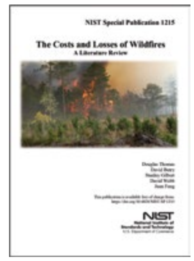
(Zybach et al., 2009)

FINDINGS: The full "cost-plus-loss" values from wildfire range from 10 to 50 times greater than suppression costs.

Costs were organized under 11 categories:

1) suppression;
2) property;
3) public health;
4) vegetation;
5) wildlife;
6) water;
7) air and atmospheric effects;
8) soil-related effects;
9) recreation and aesthetics;
10) energy; and
11) heritage

The study presented a general conceptual typology, without details on any case studies or cost calculations.

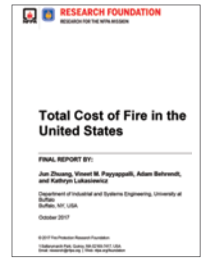


THE COSTS AND LOSSES OF WILDFIRE

(D. Thomas et al., 2017)

FINDINGS: The annual economic toll from wildfire, as of 2016, was between $63.5 billion and $285 billion.

Taking a microeconomic production function approach, this report attempted to estimate how the amount invested in mitigation measures might relate to the ultimate realization of costs, finding that this is a highly complex and only partially answerable question.



TOTAL COST OF FIRE IN THE UNITED STATES

(Zhuang et al., 2017)

FINDINGS: The total costs related to wildfire for 2014 (the latest year it included) were $328 billion, or 1.9% of the U.S. gross domestic product, and 83% was accounted for in expenditures, while "losses" constituted 17%.

The study created a unique typology of mutually exclusive expenditure and loss categories that separated expenditures into three categories:

1) active protection;
2) passive protection; and
3) net fire insurance expenditure

It separated losses into two categories:

1) direct; and 2) indirect

The largest cost component was fire-safe building construction, which totaled $57 billion under the "passive protection" category.

TABLE 2 A summary of the major previous national and state wildfire cost assessment reports, with a sampling of incident level cost reports.

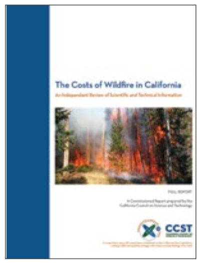
STATE LEVEL STUDIES

ECONOMIC FOOTPRINT OF CALIFORNIA WILDFIRES IN 2018

(Wang et al., 2021a)

FINDINGS: The 2018 California wildfires resulted in $148 billion in damages, or roughly 1.5% of the state's GDP. Notably, the costs associated with losses to built assets only comprised about 27% of the total.

Costs were $27 billion in capital loss (cost to repair and rebuild damaged and destroyed assets); $32 billion in health costs (medical expenses, lost working time, etc., due to the fire and subsequent air quality reduction); and $88 billion in "indirect losses" (the potential incremental loss to the state economy from disruptions across the supply chain).



THE COSTS OF WILDFIRE IN CALIFORNIA

(Feo et al., 2020)

FINDINGS: This 248-page report included a detailed cost typology with dozens of categories.

The framework distilled dozens of impacts into four high-level categories:

1) losses associated with damage to or destruction of physical assets;
2) losses associated with harm to health;
3) losses associated with changes in ecosystem processes; and
4) losses due to changes in economic activity

Under these are more disaggregated categories, like costs from mitigation, relocation, labor market impacts, local fiscal impacts, housing market impacts, secondary natural disasters, water quality and quantity, carbon sequestration and numerous ecosystem services and processes, in addition to various categories of costs associated with losses of different types of buildings and infrastructure.

Overall, this highly detailed report offered considerable guidance, but only specific to California.

INCIDENT LEVEL STUDIES

A FULL COST ACCOUNTING OF THE 2010 SCHULTZ FIRE

(Combrink et al., 2013)

FINDINGS: In Arizona, there was a $67 million decline in property values due to the Schultz Fire burn scar. It also led to an increased awareness of fire hazard.

This study presented a detailed accounting methodology and illustrated the types of fire-related costs that are often overlooked, along with cost categories such as destruction of habitat, cleanup, and flood armoring.

WHAT DO FOREST FIRES REALLY COST?

(Lynch, 2004)

FINDINGS: This is a cost accounting for a group of wildfires that occurred within a 10-year period in Colorado.

It lists estimates for 20 direct and indirect costs for each wildfire. Among the costs covered in this report were those related to post-fire water supply disruption through sedimentation, debris flows, and erosion.

Broadcast seeding by helicopter takes place after the Soda Fire in Idaho. Photo: Bureau of Land Management

COST typology

Cost Typology Background

This report presents a hierarchical cost-accounting typology framework that is based on a review of the literature and input from diverse stakeholders in the fire management community. The typology serves as a system for organizing categories of costs, helping enable full-cost accounting and tracking of the impacts of wildfire. It also helps track how costs are distributed among different sectors, geographies, and stakeholder groups.

This typology builds on those previously developed but incorporates the latest data and research in a somewhat different approach toward categorization. At the highest level, the typology is broken into three groups:

1) Direct Costs
2) Indirect Cost — Losses
3) Indirect Cost — Mitigation Investments

The last subcategory is included to highlight the critical point that some items society typically categorizes as costs are actually deliberate investments that are strategically targeted to reduce the future costs of wildfire.[3]

Ultimately, the information and analysis contained in this report is designed to help decision makers better weigh the value and need for these types of investments by highlighting the types of costs and losses that they help to avert. Underneath these three large categories is a hierarchy of subcategories (Table 3), each with a description of what it is and reasons why it is included. Citations to studies that quantified or utilized that cost category in some context are also included, where relevant, as well as information about the level of availability of applicable data. In many cases, information is also included about the feasibility, uncertainty or challenges of calculating a cost. When known, how costs were quantified or monetized is discussed. Understanding this is important given that relying only on purely monetary accounts of the costs of wildfire will leave out important elements.

It is important to establish conceptual boundaries in this type of typology since the costs of wildfire cascade indefinitely and unmeasurably through society over time. To keep the typology manageable, the focus remains on direct and indirect costs that can be clearly and convincingly attributed to wildfire, with an emphasis on cost categories with connections to wildfire that have been well established in the literature and by practitioners.

Finally, this typology does not distinguish between costs and losses. For simplicity's sake, these two terms are used interchangeably.

3 Some cost types in Indirect Costs — Losses may occasionally result in indirect benefits — for instance, a forest type conversion after a wildfire may reduce the chance of future catastrophic fire — but these are uncommon, unintentional, and uncontrollable.

A crew member from the Bureau of Land Management's (BLM) Fire program works on a fuels project near Albuquerque, New Mexico. Photo: Avi Farber/for BLM

COST TYPOLOGY SUMMARY

TABLE 3

1 Direct Costs include:

- Suppression
- Natural resources
- Structures and property
- Utilities and infrastructure
- Evacuations, sheltering, and donations
- Loss of life and injuries
- Immediate health/ well-being impacts from fire and smoke
- Immediate economic impacts during incidents

2 Indirect Costs — Losses include:

- **Economics**
  - Forestry and natural resource industries
  - Recreation and tourism
  - Other business activity
  - Labor markets
  - Lowered property values and tax bases
  - Increased insurance premiums or loss of coverage
  - Disrupted interstate and intercity commerce
  - Low recruitment/ retention to fire agencies
- **Water supply**
- **Flooding, slides, and erosion**
- **Health, safety, and well-being**
  - Long-term air quality effects on public health
  - Long-term effects on mental health
  - Long-term air quality effects on built assets
- **Ecology and landscape**
  - Atmospheric carbon emissions, loss of carbon stocks and sequestration potential
  - Post-fire invasive species
  - Lost wildlife and biodiversity
  - Ecological restoration and cleanup
  - Post-fire monitoring and assessment

3 Indirect Costs — Mitigation Investments include:

- Pre-planning, risk assessments, zoning efforts, evacuation routes, safe zones
- Defensible space and home hardening
- Fuel treatments
- Infrastructure and utility hardening
- Pre-emptive depowering
- Training and preparedness

Cost Typology Details

Direct costs

1 DIRECT COSTS

SUPPRESSION

The cost of wildfire suppression includes activities aimed at restricting the spread of a wildfire after its detection (Florec et al., 2019). Money for suppression covers a wide array of purposes, including pay for firefighters, Hotshots, smokejumpers and support personnel; food, shelter and supplies; ground support equipment like water tenders and bulldozers; and air assets, like fixed-wing tankers and helicopters, which is frequently one of the largest cost items. Costs vary significantly depending on the extent to which a fire threatens urban areas, power lines and other infrastructure, fuels, remoteness, and topography, among other factors (Gilpin & Print, 2016). Some of the most expensive fires in terms of suppression cost include the 2016 Soberanes Fire in California ($260 million), the Biscuit Fire in Oregon ($150 million), the Rim Fire ($127 million) and the Rough Fire ($120 million), both also in California, among many others.

Firefighters conduct a burnout on California's Gap Fire in 2008. Suppression costs can be hard to quantify because federal, state, and local government, tribal agencies and private/contract response varies greatly. Photo: Taro Pusina/Spatial Informatics Group

Throughout the West, there are different approaches to fire suppression response between federal, state, local government and tribal entities (Pennick McIver, et al., 2021). Fire responsibility depends on whether an incident is within a federal responsibility area (FRA), state responsibility area (SRA), or local responsibility area (LRA). Federal and state fire suppression costs can be determined from a number of sources, including National Interagency Fire Center (NIFC) estimates (which often do not include total suppression costs), Incident Status Summary (ICS-209) reports and published Wildfire Decision Support System (WFDSS) decisions where available. The ICS-209[4] data is typically available for interjurisdictional or unified command incidents between federal and state suppression responsibility areas; however, limited data is available for incidents prior to 2014 or from local jurisdictions.

Some state suppression costs can be derived from legislative meeting minutes as well as from personal communications with state fire administrators. For example, Vaughn T. Jones (Chief of the Wildland Fire Management Section for the Colorado Department of Public Safety - Division of Fire Prevention and Control) was able to confirm suppression costs for a given year for Colorado. Suppression costs borne by local jurisdictions are typically not publicly available and are limited unless they are included in ICS-209 reports, as states typically do not require reporting this information. Total suppression cost summaries by year are available from NIFC.[5] All this underscores that extensive data exists on suppression costs, but it is inconsistent

4 An ICS-209 report is required for any fire under a full suppression management strategy that exceeds 100 acres in timber (fuel models 8-13), 300 acres in grass and brush (fuel models 1-7), or has a Type 1 or 2 incident management team assigned. (Geographic areas and agencies may have more stringent reporting requirements.) Wildland fires managed under multiple strategies may, or may not, require an ICS-209 to be submitted daily, depending on the size and complexity of the incident.

5 https://www.nifc.gov/fire-information/statistics/suppression-costs

and incomplete, particularly for nonfederal partners in suppression. Data availability ranges from excellent to nonexistent for these nonfederal jurisdictions, meaning it is difficult to get a complete picture of suppression costs by fire nationally, although the largest fires typically have relatively complete suppression cost data.

The smoke plume from the Lava Fire rises behind a Roseburg Forest Products lumber mill in Weed, Calif., in 2021. Wildfire can destroy a variety of natural resources in a forest, including standing or felled timber awaiting harvest. Decades of growth can be decimated in minutes during a wildfire, changing the economic landscape long into the future. Photo: Taro Pusina/Spatial Informatics Group

NATURAL RESOURCES

The losses to forests, rangelands, and other natural resources are realized as both direct and indirect costs. The direct costs, or immediate effects of wildfire on natural resource industries during an incident, are discussed here. Indirect costs, discussed in detail in the following section, include longer-term changes to natural resource markets and economies that are triggered by an initial loss in natural resource supply.

Wildfire can damage or destroy a wide range of economically valuable natural resources, including standing and felled timber, row crops, orchards, and rangelands, among others. Because crops and rangeland forage can grow back, and orchards rarely burn, timberlands are the biggest concern in this category, especially given that decades of growth can be decimated in a matter of minutes. While the area of working forest affected by a wildfire is relatively easy to calculate by overlaying the fire perimeter boundary on a map of land cover, calculating the actual volume or economic value of timber lost is far more complicated. In the absence of pre-existing forest inventories, timber volumes must be modeled or estimated from remote sensing data. This is theoretically possible with newer 3-D remote sensing technologies like Light Detection and Ranging (LiDAR), which is useful for estimating several key forest inventory characteristics such as height, basal area, and volume. However, other characteristics needed for complete economic valuation, such as species and grade, are not yet feasible (White et al., 2016).

The ability to make these calculations nationally is aided by the existence of the USDA Forest Service's Forest Inventory and Analysis (FIA) program, which provides biometric data for hundreds of thousands of sample forest plots. However, because the data set represents a sample (collected in three stages) of one field site per 6,000 acres of actual forest, the vast majority of locations are unsampled. As a result, FIA is only of limited value in estimating the economic value of lost timber from wildfire. Another piece of information which is largely missing at the national scale that is important to calculating timber losses from wildfire is insurance coverage for private timberlands, although it has been reported that overall timber insurance coverage is relatively rare and so likely only applies to a fraction of private timberlands (Zhang & Stenger, 2014).

Other direct natural resource losses from fire, including rangelands and agriculture impacts, have been increasing in frequency and extent in recent years. In addition to incineration, wildfire can inflict significant smoke and heat damage to crops and grasslands, as well as kill livestock and destroy irrigation and fencing infrastructure (Powell, 2021). The fact that croplands are often located along transportation corridors that can serve as ignition vectors adds to the risk. Nonetheless, the impacts of agricultural and rangeland losses (with the exception of orchards) are typically not as long-lasting as forest losses, given how long it takes timber to regenerate relative to other resources.
An example of a wildfire with particularly high agricultural losses was the Beaver Fire in the Texas panhandle. Although only 2,962 acres in size, it killed about 4,000 head of livestock and accounted for approximately

$25 million in damages (U.S. Department of Commerce, n.d.). However, under the 2014 Farm Bill Indemnity Program, ranchers can be compensated, to a preset limit, for up to 75% of livestock losses with proper documentation (Ledbetter, 2017). The result is that some of the costs of some types of agricultural wildfire-related losses are redistributed from farmers to general taxpayers.

While timber and livestock losses on public lands are typically reported, data on other natural resource losses is scarce or inconsistent, making the calculation of natural resources losses on lands with diverse land use and ownership highly challenging.

STRUCTURES AND PROPERTY

Data from the insurance industry indicates a steep rise in property loss from wildfire. From 1964 to 1990, the average annual insurance industry payout for wildfire structure losses was less than $100 million, that annual average jumped to $600 million for the following two decades, and then to $4 billion from 2011 to 2018 (CRC Group, 2021). A staggering statistic comes from Allstate, one of the largest property insurers, which saw property losses in the five-year period from 2016 to 2021 increase by 1,655% relative to losses from the previous five-year period from 2010 to 2015.[6]

Recognizing the lack of a data portal for tracking national structure loss from wildfire, Headwaters Economics assembled the *Structures Destroyed by Wildfire* data site,[7] based on data from the National Fire and Aviation Management's FAMWEB and NIFC's *Incident Year-to-Date Report*. The data portal summarizes estimated total structure losses by year going back to 2005 and can sort data by state and by fire event. It calculates that 89,210 structures were destroyed by wildfire between 2005 and 2020, with 2018 being the most destructive year. The NIFC reports, upon which much of this dataset is based, detail all large fires in the U.S. and give a count of structures lost by incident, but many smaller fires involving structure destruction are not included. A similar data resource comes from researchers at the University of Colorado, Boulder, who mined and cleaned data records from the U.S. National Incident Management System from 1999 to 2014 and maintain an open-source database (St. Denis et al., 2020).

There is not, however, a national data resource that tracks the improvement value lost or cost to rebuild structures lost to wildfire. This is important, because without such data it is hard to put a price tag on the actual total property losses or reconstruction costs. In many cities and counties, this value can be indirectly estimated by using property assessment records, if the location of destroyed structures is known. While they are not always perfect reflections of home value, assessments are useful for this purpose since they are typically split into separate land and improvement value components, allowing for the estimation of the cost to rebuild.

There are many different approaches for documenting losses to structures from wildfires at different levels of government. Many states have their own approaches for this. For instance, California uses the official Damage and Inspection Team Reports, generated by teams that assess structure damage, loss, and location using parcel information, unmanned aerial vehicles (UAVs), and satellite imagery. At the federal level, there is no comprehensive database that tracks all these losses (D. Thomas et al., 2017). The closest to such a product is the Federal Emergency Management Agency's (FEMA) National Fire Incident Reporting System (NFIRS) which serves as a standardized approach to report damage and losses to structures and buildings. However, this is not nationally required (although many states do require it) and therefore it may not represent a complete national picture. Further, fire departments in WUI zones, where wildland fire is most relevant, typically do not report data in this system. Nonetheless, NFIRS data can be helpful in some cases and at least one study attempted to estimate national structures losses from NFIRS data, despite these shortcomings, coming up with an

6 From the Aspen's Institute's *Wildfire Resilience: Protecting Communities and Forests from Megafires* (https://www.youtube.com/watch?v=DBJrKhoM5As; marker 1:12)

7 Headwaters Economics *Structures Destroyed by Wildfire* database: https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire/

estimated annual structure loss of $160 million from 2002 to 2006 (D. Thomas & Butry, 2012).

It is important to remember why the loss of homes matters. They are typically the most valuable asset held by families and act as both shelter and financial buffer. Losing a home can be devastating to a family and uproot their lives. Frequently payouts from insurance fail to cover the full cost of reconstruction, contents, temporary displacement, and moves. Further, when enough homes are destroyed in one area, it can undermine the entire fabric of a community, and often only a fraction of residents will return. Hence, the true cost of housing loss from wildfire goes far beyond just the dollar value of rebuilding.

A mural by California artist Shane Grammer adorns the former Pioneer Cafe in Greenville, California. It and the Sierra Lodge, where residents lived above the old cafe, were among the buildings burned by the Dixie Fire in 2018. The wildfire caused massive damage to the town's infrastructure, businesses, and homes. Photo: Jason Moghaddas/ Spatial Informatics Group

UTILITIES AND INFRASTRUCTURE

The infrastructure subjected to damage from wildfires includes assets such as highways, electrical power lines and grid infrastructure, communication structures and networks, water delivery systems and sewer systems, among many others (Diaz, 2012). The resulting loss of basic services can be crippling to communities in the immediate aftermath of wildfire, and generally repairs to restore these services takes high priority after suppression is complete. These losses are sometimes accounted for but can often be difficult to get accurate information on, particularly for smaller scale and/ or localized critical infrastructure.

Roads and highways are a particularly important class of asset. They are rarely fully destroyed by wildfires, but fire can cause cracks, potholes and deformations, and significantly reduce their lifespan. In some cases, road structures need to be repaved or even rebuilt, such as in the case of complex structures like viaducts (see the Grizzly Creek Fire case study). While costs to repave or rebuild may be able to be determined, damage function models that could be used to estimate costs to infrastructure from wildfire are lacking and in need of further research compared to other hazard types, according to a recent review of 166 journal articles (Habermann & Hedel, 2018).

A more common impact of wildfire on roads is deposition of debris during subsequent rainstorms. Debris removal can be extremely costly, and the responsibility for covering these costs varies significantly, from utilities to special districts, local governments, counties, states, and federal agencies. How wildfires directly damage roads is not well understood, but experience shows that one of the major ways wildfires can affect transportation is through post-fire slides and debris flows, which can lead to long road closures. This process is discussed in more detail in the “Flooding, Slides, and Erosion” section.

The electricity grid is particularly vulnerable to wildfire. Large populations can be impacted if critical components, such as transmission trunk lines, substations, or transformers are disabled. An example of this exposure was shown in 2021, when the Bootleg Fire in Oregon knocked out a portion of the California-Oregon Intertie, a high-voltage interstate transmission line that supplies electricity to large swaths of California. This occurred during a time when the grid was already strained by demand from unusually high temperatures, and ultimately resulted in 4,000 megawatts of imported energy (10% of peak demand) being taken offline. To meet the supply shortfall, California’s Independent System Operator (CAISO) had to rapidly engage gas and hydroelectric plants while also declaring a

1 DIRECT COSTS

Stage 2 emergency and ordering utilities throughout the state to prepare for rolling blackouts (Roth, 2021). Ultimately, significant impacts on electrical consumers were narrowly avoided, but this experience highlighted just how vulnerable the electrical grid in this region is to future wildfire activity. A detailed 2011 report from Lawrence Berkeley National Labs found wildfire to be one of the biggest threats to California's electrical grid, concluding that even nonflammable structures, like high-tension power lines, can lose function in wildfire due to heat and smoke (Sathaye et al., 2012). Ultimately, investments will be required to increase the grid's resiliency to wildfire, including expensive investments in distributed energy resources (e.g., onsite generation) and large-scale battery storage (Matson, 2021).

Data for these costs are again limited and inconsistent and come from diverse sources including utilities, public works and transportation departments, and local and state governments.

EVACUATIONS, SHELTERING, AND DONATIONS

Evacuations are critical to avoid loss of life or injury. In Australia, which has a similar pattern of WUI development to the Western U.S., the leading cause of civilian fatalities between 1901 and 2011 was late evacuation (204 of 674 total fatalities or 30.4%). Evacuations can cause a range of personal, community, and regional disruptions, depending on their duration and scale. If a property isn't damaged by wildfire, residents can sometimes return home within a day. But if wildfire causes extended evacuations, residents can incur extensive costs related to lodging, loss of work, missed school days, and additional costs for transport and pasturing or kenneling of livestock or pets.

During the 2021 Dixie Fire in California, residents were evacuated for 42 days, with many of the associated costs (e.g., hotel, food) incurred by the evacuees unless they stayed in a local shelter. Wildfire evacuees are often provided short-term sheltering options at local schools, fairgrounds, or similar facilities, all of which incur costs. Yet, finding long-term housing for people who lose homes to wildfire can be far more challenging, particularly in areas already experiencing a housing shortage (Levine, 2018). Providing food, shelter, and supplies for long-term evacuees is often supported locally by restaurants, thrift stores, friends, and more recently via direct donation sites such as Go Fund Me. Still, the costs to evacuees can reach well beyond out-of-pocket expenses to include difficulty accessing work, sending children to school, and accessing needed services.

Research is limited on these costs for wildfire but reporting on hurricane evacuations suggests that the cost for an average family to evacuate can be around $5,000 (Scipioni, 2017). Overall, data on wildfire evacuations and associated costs, including feeding and housing, ranges from negligible to nonexistent.

LOSS OF LIFE AND INJURY

People can be directly injured or killed in wildfire suppression operations, while sheltering in place, or while evacuating, including through vehicle accidents (Diskin & Wyloge, 2019). Loss of life directly due to wildfires is generally well documented for both civilians and firefighters within the Incident Status Summary (ICS-209) reports. Similar to loss of life, fire-related injuries to civilians and firefighters are also well documented in the ICS-209s.

Animal mortality is also a consequence of wildfire. While loss of livestock is described in detail in the "Natural Resources" section since it represents an economic loss, an additional impact is the loss of pets. It is well documented that human-pet bonds are extremely powerful and therapeutic, and that loss of pets can be traumatic (Julius et al., 2012). Wildfires can result in domestic pets such as cats and dogs either dying or becoming separated from owners. The loss of a pet can exacerbate the emotional impact of a fire on a person or family. In some cases, pets survive a wildfire, but it is difficult to reunite them with their owners, particularly when a community has been destroyed. Wildfires have claimed many pets, but only limited data exists on these losses or how they impact pet owners.

IMMEDIATE HEALTH AND WELL-BEING IMPACTS FROM FIRE AND SMOKE

Both firefighters and civilians can suffer burns or other heat-related injuries during wildland firefighting and evacuations. According to FEMA, rates of

During the Road 702 Fire in 2022, community donations filled an engine bay at the Cambridge Fire Station in western Nebraska. The fire began in Kansas but winds quickly fanned it north into Nebraska, where the majority of the wildfire's impact took place. Photo: Nebraska Forest Service/ for the National Interagency Fire Center

wildfire-related death in the U.S. have ranged from 10-11.7 per million over the last decade, with total deaths per year ranging from 3,400 to 3,800 during that time (FEMA, 2021).

A range of direct short- and long-term health effects from wildfire have been widely documented, including post-traumatic stress disorder (PTSD), suicide, (Stanley, 2021) and respiratory issues from wildfire smoke (B. A. Jones et al., 2016). Wildfire smoke can result in school closures, impacts to workers in industries with extensive outdoor work, such as agriculture or construction, and can compromise transportation networks, all of which can impact individual and community well-being. In addition, wildfire smoke can impact livestock during an incident.

Increasingly, wildland firefighters are reporting high rates of job-related burnout due to extended wildland fire seasons, and they are suffering from higher rates of depression, addiction, anxiety, and suicidal ideation relative to the general public (Sacks, 2021). This has led to difficulties in firefighter hiring and retention across the wildland firefighting community.

IMMEDIATE ECONOMIC IMPACTS DURING AN INCIDENT

Economic impacts that occur during and immediately after a major wildfire event include reductions in revenues and temporary or permanent business closures, among other things. A recent study found that, in the days immediately following wildfire events, revenue dropped significantly for many economic categories, from about 5% to 50%, depending on category. For instance, food and beverage shop revenues dropped by 12%-13% after both the Camp and Carr fires, and arts and entertainment outlets lost 44% of their revenue after both the Easy and Maria fires. However, other economic sectors saw increased revenue. For instance, lodging revenue increased by 138% after the Camp Fire.

The study also looked at which businesses closed and did not reopen within three months of an incident. In California for example, 13% of businesses did not reopen after the Camp Fire, 6.6% after the Kincade Fire, and 5% after the Carr Fire. These closures varied by business type. For instance, food and beverage stores saw the largest impact with 24% closure after the Camp Fire (Womply Research, 2021). Closures affect business in a number of ways. Not only do business owners forgo revenues when their stores are closed, but they also have expenses that might need to be paid during those times, or inventory that is perishable, a particularly important issue for food service.

Evacuations and smoke-related impacts also lead to government services closing that are critical to the economy, with schools being a notable example (Lambert, 2021). One economic sector that may buck these trends is construction, which often is in high demand to perform repairs immediately after a fire.

Overall, data on these types of revenue losses and closures are negligible to nonexistent, often only available when a specific study has been done for a particular region or fire.

Indirect Costs — Losses

ECONOMICS

Forestry and Natural Resource Industries

Teasing apart the long-term economic effects of wildfire on timber markets can be complicated. Many forest owners will lose their marketable timber, presenting them with an outright economic loss that may or may not be insured. Others will be able to salvage damaged timber; however, this can lead to a short-term glut in local timber markets, in turn depressing prices (Butry et al., 2001). For instance, after Hurricane Hugo damaged nearly 20% of timber in the Carolina coastal plains, this caused up to 30% price drops regionally (Prestemon & Holmes, 2000). Long-term effects can be much more consequential. For instance, in the 18 counties of the greater Saint Johns River Water Management District affected by the catastrophic 1998 Florida wildfires, regional consumers were estimated to have lost somewhere between $21 million and $403 million (depending on elasticities used) due to loss of raw materials for the timber industry. When costs and benefits are weighed across all affected sectors, the total welfare effects of these fires on the softwood timber market were conservatively calculated between $350 million and $600 million (Mercer et al., 2000).

An additional effect of wildfire on the timber industry that is suggested anecdotally is the loss of mills and other industrial infrastructure following major fires, due to a loss of raw materials, but data or studies on this phenomenon are currently lacking. Assessments of price impacts are aided by numerous organizations that track timber stumpage prices within a multi-state region, such as Timbermart-North and Timbermart-South.

The indirect, long-term effects on agricultural markets are equally difficult to quantify. For range management, an increasingly common short-term impact is that livestock herds lose their immediate source of forage, which requires expensive substitute feeds. For instance, following the 2017 North Texas wildfires, 13,000-14,000 head of cattle lost their rangelands, requiring nearly $1 million in costs for imported feed (Ledbetter, 2017). Over time, row and forage crops regrow far more quickly than timber, which makes the economic impact shorter for agriculture than for forestry, although orchard damage can have much more lasting impacts. Regardless, agricultural areas that experience repeat burning may find a gradual retreat of the agricultural economy, as farmers sell off lands vulnerable to wildfire and suppliers and middlemen ultimately leave the local economy.

Recreation and Tourism

Wildfires can have devastating short- and long-term regional effects on nature-based recreation and tourism as landscapes are degraded, potentially making recreation undesirable, unsafe, or inaccessible. In the short term this can result in costs related to repairing and rebuilding tourism infrastructure and restoring degraded landscapes, while in the long term this can result in the decline or loss of recreation industry businesses in the region, even after landscapes may have recovered.

The wildfires in the Florida case mentioned previously were calculated to have cost $138 million in tourism and recreation revenue. However, a complicating factor in making these calculations is that in some cases, those recreation dollars are not entirely lost but rather displaced to other, nearby locations, at least in cases when substitute recreation opportunities exist nearby. For instance, a study of the 2002 Hayman Fire in Colorado found that while outfitter and guide business revenue declined in the immediate vicinity of the fire, much of that loss was offset by gains in those same sectors in other locations, as recreationalists simply altered their destinations (Kent et al., 2003). This is not surprising in a place like the Colorado Front Range, where many recreational substitutes exist. Hence, in cases where alternatives exist in proximity, there may be no overall loss in economic welfare measures, but merely a geographic redistribution.

The literature makes clear these dollars spent on these recreation and tourism-related businesses reflect consumers' willingness to pay (WTP) to experience nature. Therefore,

when a wildfire undermines the recreational capabilities of the land, not only does it negatively affect businesses, but it also means consumers now have a lower WTP for those landscapes. A number of studies have quantified the resulting welfare changes using nonmarket valuation methods that infer values from observed behavior or stated preferences, like contingent valuation, travel cost, or contingent behavior. A recent review paper summarized a large body of research about changes in consumer welfare due to fire-driven closures of recreational landscapes (Bawa, 2017). It found that these losses in consumer welfare are both quantifiable and substantial, often in the millions of dollars per site, but that they vary significantly based on activity, ecosystem, region and, importantly, fire severity. In fact, visitation can actually increase in the period following low intensity fires, as was found in Southern California (Sánchez et al., 2016) and New Mexico (Starbuck et al., 2006).

Overall, data and studies on long-term economic impacts on recreation and tourism industries from wildfire are sparse.

Other Business Activity

Beyond natural resource-dependent industries, wildfires often result in the loss or closure of business and industrial establishments more generally in an affected area. Even when business facilities are not directly damaged or destroyed by fire, their activities may be curtailed or rendered more costly by reduced access, interruptions of utility services, shipping delays, supply chain disruptions, loss of employees, reduced employee mobility or loss of customers, among other impacts. These effects reverberate downstream through the economy as businesses and institutions that were not directly affected by the fire, but depend on the affected businesses, lose access to those upstream products, or services. These impacts can reach far through the economy.

Measuring the economic impacts directly attributable to a wildfire is notoriously difficult for several reasons. First, there are many potentially confounding factors, such as local economic slumps or sectoral shifts among locations. For instance, after the 1998 Florida wildfire season previously mentioned, business revenue in the 18-county area actually went up by $1 billion from the previous year, for unrelated reasons (Mercer et al., 2000). Second, while many businesses experience impacts from supply chain delays to reduced employee mobility, few businesses actually keep track of these fire-related costs (Diaz, 2012). Generally, the larger a geographical region looked at, the harder it is to isolate these effects. For instance, a study of the 2002 Hayman Fire in Colorado found only weak statistical evidence of an economic effect attributable to the fire in the larger four-county primary impact area (Kent et al., 2003).

Doing a full post-fire economic impact analysis requires an enormous effort that includes studying all sectors of the regional economy before the fire and how these changed afterwards, all while controlling for confounding forces. It is therefore not surprising that this is rarely done. One of the few examples was a recently released economic analysis of the 2018 Camp Fire (Economic and Planning Systems Inc & Industrial

After wildfire, recreation can become undesirable, unsafe, or inaccessible. But costs of these impacts are difficult to track. Photo: Jason Moghaddas/ Spatial Informatics Group

Economics Inc, 2021). It was able to quantify employment by sector as well as pre-existing trends in those sectors before the fire hit, with a level of detail that made it possible to definitively isolate the effects of the fire. Among the findings was a decline in gross regional product (GRP) for the fire footprint area of between 64% and 81% in the year following the fire. However, that effect was much smaller for the overall tri-county region, at only a 1.6% decline in the following year.

Labor Markets

During or immediately after a major wildfire there is often workforce displacement or loss of mobility due to evacuations, road closures, mandatory shelter-in-place requirements, or loss of internet access. These short-term losses in employment can often be offset locally by labor market and wage growth associated with fire suppression during the incident, which can give local economies a short-term boost. However, in cases where the local economy is "service-specialized" this boost in short-term local spending fails to offset the short-term business employment losses. A study of this effect found less than 10% of short-term suppression expenditures go toward the local economy, with the rest going toward labor imported from other regions of the country (Nielsen-Pincus et al., 2013).

Following the end of suppression, significant variability exists in how local employment sectors respond. One study over 413 western counties found that, after the initial pulse of suppression investment, volatility in the employment market increased, resulting in an amplification of pre-existing workforce boom and bust cycles. Counties with more persistent wildfire patterns and more seasonal economies tended to have greater post-fire labor market volatility, particularly when it came to seasonal losses in employment. In turn, workers were more reluctant to move to locations perceived as economically volatile, constraining access to labor in these areas (Nielsen-Pincus et al., 2013).

Quantifying these effects is highly challenging for the reasons given above: it is difficult to control for confounding and to isolate the direct effect of a wildfire. Nonetheless, some inferences are possible using the county-level Bureau of Labor Statistics Quarterly Census of Employment and Wages data set, which covers 98% of all U.S. employment.

Lowered Tax Base and Revenues

When a home burns down or is significantly damaged, the owner may request a reassessment of property taxes. The resulting reduction in assessed values can affect county revenues needed for public expenditures, such as roads, schools, law enforcement, and fire protection. Further, reduction in business activity can result in lowered sales tax.

Although this fiscal impact seems self-evident, it is recognized in the literature that the impact is poorly understood, lacking in data, and needing more research. Obviously, when homes are destroyed by fire, the tax base of the property is significantly reduced if and until the homes are rebuilt. But homes that remain mostly undamaged can still be devalued because of their proximity to recent wildfires.

A study by Troy & Romm (2007) found a 5% decrease in the value of California homes selling near the perimeter of a major wildfire that were also in a fire hazard disclosure zone. Another study in Colorado found a 10% reduction in sale prices for homes with a single wildfire footprint nearby, and a 23% reduction for those near two wildfires (Mueller et al., 2009). Thomas and Butry (2014) estimated that between 2001 and 2010, 4.8 million residential structures were in proximity to a fire perimeter. Considering the cost reduction and proximity data together, Thomas et al. (2017), was able to roughly estimate the loss in standing real estate tax base due to prior nearby wildfires at $28.3 billion for 2001- 2010.

Much less is known about the overall municipal fiscal impact of

Another study in Colorado found a 10% reduction in sale prices for homes with a single wildfire footprint nearby, and a 23% reduction for those near two wildfires ... [It's] estimated that between 2001 and 2010, 4.8 million residential structures were in proximity to a fire perimeter.

this tax base erosion stemming from fire. One of the few studies to address this, which looked at California for the years 1990-2015, came up with a surprising result that revealed more about the peculiarities of property taxation in California than about the general impacts of wildfire on property values (Liao & Kousky, 2021).

Using a "difference-in-differences" econometric analysis (comparing exposed and control municipalities) with data from municipal budget records, it found that wildfire damage to property led to increased municipal revenues, with 15% greater general revenue and 20% greater tax revenue five years after a wildfire, compared to control municipalities. The reason for this has to do with California's Proposition 13, which limits appreciation of property tax assessments to 2% per year, keeping tax revenues artificially low. However, when major property damage or destruction occurs that requires construction, homes get reassessed without the appreciation cap. Hence, in the case of California, wildfire damage to property may act as an unanticipated mechanism at undoing Proposition 13 tax base increment limitation. Little is known about the fiscal impacts in other states, where the lowered tax base might negatively affect local finances.

As with business activity, directly isolating the local fiscal impacts of fires is quite difficult, given how many potentially confounding factors exist. Nonetheless, it is possible given the widespread availability of municipal and county financial records, property assessment data, and the existence of statistical tools to control for confounding effects.

Increased Insurance Premiums or Loss of Coverage

Wildfire-prone states have seen massive and systemic changes to the availability and pricing of home insurance due to wildfire. First, insurers in the most fire-prone states are canceling policies and dramatically reducing the geographic areas they cover. This is a serious impediment to the property market, given that lenders require home buyers have insurance to qualify for a mortgage. For instance, the state of California reported that private insurers declined to renew over 235,000 home policies in 2019, up 31% from the previous year and up 61% for high-risk zip codes (Chiglinsky & Chen, 2020).

As insurance access has waned, premiums have increased. For instance, a recent rate filing resulted in property owners seeing up to an 80% increase in premiums for properties considered high wildfire risk in California; in total $1.3 billion in rate increases were approved for California homeowners between 2017 and 2020 (California Department of Insurance, 2020). Anecdotal evidence has noted insurance premiums increasing from $200/month to up to $1,100/month for primary residences in some rural areas of California. (Walters, 2021). One reason for these increases is the rise in rates from re-insurers in recent years following catastrophic wildfire seasons, such as 2017-2018 (S. Jones, 2019). Also anecdotally, it appears other

> *Wildfire-prone states have seen massive and systemic changes to the availability and pricing of home insurance due to wildfire ... insurers in the most fire-prone states are canceling policies and dramatically reducing the geographic areas they cover.*

states are seeing similar effects, although insurance data is less available. For instance, although still too early to fully assess, insurance experts expect Colorado residents will see higher premiums and the withdrawal of coverage in many areas in the wake of the 2021 Marshall Fire (Nelson, 2022).

Regardless of where a home is located, its destruction by wildfire will result in a significant increase in insurance premiums for any rebuilt structure on the same site. The average increase in premiums after a wildfire has been calculated at 27% nationwide, with some western states, such as Oregon and Idaho, having rate increases above 40%. In raw dollar terms, Colorado has the highest post-fire average annual premium cost, at $4,097 (in 2021), followed by Oklahoma at $3,997 (Hurst, 2022).

Those who live in areas where private insurance is no longer available must rely on Fair Access to Insurance Requirements (FAIR) Plans, or state-mandated, high-risk insurance industry pools. These act as insurers of last resort, and their availability and quality varies by state. Many fire-prone states (e.g., Arizona, Colorado, Montana, Idaho) do not have FAIR Plans. However, in places that do, the quality of coverage is highly variable by state; for instance California has a maximum dwelling coverage of $3 million while Indiana has a maximum of $250,000. FAIR Plans are intended to be infrequently used, for the rare cases where the private market cannot accept the risk for a geographic region, but they are increasingly becoming the norm, even though the quality of their coverage relative to cost is frequently substandard (Troy, 2007). California saw an average 36% increase in FAIR Plan policies from 2018 to 2019, according to the Department of Insurance. In the 10 California counties with the most risk-exposed homes, FAIR Plan policies rose by 177% from 2015 to 2018, compared to a 4% increase for the counties with the lowest risk (Jergler, 2019).

FAIR Plan policies are considered expensive because their coverage often will not cover the full value of the home, requiring costly supplemental coverage from other sources, when available. With the recent increase in wildfire damages to structures, they are becoming even more expensive. In Texas, FAIR Plan premiums were raised by 10% in most parts of the state, but the "indicated rate changes" (the actuarial estimate of expected value of future losses) was as high as 50% for the fire-prone parts of Texas. That means the premium increases do not actually cover the risk and that most of those expected losses will be subsidized by taxpayers, not insurance ratepayers.

Studying insurance impacts from wildfires is generally quite straightforward. Although no national resource exists for data on home insurance rates, each state has insurance departments or commissions that track data on coverage and premiums, so changes are relatively easy to track back to recent wildfire activity.

Disrupted Interstate and Intercity Commerce

While the immediate impacts to transportation are discussed in the Direct Costs-Infrastructure section, fires can also yield many longer-term effects to transportation routes and supply chains. Indirectly, smoke can impair visibility in areas not experiencing a wildfire, which can slow or halt transportation of goods and services. Traffic associated with fire evacuations can clog transportation routes, even creating direct exposure to an impending fire. Areas directly impacted by wildfire can act as bottlenecks to interstate and intercity commerce for days or weeks, depending on the severity of the fire. Transportation corridors can further be impacted following a fire to allow for post-fire mitigation efforts (e.g., to remove hazards, re-establish power utilities, clear debris, stabilize slopes).

Wildfires in California have led to impacts and delays in both passenger (Siess, 2021) and freight (Marsh, 2021) rail transportation across critical north-south and west-east rail lines crossing the Sierra Nevada Range, creating a ripple effect to the transport of goods and services to interior portions of the United States. It's estimated that wildfire-related economic damages in California in 2018 totaled $148.5 billion — roughly 1.5% of California's annual gross domestic product — with $27.7 billion (19%) in capital losses, $32.2 billion (22%) in health costs and $88.6 billion (59%) in indirect losses (Wang et al., 2021b). Those same study results revealed most economic impacts related to California wildfires may be indirect, and often affect industry sectors and locations distant from the fires. For example, 52% of the indirect losses — 31% of total losses — in 2018 were outside of California.

Data on these impacts is not widely available, but rather has to be calculated or modeled from transportation data, often coming from state or local departments of transportation.

Low Recruitment and Retention to Fire Agencies

Agencies have struggled over recent years to recruit and retain wildland firefighters in part due to low pay. This is compounded by overwork, exhaustion, stress, and high costs of living around the areas they are hired to protect. The size, intensity and complexity of wildland fires is increasing exponentially, contributing to significant long-term workforce attrition. Throughout the nation, many Hotshot, engine, water

tender and other modules have unfilled vacancies and are reduced to five- vs. seven-day staffing or they are not staffed at all. Also, during high planning and preparedness levels (driven by fuel and weather conditions, fire activity and fire suppression resource availability) there are periods when there are insufficient Incident Management Teams and personnel available to respond to the number of concurrent, complex, Type 1 and 2 incidents occurring throughout the Western U.S.

The compounding effects of firefighter attrition on incidents and Incident Management Teams (IMTs) is multifold. During busy fire years, some incidents were triaged and either left unstaffed or portions of large incidents could not be responded to in a timely manner. Some complex incidents were left to a local, often under-equipped home or host entity to manage, or an IMT of lower qualification was utilized until a higher-level team became available. These are all contributing factors to incidents in which inadequate initial and extended attack wildfire response may have occurred.

The recently signed $1.2 trillion Bipartisan Infrastructure Law[8] includes some reforms to federal level wildland firefighter pay and benefits. In addition to establishing a new position occupational series, the law also instructs Agriculture and Interior agencies to provide an increase in base salary of 50% or $20,000 — whichever is smaller — if agency leaders "make a written determination" that the position is in a region where it is difficult to recruit or retain firefighters. Other provisions include conversion of at least 1,000 seasonal to permanent, year-round federal workers. The law also requires the Interior and Agriculture secretaries to develop recommendations to mitigate firefighters' exposure to environmental hazards and to provide all seasonal and permanent wildland firefighters with mental health benefits, including treatment for post-traumatic stress disorder.

WATER SUPPLY AND STORAGE COSTS

In watersheds that supply municipal water, the loss of vegetation due to wildfire can result in the massive transport of sediments and debris, which ultimately end up in reservoirs and other surface waters. This increases costs related to water treatment needs, sediment and debris removal, erosion control measures, loss of storage capacity (Bart and Tague, 2017) and groundwater quality remediation (Campos & Abrantes, 2021), among other factors.

Massive flooding occurred after the 26,532-acre Pipeline Fire in Arizona in June 2022. That summer, 45 post-wildfire flood events sent ash, downed trees, boulders, mud, silt, and debris into downstream neighborhoods, overwhelming drainages, damaging roads and properties, and endangering thousands of lives. Flood modeling shows flows are 10 to 22 times greater across nine watersheds than before the fire. Photo: Coconino County Arizona Flood Control District

8 Infrastructure Investment and Jobs Act (IIJA) (Public Law 117-58) https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

Water quality can be particularly affected because wildfires result in harmful compounds, like soil black carbon, which acts as an absorptive surface for heavy metals, disinfection byproducts, and other harmful compounds, all of which can be transported to reservoirs (Smith et al., 2011). As wildfires worsen, this could disproportionately affect WUI communities that rely on water from watersheds where these increases are projected. The U.S. Geological Survey (USGS) analyzed a collection of climate, fire, and erosion models for 471 large watersheds throughout the Western U.S. and found that by 2050, the amount of sediment in more than one-third of watersheds could at least double. In nearly nine-tenths of the watersheds, sedimentation is projected to increase by more than 10 percent (USGS, 2018).

A recent study has found that costs associated with water supply damage may equal or exceed the direct costs of some wildfires and that impacts can last for decades, posing a risk to long-term water security and economic activity, in addition to ecological function (Robinne et al., 2021). Destruction or extensive damage to municipal water systems, through direct exposure to wildfire, or as a consequence of breaking water lines to fight the fire itself, has been documented in several recent California fires including the North Complex, CZU Complex, Camp Fire, and Dixie Fire. Repair and/or replacement of these systems can take months and impact the sales of homes that utilize these systems. The direct costs required to repair and replace destroyed water systems and the impacts of damaged or destroyed water systems on real estate values and home sales is not systematically documented.

Denver Water is one of the nation's water utilities that has experienced the greatest impact to supply because of wildfire. Both the 1996 Buffalo Creek and 2002 Hayman fires raged through watersheds that fed their reservoirs. The flash flooding occurring after the former of the two transported nearly 160,000 cubic yards of sediment and debris into Strontia Springs Reservoir. Ultimately, between these fires, the utility spent $27 million to repair supply infrastructure and remove sediment and debris, with $18.5 million going toward the latter. The reservoir was estimated to have lost roughly 13% of its storage capacity due to sediment, enough to supply 4,000 households with water (Hartman, 2020). Not only does this sedimentation remove functional storage capacity, but sediments also cause abrasion that increases wear and tear on pipes, valves, and other hardware (Adams, 2022). Ultimately, Denver Water realized that no amount of sediment removal would fully restore the capacity of the reservoirs, so a lasting impact of these fires was a permanently reduced reservoir storage capacity, which ultimately means more costs for building future reservoirs. To avoid future impacts from fires, Denver Water has spent over $60 million since 2010 in forest health and restoration projects, with some of this coming as contributions from the USDA Forest Service through its Forest to Faucets Partnership; they have also invested in hardware, such as sediment traps, which have a price tag of $850,000 each.

This pattern of wildfire-driven sedimentation has been accelerating throughout the West as the extent and intensity of wildfire increases due to climate change. A USGS study from 2017, found that 87% of Western U.S. watersheds are expected to see more than a 10% increase in fire-driven sedimentation and one-third are expected to see an increase greater than 100% by 2050. The watersheds predicted to have high sedimentation levels include some that supply water to major urban areas (Sankey et al., 2017).

Overall, little impact has been accomplished to systematically quantify the costs of these impacts at a scale beyond the few individual water utilities that have highlighted this issue.

FLOODING, LANDSLIDES, AND EROSION

Slides, erosion, and flooding are combined in a single section because, often, floods are what trigger slides and transport debris, so disentangling these effects is difficult. Across the Western U.S., post-fire flooding and debris flows are becoming more prevalent with increases in wildfire frequency and urbanization (Cannon & DeGraff, 2009). Flood risk increases after wildfire due to the loss of vegetation and the fact that intensely burned soils become hydrophobic. Both factors decrease water infiltration into soils and lead to higher peak flows and greater surface runoff. With higher energy, these peak

flows mobilize sediments and debris, leading to erosion and landslides. The increases in flood flows following a wildfire are stark. Peak storm flows after wildfires have been measured between 1.5 to 870 times greater than pre-fire flows (Neary & Gottfried, 2002). In Arizona, there was a greater than 50% probability of debris flows in watersheds where a recent wildfire occurred (Fraser et al., 2020).

Significant differences in erosion and debris transport capability exist based on prevailing climate, geology, topography, and fire regimes. Ultimately, the probability of such events depends on the occurrence of intense storms during a window of susceptibility to surface erosion and mass wasting following intense wildfire (Wondzell & King, 2003). This pattern is particularly pronounced in the Pacific coastal states, where heavy seasonal rains often arrive shortly after the end of fire season.

Floods and landslides can do significant damage to property, but a disproportionate share of their impact is on roads. Many examples exist of major road closures and expensive cleanups and repairs as a result of post-fire floods and landslides. One of the most notable examples of a major highway closure due to post-fire debris flow is the 2020 Grizzly Peak Fire in Colorado, which closed Interstate 70 for weeks. It is described in detail in the case study section. Another frequently cited example is the flooding and landslides that occurred in Montecito, California, one month after the Thomas Fire in 2018, resulting in the closure of U.S. Highway 101 for nearly two weeks. This is also described in the case study section.

Data on infrastructure and property loss due to landslides and floods is nationally available, but only for claims covered under the National Flood Insurance Program (NFIP). However, these data sets do not clearly indicate which of these events are triggered by wildfires. Further, national data does not exist for most flood and landslide claims that are not covered under the

Hermits Peak and Calf Canyon Burned Area Emergency Response (BAER) firefighters work to remove debris in the upper Gallinas Canyon in New Mexico in 2022. Photo: Daniel R. Patterson/USDA Forest Service, for InciWeb

NFIP. Hence, tracking post-fire flood and landslide losses is not feasible at a national level.

HEALTH, SAFETY, AND WELL-BEING

Long-term Air Quality Effects on Public Health

Wildfire smoke is a prominent source of air pollution, and most of the U.S. population is exposed to it at some point each year. It has been identified as one of the top sources of overall air quality declines (Fann et al., 2013; Kinney, 2008; McMichael et al., 2006). Wind can transport wildfire smoke thousands of miles, generating exogenous air pollution events that are geographically dispersed and widespread (Langmann, B., 2009). Wildfire smoke exposure has been found to be associated with asthma, chronic respiratory pulmonary infections and disease, morbidity and all-cause mortality, although more research is needed to identify the most susceptible subgroups (Reid et al., 2016).

Climate change, drought and fuels build-up are expected to increase the frequency, severity, size — and subsequent smoke — of Western U.S. wildfires. This is predicted to significantly increase "smoke days" (a day of smoky conditions at the county level, summed across counties) starting in the 2040s (Liu et al., 2016). This would result in a statistically significant increase in respiratory hospital admissions in the hardest hit states, particularly central California, Colorado, and Washington.

Quantifying the morbidity, mortality, and healthcare costs directly attributable to wildfire is extremely difficult since there are a wide range of air quality stressors associated with other sources. Nonetheless, attempts have been made to develop modeling approaches to make estimates. One example used a benefits transfer methodology (BenMAP-CE), a form of meta-analysis, to study Arizona's massive Wallow Fire. The study estimated downwind emergency room asthma costs in Albuquerque went up by 2,535% and hospital admissions for all respiratory conditions went up by 44% relative to non-wildfire conditions. They further estimated an individual marginal willingness to pay of $130.79 for a reduction in wildfire smoke effects (B. A. Jones et al., 2016).

Wildfire smoke exposure leads to statistically and economically significant losses in annual labor income; each day of smoke exposure over the year causes a roughly linear reduction in labor income of 0.07% in the year of exposure. The annual average of 17.7 days of wildfire smoke reduces U.S. annual labor income by 1.26%, or $93 billion in 2018 dollars. Summing the smoke effects in the year-of and year-after exposure produces losses of 1.98%, or about $147 billion in 2018 dollars (Borgschulte et al., 2018).

Air pollution, including from wildfire smoke, is monitored by instruments at locations throughout the country, and data can be accessed through portals like PurpleAir. However, little tracking is done related to the health impacts of poor air quality or their costs. A few national data sets exist that include a respiratory component, such as the *National Health and Nutrition Examination Survey*, but its data represent only a limited sample.

Long-term Effects on Mental Health

Wildfires have been documented to impact the mental health of responders, fire victims, evacuees, and the public. For responders, extended deployments on wildfires, time away from family, injuries, fatalities of co-workers, and the loss of their own homes to wildfire are causing many to reconsider the profession of wildland fire (Parker, 2021). Individual wildfire victims and portions of or entire communities can suffer from wildfire related trauma, long-term displacement, loss of loved ones, or destruction of property that can impact individual and community health (O'Neill, 2019). Mental health challenges result from a culmination of stresses including low pay, extremely arduous work environments, separation from family, and the pressure to perform and meet public expectation. Wildland firefighters are at elevated risk for depression, alcohol abuse, sleep deprivation, post-traumatic stress, and suicide. These firefighters typically work over 1,000 hours of overtime to meet their bills during the off-season and sleep in their vehicles because they cannot afford housing in the communities where they work. Fifty-five percent of wildland firefighters reported clinically significant suicidal symptoms compared to 32% of non-wildland firefighters (Stanley, 2021).

A Ruby Mountain Interagency Hotshot crew member sharpens her field tool while working on the Dixie Fire in the Lassen National Forest in California. Photo: Joe Bradshaw/ Bureau of Land Management

Further, individuals helping with post-fire recovery may suffer from long-term mental trauma (O'Neill, 2019) but this is not systematically documented or may not be related to an individual wildfire. The extent and costs of these mental health impacts are poorly tracked and understood.

Long-term Air Quality Effects on Buildings and Building Occupants

Indoor air quality, and the ability of buildings to protect occupants from poor outside air quality are highly important. Many urban residents are estimated to spend up 90% of their time indoors (Lai et al., 2004). Studies of indoor fine particulate matter (e.g., PM 2.5) from wildfire indicate that, while building interiors can have better air quality than outside during smoke events, the ability of these pollutants to enter buildings and impact occupants is highly variable. The presence of central air conditioning or filtration systems is an important predictor of better indoor air quality (Liang et al., 2021).

In areas with high exposure to wildfire smoke, building owners will increasingly need to install expensive central air systems and undertake better building sealing. A study of the 6.9 million homes exposed to the 2003 California wildfires found that the electricity cost of operating the needed forced-air fan systems continuously during the wildfire period, plus the cost of needed filters would have been $133 million (Fisk & Chan, 2017). The same study found such interventions would have prevented up to 261 respiratory hospital admissions and up to 52 premature deaths.

Wildfire smoke particles also damage both the interior and exterior surfaces of structures and create lingering unpleasant odors. Typical remediation costs after a wildfire are from $3,000 to $26,000. Many factors influence this cost, including the size of the property and the extent and duration of the fire and smoke impacts (American Family Insurance Co., n.d.). Wildfire smoke can carry compounds that are particularly corrosive to electronics, appliances, and electrical systems in addition to discoloring and leaving odors in flooring, glass, and fabrics (Brotherhood Mutual, 2021).

ECOLOGY AND LANDSCAPE

Atmospheric Carbon Emissions, Loss of Carbon Stocks and Sequestration Potential

Wildfires directly release carbon dioxide in quantities that can impact efforts to use forests to offset carbon emissions. In 2021, wildfires in the Western U.S. released 130 million tons of CO2, based on data published by the Copernicus Atmospheric Monitoring Service (Fountain, 2021). In 2020 and 2021, wildfires released 6.8 million metric tons of stored carbon dioxide from forests that were enrolled in the California Cap and Trade Program; this represents nearly

20% of the carbon that was set aside to buffer the program for wildfire and insect losses over a 100-year period (Carlton, 2021). With carbon prices in California's Cap and Trade Program between $150 and $200 per metric ton in 2022, these losses from fires represent a significant economic liability.

In 2020, wildfires in California alone were responsible for 106.7 million metric tons of CO2 emitted (California Air Resources Board, 2021). The forgone sequestration capacity of acreage burned at stand-replacing severity is not considered in this estimate. The emissions associated with wildfires become a driving force in net carbon sequestration capacity in western forests with some states — namely Colorado, Montana, Idaho, New Mexico, and Utah — starting to turn into net carbon emitters from a forest perspective (Domke et al., 2020).

Besides causing high levels of tree mortality and soil impacts, high-severity fires in forests can also result in the delayed regeneration of forest cover and, in its place, leave a dominant vegetation of grassland or shrub types over extended periods of time, which can reduce sequestration potential (Collins & Roller, 2013; Coppoletta et al., 2016; Roccaforte et al., 2012; Rother & Veblen, 2016; Stevens-Rumann et al., 2018; Tubbesing et al., 2019). Prescribed burning and mechanical fuel thinning can result in reduced greenhouse gas (GHG) emissions over time (Buchholz et al., 2021; Hurteau et al., 2011). Emission savings resulting from fuel treatments are difficult to generalize since calculations depend on multiple input variables including fuel treatment type, biome, wildfire probability, delayed regeneration, etc. The GHG emissions from wildfires can be modeled, but accuracy depends on data inputs, such as vegetative biomass. Several organizations conduct their own modeling and provide packaged data, such as Copernicus Atmosphere Monitoring Services.

High-severity wildfires that burn with intense heat affect soil runoff, forest regeneration and pave the way for invasive plants to take root. Photo: Jason Moghaddas/ Spatial Informatics Group

Post-fire Invasive Species

Invasive species are plants, animals, and other organisms that are both nonnative to an ecosystem and that cause, or are capable of causing, environmental, economic, or human harm (M. Brooks & Lusk, 2008; National Invasive Species Council (NISC), 2016; National Wildfire Coordinating Group (NWCG), 2017).

Not all species cause significant harm. A species becomes invasive when it competes aggressively for resources and/or when it lacks natural control factors in a new ecosystem. When invasives become established in a landscape, they can affect how ecosystems function and can have negative impacts in a variety of ways. If left unchecked, many invasive species will outcompete native species, and can eventually replace them entirely. Invasive species often displace native species and disrupt important ecosystem processes. In total (from all sources of introduction), invasive species in the U.S. have caused major environmental damages and estimated losses adding up to almost $120 billion per year (Pimental et al., 2005).

Post-fire invasive plants often grow quickly because of high light conditions on an exposed forest floor. They reach reproductive maturity and produce large volumes of seeds within 1-3 years after establishing (Brooks and Lusk 2008). However, the abundance of these invaders can decrease following regeneration of the forest canopy, if subsequent wildfire does not disrupt the regeneration process. Invasive plants can alter fire regimes by increasing or decreasing the frequency and severity of wildfires in ecosystems where they alter the fuel characteristics (the volume, moisture content, and continuity) associated with native vegetation (M. L. Brooks, 2004; Mandle et al., 2011). For example, nonnative cheatgrasses that invade arid sagebrush plant communities can increase fuel continuity, which can lead to more frequent and larger fires. When invasive plants reach high densities and occupy large contiguous areas across a landscape, their impacts on fire increase. Often when post-fire invasive plants reach a certain prevalence, additional costs must be incurred to control their spread through practices like weeding, grazing, and herbicide application. While the cost varies with the species, one case study found control costs of $300/acre (Jardine & Sanchirico, 2018).

A Hairy Woodpecker investigates the burn area after the Peekaboo Fire in Colorado in 2017. Photo: Rachel Portwood/U.S. Fish and Wildlife Service

Effects on Biodiversity and Habitat

Biological diversity accounts for the variety of life across all ecological levels, from genes to species to ecosystems. Wildfire has shaped the habitat structure and biological diversity of landscapes for hundreds of thousands of years.

Fire regimes (the type, frequency, intensity, seasonality, and spatial dimensions of recurrent fire) within a normal range of variability enables most vegetation communities in the Western U.S. to persist, creates habitats for a range of animals, and maintains the heterogeneity of ecosystems (Kelly, 2020; Nasi et al., 2002). However, substantial changes or shifts in fire regimes can transition vegetation communities and/or otherwise impact plant and animal populations (Kelly et al., 2020). For example, for animals, more frequent and/or intense fire regimes (partially due to climate change) can reduce the availability of key resources, such as food and shelter, limiting a population's capacity to recolonize a particular habitat for an extended period. In forests, a more frequent and intense fire regime can result in a "fire trap," where the succession of a plant community is arrested perpetually at a primary successional stag, for example as a shrub community, instead of maturing to a climax forest community. Although it is possible to characterize biological diversity or habitat value associated with fire-related impacts, these types of analysis are rarely undertaken following a wildfire event due to the complexity of estimating non-use values and a lack of monetary valuations of ecosystems (Lazdinis, 2001).

While there are a number of databases that map biodiversity across certain taxa, there has been no systematic attempt to measure changes in biodiversity or habitat immediately following wildfire beyond studies at individual sites. For example, Burned Area Emergency Response (BAER) reports frequently highlight the loss of designated ecologically significant areas and/or protected activity areas associated with a limited suite of special status species.

2 INDIRECT COSTS LOSSES

Ecological Restoration and Cleanup

Post-wildfire cleanup can include mitigating and removing hazard trees, clearing large areas of burned vegetation, removing burned structures, damaged or destroyed infrastructure, stabilizing the soil, and restoring impacted watershed values. The cost of restoration varies significantly by ecosystem, the level of damage to it, and location. Once initial damaged vegetation is removed, additional costs can be incurred with reforestation or revegetation of burned areas. Often, the initial BAER, Watershed Emergency Response Team (WERT), or Damage and Inspection (DINS) Teams provide the first detailed assessments of fire-related damage and response. But mitigation of these damages can take years or decades, being paid for across multiple entities (i.e., FEMA, the Office of Emergency Services, counties, or utilities) and public, private, or insurance-based funding sources, and are not often systematically tracked to a single wildfire and/or project tracking code.

Post-fire Monitoring and Assessment

Initial post-fire monitoring for structures is typically completed by Damage and Inspection (DINS) Teams. Requirements for documentation of structure loss may vary from state to state, but typically include an assessment of damaged or destroyed properties and, where available, UAV or ground imagery of the damaged structure or neighborhood. Additional site-level damage inspections are conducted for impacted utilities and other critical infrastructure.

Wildfire impacts to vegetation are typically assessed using the Rapid Assessment of Vegetation Condition after Wildfire (RAVG) program (USGS, n.d.). Post-wildfire monitoring can occur for weeks, years, or even decades after a wildfire is contained. Key items monitored typically include vegetation recovery and water quality. Advances in satellite imagery and analysis have made vegetation monitoring more efficient while automated water sampling and monitoring has helped managers better understand the long-term effects of wildfire on water quality. Using an example, such as Google Earth Engine, the trend in technology is greater data availability, more frequent measures, and higher resolution of post-fire conditions.

The cost of monitoring, inspections and assessments is highly variable and is generally not studied or published.

Erosion barriers are installed after the 2012 Charlotte Fire in Idaho to help deter runoff and stabilize the soil. Photo: Bureau of Land Management

The Trout Springs prescribed fire in southwest Idaho improved rangeland wildlife habitat by removing encroaching Western juniper stands. The Bureau of Land Management project took place in the Juniper Mountain area, with help from a hand crew from the Idaho Conservation Corps. Photo: Neal Herbert, Department of the Interior

Indirect Costs — Mitigation Investments

FIRE-SAFE LAND-USE PLANNING AND REGULATION

Local and regional planners are increasingly cognizant of the role of land-use planning in mitigating exposure to risk of wildfires. A new generation of research has found that development policies, particularly as they affect the density and layout of housing, have a significant impact on the probability of loss and damage (Syphard et al., 2013). The American Planning Association got involved in the issue of fire-safe planning with the recent release of *Planning the Wildland-Urban Interface*, its guide to land-use planning in the WUI. It covers a wide range of best practices related to zoning, subdivision codes, building codes, landscape codes, infrastructure standards, and design guidelines, among other considerations (Mowery et al., 2019). Research has found local officials often become interested in this type of fire-safe planning after major wildfires (Mockrin et al., 2020). Revamping local codes and ordinances is expensive and requires extensive staff time and public input, but estimates of the costs are elusive.

EVACUATION PLANNING

Jurisdictions and landowners within fire-prone areas of the West are spending more resources to better plan for wildfire-related evacuations. These efforts include using county-wide Community Wildfire Protection Plans (CWPPs) and online evacuation maps, improving evacuation route vegetation clearance, and identifying road network constraints that can hinder future evacuations. Fire management and public access to real time evacuation zones has been enhanced via development of web- and app-based evacuation platforms such as Zonehaven (Zonehaven, n.d.) and Intterra (Intterra - Cloud-Based Data Visualization for Fire Agencies, n.d.).

FUEL TREATMENTS

Fuel treatments include a range of interventions that reduce surface, ladder, and canopy fuels using mechanical equipment, hand crews, and prescribed fire (McIver et al., 2013). These treatments generally include "thinning from below" in forested areas (Johnson et al., 2007), mastication of brush and small trees (Knapp et al., 2011), underburning of surface and small ladder fuels in forests and woodlands, and intentional burning of grassland and shrubland ecosystems. Whether ignited by lightning or by Indigenous communities using burning to manage the land, fire once shaped many North American ecosystems. Euro-American settlement and 20th-century fire suppression practices have altered historic fire regimes, and the increased fire suppression and excessive fuel accumulation have led to more uncharacteristically severe wildfires.

Prescribed fire is a valuable tool for reducing these fuel loads and restoring ecosystems, but the practice comes with controversy and uncertainty. It is used in many locations, yet broader use is needed to keep up with the accumulation of fuel loads. Expanding the footprint of prescribed burning in the Western U.S. will require increased integration of science, policy, and management, together with greater societal acceptance, understanding of the practice, and engagement in land-management issues (Ryan et al., 2013). Prescribed fire will further require a balancing of the suppression/prescribed fire equation through increased tolerance and incentives to shoulder more prescribed fire risk.

Fuel treatments can be costly, with funding provided primarily by state and federal entities, utilities companies, or in some cases the sale of merchantable sawlog or biomass material. Treatment costs vary widely by region with some treatments generating net positive revenue via the sale of wood products (Hartsough et al., 2008). Other mechanical or hand-thinning type treatments cost up to $5,000/acre or more, for example within urban areas of California. Fuel treatment costs can include planning, implementation, and long-term maintenance of fuel breaks and can vary by location. These varying treatment costs have not been well documented. Additionally, the potential "avoided costs" of wildfire impacts — where treatments are used to reduce wildfire size, severity, or community impacts — are not consistently evaluated or documented.

The USDA Forest Service has increasingly extensive collections of data on fuel treatments on federal, and sometimes nonfederal land (Forest Service FSGeodata Clearinghouse - Download National Datasets, n.d.).

DEFENSIBLE SPACE AND HOME HARDENING

As the threat from wildfire increases in many neighborhoods and regions, home mitigation measures, including defensible space and home hardening, are increasingly going from being recommended to required, either by government codes or to qualify for insurance. Eventually, it is likely that most, if not all, homes in the WUI will have to follow at least some version of these best management practices. These measures represent another cost, albeit preemptive, to living within a WUI.

The creation and maintenance of defensible space can be labor intensive, costly, and generally requires an initial investment followed by regular maintenance over time for long-term effectiveness. Initial projects include thinning and pruning trees, disposing of slash, posting signs for emergency responders, and ensuring proper driveway width. Continuing maintenance activities include mowing, deck and gutter cleaning, raking, and trash removal. Costs can vary significantly depending on the defensible space requirements, lot size, and vegetation type and density, among other factors. Studies of these costs are scarce. One of the few such studies from Colorado found defensible space costs to be around $1,000/acre, although for properties smaller than an acre the cost is still about $1,000, implying the presence of considerable fixed costs. Cost also was found to be the biggest barrier to implementing defensible space for survey respondents; only a fifth of respondents were willing to pay that amount (Vaske, 2016).

Home hardening has the potential to increase individual structures' resistance to fire and is required in several states, such as California, which passed several stringent updates to its statewide building code (Chapter 7a) for structures in the WUI. Measures that have been found to reduce the probability of structure loss include using fire-resistant roofs and siding, double-paned windows, vent screens, enclosed eaves, and

other hardening factors that reduce opportunities for ember penetration (Syphard & Keeley, 2019; Troy et al., 2022).

Such upgrades can be costly for both new construction and retrofits, making them disproportionately more difficult to implement in lower income communities. A recent study by Headwaters Economics (Quarles & Pohl, 2018) found that costs vary significantly depending on the structural component in question and whether construction is new or a retrofit. For retrofits, costs can be quite significant. One study found retrofitting an existing roof to wildfire-resistant standards was $22,000 for an average home, while wildfire-resistant modifications to associated fascia, soffits and gutters added $5,860, or 27% of the roof cost. However, for new builds, the cost of construction for an average wildfire-resistant home was only about $2,100 more than for an average non-fire-resistant home. Interestingly, some components of a wildfire-resistant home are cheaper than for certain types of nonresistant homes. For instance, in comparing siding costs, the Headwaters Economics study compared a "typical" cedar shake home to a fire-resistant home and found that siding for the latter was actually $12,190 less expensive because, ironically, the flammable wood siding cost more per unit (Quarles & Pohl, 2018).

The cost of defensible space and home hardening is typically assumed by the homeowner, though cost-share programs exist and funding is available for treatment of defensible space around homes of the disadvantaged, elderly and disabled in some states and counties. In some areas, states provide funding for community fuel breaks via local Resource Conservation Districts and Fire Safe Councils. While data exists on average costs for homeowner actions, data on aggregate expenditures for these is lacking.

INFRASTRUCTURE AND UTILITY HARDENING

Utility companies have been working to upgrade fire weather forecasting capacity to better implement preemptive energy system depowering. In addition, many utilities are upgrading their power distribution grid by increasing vegetation management, burying utility lines underground, installing cameras to monitor local fire activity, and upgrading line and distribution infrastructure (e.g., increasing circuitry along distribution systems, upgrading power poles, and installing covered conductors), all of which can be expensive investments. Few data

Good defensible space surrounds homes in the Pine Lake community south of Kingman, Arizona, in 2022. Photo: Suzanne Allman/for the Bureau of Land Management

are readily available on the extent to which these are implemented or how much has been spent on them.

PREEMPTIVE ENERGY SYSTEM DEPOWERING

Power grid faults frequently cause catastrophic wildfires, particularly in regions with high winds, persistent high temperatures and low humidity (Rhodes et al., 2020). With the continuing threat of wildfire, utilities often preemptively cut power to electrical lines that are at risk of failing (i.e., causing ignitions) in certain weather conditions. Depowering, also known as Public Safety Power Shut-off (PSPS California Public Utilities Commission, 2021), can cut the risk of a wildfire ignition from the power infrastructure. However, when power is shut off, especially for extended periods, government entities, businesses, schools, and residents are left without power. Power shut-offs can result in lost wages and productivity, income, teaching time, potential health impacts for hospital patients dependent on power, and much more. Further, the act of depowering is costly to the utility — these costs may ultimately be passed onto the ratepayer. Depowering is included as an investment because it requires extensive pre-planning and preparation in order to staff and implement.

Several of the most destructive and deadly wildfires in recent years were ignited from an electric power infrastructure. In Victoria, Australia, the 2009 Black Saturday wildfires killed 179 people. In Texas, two 2011 wildfires in Bastrop County were started by trees coming in contact with nearby power lines. They became Texas' most

The Ruby Mountain Hotshots participated in their annual Critical 80 training. Physical fitness is an extremely important part of the crew's training regiment. Photo: Jennifer Myslivy/ Bureau of Land Management

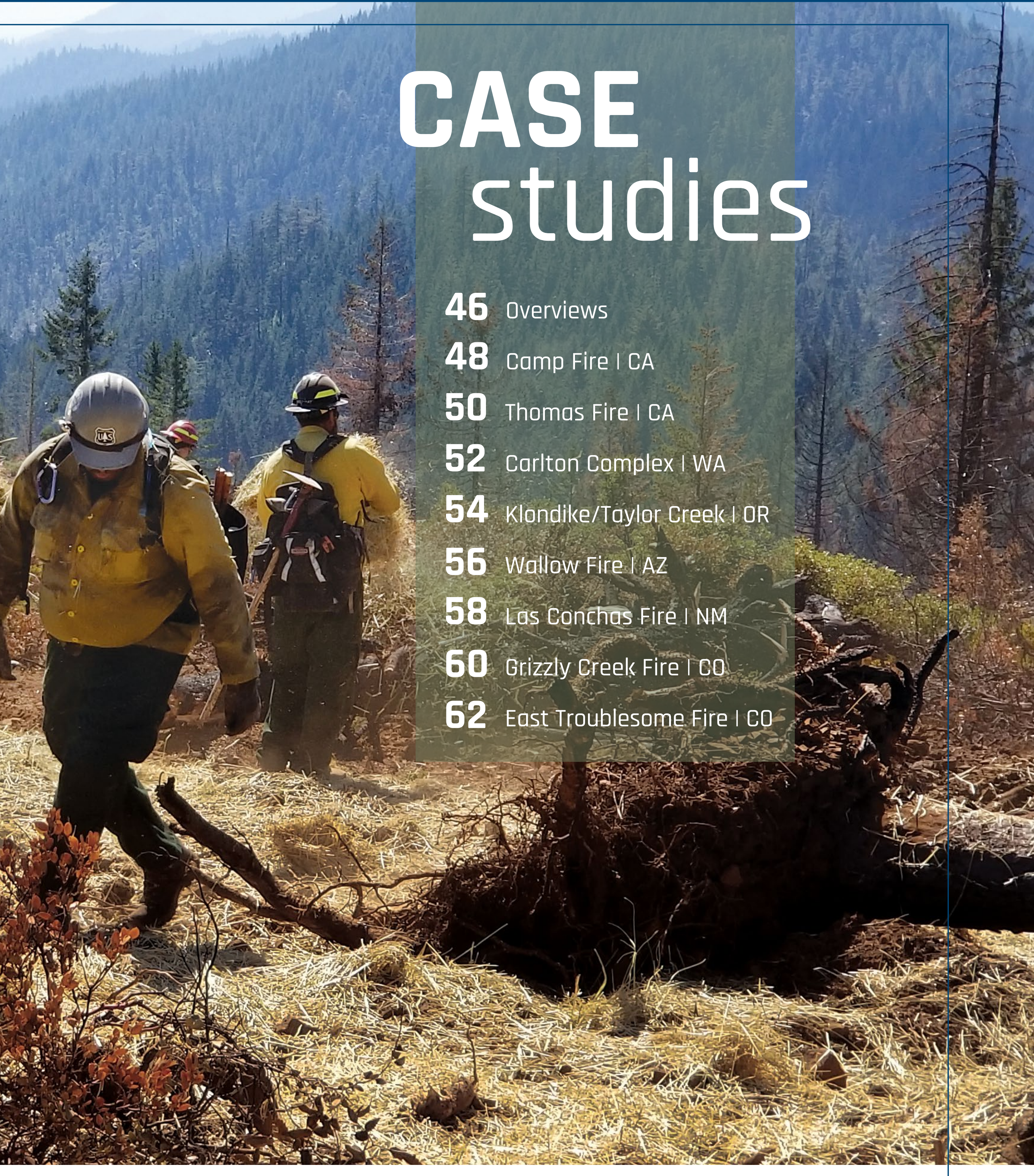
destructive wildfires in history, killing four and causing more than $300 million in damage. In California, the 2018 Camp Fire, which was ignited by a power line, killed 85 people. This and other fires ignited during the 2017 and 2018 California wildfire seasons led the utility responsible, Pacific Gas & Electricity (PG&E), to file for bankruptcy and accept charges for involuntary manslaughter.

Data on depowerings are typically available from regional utilities or utility regulators, although the costs of them are typically not openly reported.

TRAINING AND PREPAREDNESS FOR EMERGENCY RESPONSE

Federal and state wildland fire agencies adhere to National Wildfire Coordinating Group (NWCG) standards for wildland fire position qualifications (PMS 310-1), which establishes minimum position qualification standards for training, experience, physical fitness and currency for national mobilization to wildland fire incidents. Federal response agency minimum standards include U.S. citizenship, age of 18, high school diploma/GED, relatively clean criminal record, driver’s license, drug test and background check. In addition, an initial 40-hour basic wildland fire training and subsequent annual eight hours of currency training and an arduous fitness test requirement must be met. Required all-hazard training is generally limited to basic first aid/CPR, basic hazardous materials mitigation, and basic self-contained breathing apparatus training (Region 5/ California only) for vehicle fire response. The costs of these trainings are not readily available.

When Oregon's Klondike Fire burned through the Rogue River-Siskiyou National Forest in 2018, firefighters cut control lines to fight the blaze. After, USDA Forest Service crews scattered straw and seed to rehabilitate the old lines and lower the risk of flooding, washouts, and potential road degradation. The forest has the second-highest botanical diversity in the nation, so crews focus on keeping weeds out of the forest.
Photo: Melissa Yunas/
USDA Forest Service
Pacific Northwest Region



CASE studies

Eight Wildfires: How Their Impacts, Economics Influence the West

This section includes eight case studies of major western wildfires that have occurred since the last *True Cost of Wildfire* report. They cover a wide geographic range and are illustrative of some of the major types of costs incurred and their variability, referencing cost categories from the typology above.

Each case includes a description of how costs were quantified, when possible, and what data sources were used. Several federal cost data sources are widely available and were used across most of these case studies, including the National Wildland Fire Coordinating Group (NWCG) Incident Status Summary (ICS-209) reports from the Incident Command System, and the Burned Area Emergency Response (BAER) reports. Other federal incident costs were obtained from the Wildland Fire Decision Support System (WFDSS).

Many of the cost estimates, particularly for indirect costs, came from newspaper articles, academic studies, and consulting reports. A summary of key information and costs for each case study is given in Table 4, followed by detailed descriptions of each.

TABLE 4 Summary information for case study fires

Wildfire and State	Year	Acres	Suppression Cost	Other Quantified Costs and Losses	Unquantified Costs and Losses
Camp Fire California	2018	153,336	$120 million *(ICS-209)*	• **$10+ billion** insured losses (18,804 structures destroyed) • **~$12.5 billion** uninsured losses • **$5.6 billion** economic losses to Butte County infrastructure • **$2 billion** debris removal • **$700 million** to restore power	• Loss of town social fabric and economic base • Loss of water system and decline in water quality • Extensive displacement of population from Paradise to neighboring jurisdictions • Loss of tax base
Thomas Fire California	2017-2018	281,893	$230 million *(ICS-209)*	• **$2.3 billion** insured losses (1,063 structures) Post-fire flooding impacts: • **$388 million** insured residential property losses • **$110 million** basin/channel debris removal • **$55 million** bridge repairs	• Loss of power to a quarter of a million Southern California Edison customers • Impacts to wages, employment, and services from U.S. Highway 101 closure • 128 miles of perennial streams, 1,211 miles of intermittent streams heavily impacted
Carlton Complex Fire Washington	2014	256,108	$68 million *(WFDSS)*	• **$98 million** in insured losses (over 353 homes) • **$10 million** utility repair costs • **$1.6 million** damage to orchards • **up to $50 million** in long-term cost for livestock industry • **$70 million** estimated "annual secondary economic losses"	• Damage to 366 miles of power lines • Agricultural damage to fruit trees, irrigation systems, fences and grazing land • Two major highways closed from fire, blockages from slides • Fish habitat impacted

Wildfire and State	Year	Acres	Suppression Cost	Other Quantified Costs and Losses	Unquantified Costs and Losses
Klondike/ Taylor Creek Fires Oregon	2018	Klondike: 175,258 Taylor Creek: 52,839	Klondike: $104 million *(ICS-209)* Taylor Creek: $41 million *(WFDSS)*	• **$2 million** in lost revenue from the Shakespeare Festival	• Evacuations of multiple communities • Intense smoke and associated health risks • Road and trail damage
Wallow Fire Arizona	2011	538,049	$175 million *(WFDSS)*	• **$37 million**: cleanup, assessment, and rebuilding (non-structure loss)	• 70 structures lost (cost unknown) • 324 miles of trails and kiosks/ signage damaged or destroyed • Property tax base impacts • 200 miles of roadways closed, major highway segments closed for two months
Las Conchas Fire New Mexico	2011	156,593	$48 million *(NIFC)*	• **$58 million** estimated cost from six-day work shutdown at Los Alamos National Laboratory	• 112 structures destroyed (cost unknown) • Post-fire flooding threatened tribal community water supply, bridges, dams, and reservoirs • Post-fire sedimentation impacted Rio Grande and Cochiti Reservoir, and shut down Albuquerque water intakes for 66 days
Grizzly Creek Fire Colorado	2020	32,631	$41 million *(ICS-209)*	• **$116 million** estimated cost of highway repairs/debris removal • **$45 million** estimated in water-shed restoration • **at least $8 million** required for sediment removal for Glenwood Springs water supply	• Several multi-week closures of critical segment of Interstate 70 • Detours added up to four hours travel time • Major supply chain impacts • Glenwood Springs water supply interrupted for 40 days • Popular Hanging Lake recreation site closed for 8 months
East Troublesome Fire Colorado	2020	193,812	$20 million *(ICS-209)*	• **$543 million** insured losses (366 homes and 214 outbuildings and commercial structures destroyed; 1,602 structure and auto claims) • **$27 million** estimated to remove debris • **$136 million** estimated cost to restore watersheds damaged in the East Troublesome and nearby Cameron Peak fires	• Impacts on regional tourism and recreation industry • Highway closures lasting longer than two weeks • Drinking water supply for one million people threatened

Camp Fire | CA | 2018

ACRES
153,000+

FATALITIES
85

STRUCTURE LOSS
18,804

IMPACTS
community
housing
mental health
economy
infrastructure
water supply

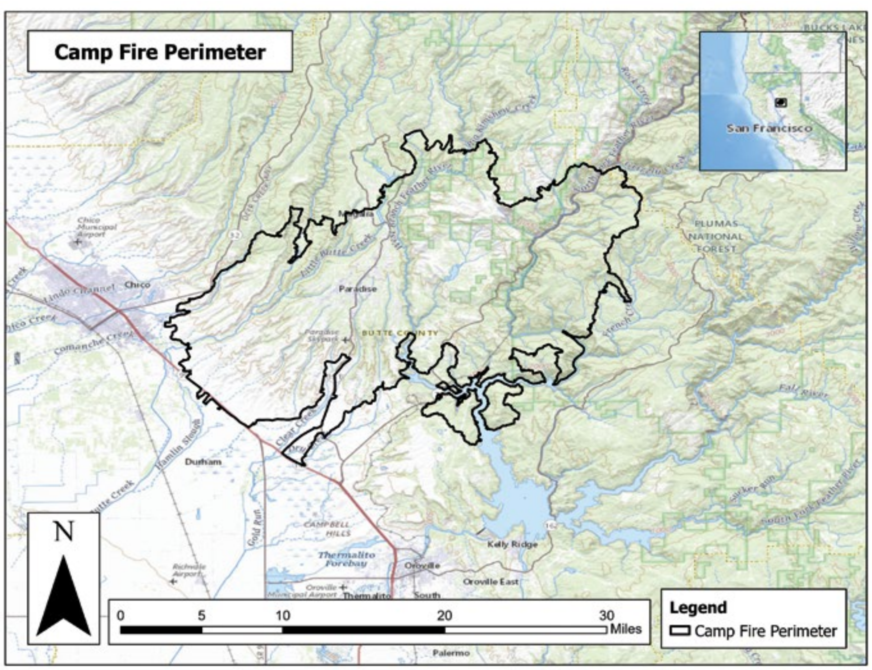
The Camp Fire provides an example of extensive structure loss, community recovery, and long-term socioeconomic consequences of a wildfire. It remains the most destructive wildfire in California history, burning over 153,000 acres (74% of which was on private land), destroying an estimated 18,804 structures, damaging 727 more, and resulting in 85 fatalities (U.S. Fire Administration, 2022). The majority of that destruction occurred less than 48 hours after the fire ignition was reported, illustrating the intensity of the fire (Epley, 2019).

The suppression costs of the Camp Fire were documented at $120 million (ICS-209), which pales in comparison to the overall damage caused by the fire. Available estimates put capital losses at $14.6 billion (Wang et al., 2021a) with the insured losses at $10 billion.[9] Estimates of uninsured losses, which are difficult to verify, range as high as $12.5 billion (Shrimali, 2019). The immediate cleanup costs for the Camp Fire included nearly $700 million to restore the power infrastructure, $1.4 billion-$2 billion to clean up burned structures and remove an estimated 600,000 hazard trees (Feo et al., 2020), and an estimated $2 billion for debris removal (Arthur, 2019).

Beyond the immediate damage to structures and natural resources, the Camp Fire almost completely destroyed a large town. This included the loss of schools and a hospital, and the town's water system. Ultimately, nearly 52,000 people were displaced during the fire, with most of them losing their homes and many unable to rebuild due to lack of insurance or being underinsured. In addition, many displaced persons are now part of the homeless population within Butte County (Levine, 2018). Years after the fire, many continue efforts to settle insurance and legal claims and also deal with symptoms of PTSD and depression (LaFee, 2021).

Indirect costs were massive with estimates that range enormously. One estimate put indirect costs for Butte County alone at $5.6 billion, or over 47% of the county gross domestic product (GDP) (Wang et al., 2021). Another estimate gives a 61%-85% reduction in gross regional product (GRP) within the fire area. This loss is in contrast to a GRP decline of 4.3% recorded for the same area during the Great Recession, from December 2007 to June 2009 (Economic and Planning Systems Inc & Industrial Economics Inc, 2021). The loss of housing stock in an already limited housing market exacerbated the availability of affordable housing, pushing vacancy rates down to 0.5% after the wildfire and increasing rents by 10%-20% (Peloton Research and Economics, 2020).

Another major cost relates to water quality. According to water officials, the extreme heat of the Camp Fire created a "toxic cocktail" of chemicals, including the hazardous compound benzene from burning homes, that permeated the network of water pipes when the system was depressurized for firefighting, making water unsafe to use for most domestic purposes in many areas (Bizjak, 2019). Ultimately, over 3,100 service line locations were tested and over 2,800 water meters were replaced as a result. Although the cost of water line replacement was initially estimated at $44 million, it was eventually reduced to about $8 million using a system of strategic sampling (Proctor et al., 2020). Perceptions of hazard presented by the water system were considerable among the remaining population, with 54% of respondents to a survey reporting that members of their household had anxiety or stress about water contamination, presenting a significant mental health challenge (Odimayomi et al., 2021).



9 Insured losses come from Insurance Information Institute: https://www.iii.org/fact-statistic/facts-statistics-wildfires

A visit to Paradise in 2022, reveals that damaged structures have been removed, but rebuilt homes are a fraction of the number that existed previously. The Camp Fire has raised questions about not only the preparedness of communities for such a wildfire, but how communities with such an extreme level of destruction recover from wildfire, especially as core commercial areas, residential real estate, critical infrastructure, and the tax revenue provided by these community cornerstones are impacted due to their destruction.

While the Camp Fire provides just one example, similar damage was seen to the communities of Louisville, Colorado, (2021 Marshall Fire), and the California towns of Berry Creek (2020 North Complex Fire), Greenville (2021 Dixie Fire), and to some extent, small communities damaged during the 2020 CZU Complex. The extent of damage and social, economic, and logistical hurdles of recovery may be something of a "new normal" in our current age of megafires.

More than 18,000 structures were destroyed in the Camp Fire, which displaced an entire community. Soldiers from the California Army National Guard conducted debris clearing operations, top, days after the Camp Fire overran the town. Photo: Crystal Housman/U.S. Air National Guard, © CC2.0 **Lower:** A CAL FIRE engine responds to the Camp Fire in November 2018 as flames crest the ridge. The majority of destruction from the deadliest wildfire in California history happened within 48 hours of when its ignition was reported. Photo: CAL FIRE

Thomas Fire | CA | 2017-2018

ACRES

280,000+

FATALITIES

2 in fire

21 in post-fire flooding

STRUCTURE LOSS

1,063 in fire

129 flooding

IMPACTS

power grid

housing

schools

transportation

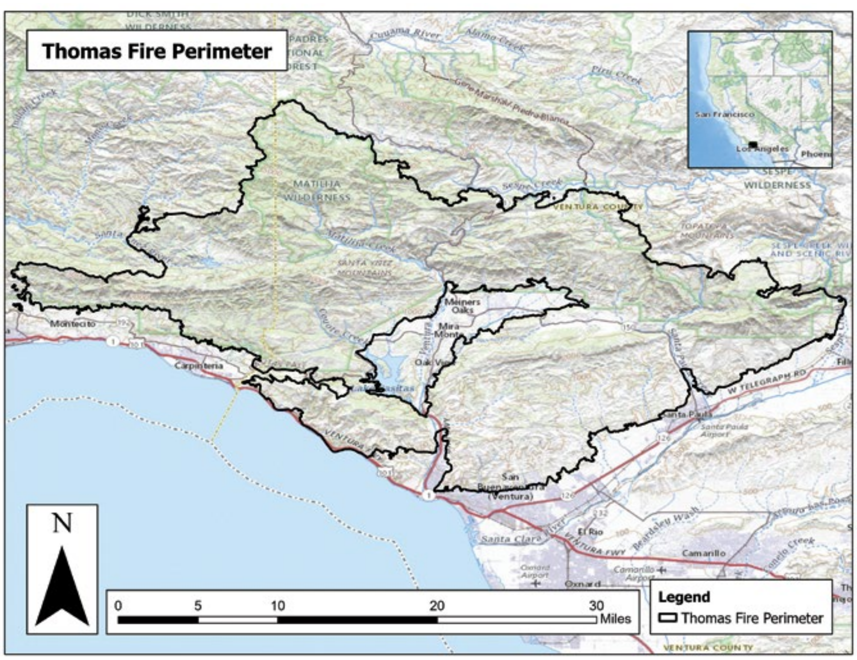
watersheds

The Thomas Fire devastated large swathes of coastal California's Ventura and Santa Barbara counties from December 2017 to March 2018, burning over 280,000 acres. Due to high winds, dense chaparral fuels, and complex topography, the suppression costs exceeded $230 million.

One firefighter and one civilian died during the fire and 1,063 structures were destroyed, with $2.3 billion in insured losses, and nearly 105,000 people evacuated. In addition to single family homes, those losses also included an apartment complex and guest-worker housing, while a psychiatric facility was heavily damaged.

Many services were disrupted by the wildfire, including loss of power to a quarter of a million Southern California Edison customers, dozens of school closures, delays and cancellations at the University of California, Santa Barbara, suspension of Amtrak rail services, the partial shutdown of three highways, and water boil requirements in response to water quality concerns in parts of Ventura. The costs of these disruptions have never been fully calculated.

The Thomas Fire presents a prime example of post-fire flooding and erosion. One of the biggest aftereffects of the Thomas Fire came when heavy seasonal rains finally arrived in January 2018, a month into the fire. They caused extreme flash flooding and debris flows over the denuded landscape, leading to another 129 homes destroyed, 307 more damaged, and 21 deaths, far more than died in the initial fire. The center of these impacts was in Montecito, an area of very high value homes.



This pattern of extreme precipitation following wildfires is expected to get far worse throughout the American West as climate change increases both fire intervals and the intensity of rainfall (Cannon & DeGraff, 2009). Post-fire flooding is so severe because the loss of vegetation and the conversion of soil organic matter to ash creates a highly hydrophobic surface. This greatly increases the volume of runoff, leading to higher flood stages that mobilize debris and mud flows (Shakesby & Doerr, 2006), as described in the subsection on flooding and slides.

The damage from these fire-induced floods and debris flows was calculated to include $388 million in insured residential property losses ($422 million in claims), $110 million in basin and channel debris removal, $55 million in bridge repairs, $55 million in county response and response costs, $11 million in highway debris removal, and $25 million in lost wages due to the closure of the critical U.S. Highway 101 (Lukashov et al., 2018).

A number of BAER reports were written following the Thomas Fire on different categories of "values at risk" including roads and infrastructure, recreation, hydrology, soils, and other natural resources. Each gives a detailed assessment of assets affected and possible future effects, broken down geographically.

As an example, the Hydrology BAER (Fudge, 2018) lists out a detailed inventory of affected hydrologic resources, including 28 HUC 6 watersheds (with a level of severity for each), 128 miles of perennial streams, 1,211 miles of intermittent streams, and 903 miles of ephemeral streams, in addition to five reservoirs.

The report goes on to detail findings on water quality, including increased water body sedimentation and temperatures, and decreases in dissolved oxygen, an indicator of pollution. The report also details how these direct impacts are likely to impact use values. For instance, trails and campgrounds downstream from burn areas — especially near channels — are likely to experience hydrologic impacts, mass wasting or obstacle deposition that could pose safety risks. USDA Forest

Service roads are at severe risk of washouts, mass wasting, plugging, culvert failure, and ultimately closure, especially around low-water crossings. In addition, reservoirs are expected to see an unnaturally high deposition of cobbles, debris and sediment, resulting in reduced storage capacity and ability to attenuate flood flows. And infrastructure, including power poles, buried lines, and highways, are expected to be at much greater risk from mudflows, erosion and peak flows.

Finally, the report goes on to outline in detail the risk to downstream residences and commercial buildings, particularly in alluvial areas, from increased mud and floodwater flows.

Firefighting resources stage along a roadway, top, in front of the Thomas Fire as they coordinate response. **Lower:** Firefighters help with structure defense for a home along a ridgetop during the Thomas Fire in November 2018. Photos: CAL FIRE

Carlton Complex Fire | WA | 2014

ACRES
256,108

FATALITIES
0

STRUCTURE LOSS
353+

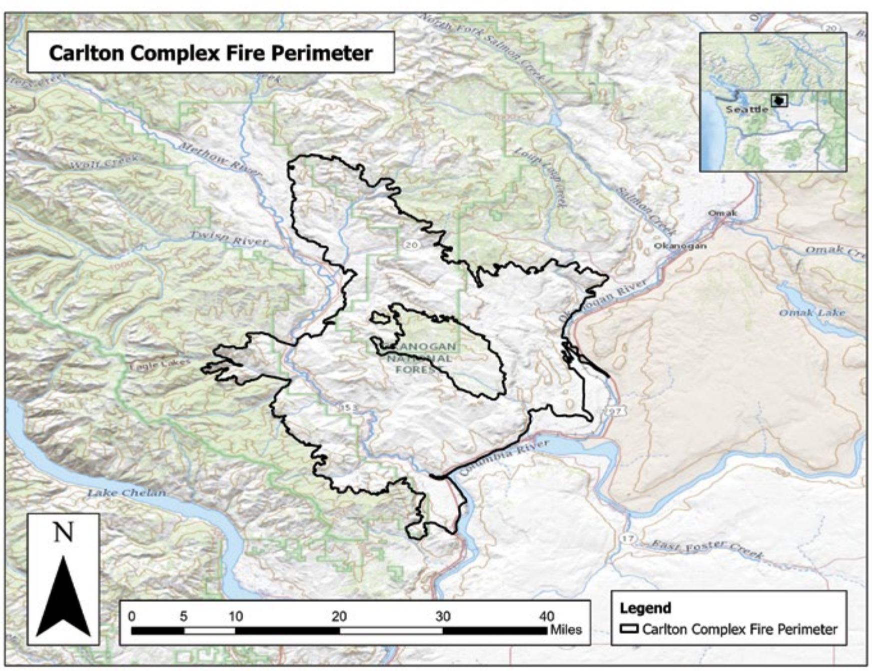
IMPACTS
housing
agriculture
livestock
power grid
transportation

The Carlton Complex burned 256,108 acres (99,082 private, 86,721 federal, 70,215 state) and was caused by four separate lightning strikes on July 14, 2014, that grew together in the Methow River Valley withing four days, becoming the largest single fire in Washington state recorded history. Total suppression costs to the state exceeded $68 million. Responding agencies included local government, state, federal, and Washington National Guard.

Fanned by strong winds, high temperatures and dry vegetation, the fire caused hundreds of evacuations and destroyed over 353 homes, accounting for at least $98 million in insured losses. However, this figure does not fully capture the impact on housing. For instance, it is believed up to 55% of structures in Okanogan County (where much of the fire impact occurred) were uninsured, due to a legacy of lower rates of mortgage financing. Combined with a tight housing market in the area, this meant there was a limited ability to meet the needs of displaced people (Washington State, Office of the Governor, 2014).

This wildfire presents an example of short- and long-term impacts to both agriculture and infrastructure. The fire destroyed 366 miles of power lines, leaving several hundred customers without power for weeks. Water systems were temporarily compromised and transportation infrastructure was highly impacted with 37 state and local roads having traffic disruptions and two main arteries — state highways 20 and 153 — closed for extended periods. Total utility repair costs were estimated over $10 million (Washington State, Office of the Governor, 2014).

A smoke plume from the Carlton Complex Fire blows up near the town of Carlton. Photo: Loren Torgerson/ Washington Department of Natural Resources



Agricultural damage included extensive losses of trees, irrigation systems, fences, and grazing land, often from deposition of debris and mud from post-fire flooding. Losses also included over 1,000 head of cattle (Curless, 2015), with 30% of those losses estimated to be uninsured. Further livestock industry impacts resulted from subsequent public grazing land closures. Total impacts to the livestock industry for the region were estimated to be as high as $50 million for the seven-year period following the fire (Mapes, 2015).

Orchard tree mortality was particularly pronounced due to heat damage and failures in irrigation systems resulting from the fire, and many perimeter rows having to be replaced at an average cost of $15,000 per acre. Damage to apple, cherry, pear, and grape orchards and vineyards was estimated at $1.6 million (Beale, 2014). Given that 45% of the workforce in Okanogan County works in the orchard industry, these impacts were particularly devastating to the local economy. Overall, the state estimated “annual secondary economic losses” over $70 million (Washington State, Office of the Governor, 2014).

This fire also represents another example of severe hydrologic and erosional impacts, similar to the Thomas Fire in California. Soon after the fire was contained, a thunderstorm released more than an inch of rain over the burn area in less than an

Firefighting crews spent days mopping up the Carlton Complex Fire. Photo: Washington Department of Natural Resources

hour, causing flooding and mudslides. Residents, firefighters, homes, roadways, and vehicles were all impacted by the debris flows, to the extent that President Obama signed a disaster declaration for the area on August 11. Flooding and debris flows resulted in major additional infrastructure damage, including the destruction of a house, wash outs of numerous irrigation dams, and blockage of several major highways with debris flows, including one flow that was 145 feet wide and 5 feet deep (Kershner, 2014). The fire and post-fire flooding were also found to threaten fish populations and habitat, including steelhead trout, chinook salmon, and bull trout (Woolley, 2014).

A multi-agency and jurisdictional burned area assessment team was assembled to ensure as timely and effective recovery as possible. Collaborators included FEMA, U.S. Army Corps of Engineers, and Resource Conservation Districts, with USDA Forest Service leadership.

A study on the effectiveness of fuel reduction treatments to mitigate the wind-driven, extreme wildfire effects on the Carlton Complex was conducted by Prichard, et. al. (2020). Across varied topography, vegetation, and fire progressions, Prichard modeled drivers of fire severity and evaluated how fuel treatments mitigated the expected fire severity. Results indicated that treatment units had much greater percentages of unburned and low severity areas in later progressions, providing evidence that strategic placement of fuels reduction treatments effectively reduced localized fire spread and severity even under severe fire weather.

Klondike/Taylor Creek Fires | OR | 2018

ACRES

Klondike: 175,258

Taylor Creek: 52,839

FATALITIES

0

STRUCTURE LOSS

n/a

IMPACTS

health

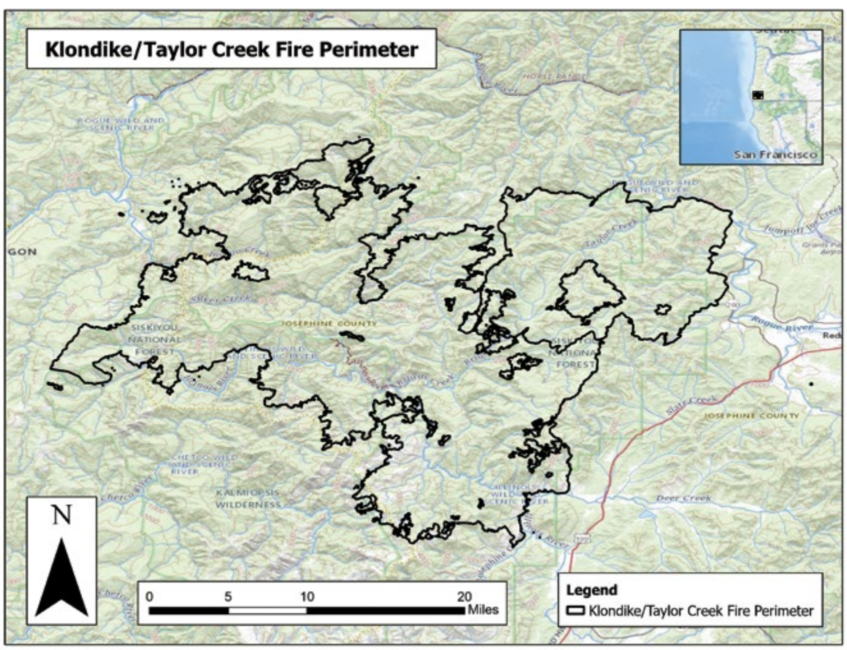
economy

tourism

On July 15, 2018, lightning ignited the Klondike Fire in southwest Oregon (near Selma, on the Rogue River-Siskiyou National Forest, in the Wild Rivers Ranger District and Gold Beach Ranger District). It burned more than 175,258 acres and cost approximately $104 million to suppress. The Klondike Fire eventually burned into the Taylor Creek Fire, which is listed as burning 52,839 acres and costing $41 million to suppress. Together, these fires became Oregon's largest wildfire in 2018.

Both fires required evacuations of multiple communities, impacting thousands of southwest Oregon residents for several weeks with either the direct threat of fire and/or thick smoke that created significant health risks and economic impacts. Homes and other critical and historic structures were also threatened by the fires.

Both fires required evacuations of multiple communities, impacting thousands of southwest Oregon residents for several weeks with either the direct threat of fire and/or thick smoke that created significant health risks and economic impacts.



These wildfires resulted in a significant decrease in tourism in southern Oregon, including a 14% drop in visits to Crater Lake and $2 million in lost revenue to the Oregon Shakespeare Festival (Skuratowicz, et al. 2019).

Debris flow modeling results from the BAER report indicated there was likely to be limited post-fire landslide activity from a 10-year precipitation storm event (Cole, 2018).

The BAER report concluded that the majority of the fire burned at low to moderate severity and highlighted the potential of small landslides to plug culverts and divert flows over the traveled width of the roads, leading to road damage and/or failure. Critical values identified by the BAER team included threats to human life and safety, road and trails, botanical resources, critical salmon habitat, and cultural resources.

Operators launch Plastic Sphere Dispensers (PSD) from a drone to ignite a burnout operation while fighting the Klondike and Taylor Creek fires. Photo: Kari Greer/for the USDA Forest Service Pacific Northwest Region

Smoke from the Klondike and Taylor Creek fires created serious health risks for thousands of residents in southwest Oregon in 2018. Photo: Kari Greer/for the USDA Forest Service Pacific Northwest Region

Wallow Fire | AZ | 2011

ACRES
538,049

FATALITIES
0

STRUCTURE LOSS
around 70

IMPACTS
recreation
wildlife
economy
transportation

Two campers accidentally started the Wallow Fire on May 29, 2011, in the Apache-Sitgreaves National Forest in Arizona, under low relative humidity and strong southwest wind conditions. These dry, windy conditions resulted in a primarily wind-driven fire that burned 538,049 acres in five weeks. The total acreage burned in this single incident was within 50,000 acres of the total acreage burned on the Apache-Sitgreaves National Forest over the previous 25 years prior to the Wallow Fire (Wadleigh, 2011). Nearly 70 structures, including four commercial buildings, 36 outbuildings, and 32 residences were damaged or destroyed by the fire, although insured losses are not reported.

Not including structure losses, the cost of cleanup, assessment and rebuilding was estimated to be $37 million and other impacts included losses of revenues from tourism, property tax base declines, and damaged or lost natural resource values (Jeong, 2016).

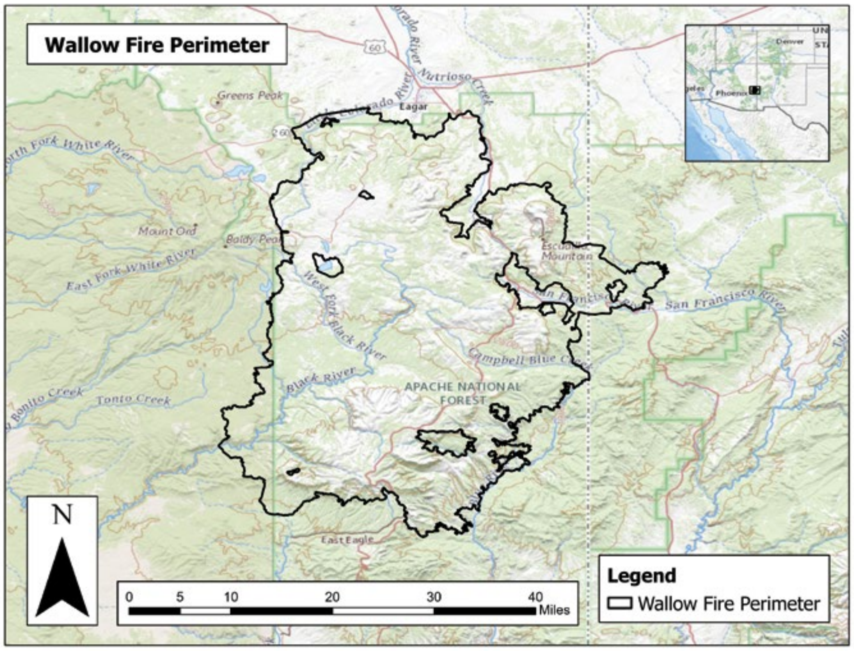
Transportation was also highly impacted, with nearly 200 miles of roadways in eastern and southern Arizona closed, including seven major highways; some highway stretches did not reopen for more than two months after initial closures and others required extensive debris removal and guardrail repairs (Targeted News Service, 2011).

This fire provides an example of extensive impacts to nature-based recreation and tourism. There were 324 miles of trails affected by the fire, with 73 miles in high-severity burn areas and an additional 67 miles in moderate-severity burn areas (Pfleiderer et al., 2011). Dead trees in high and moderate severity burn areas created hazardous conditions for trail users and extensive post-fire runoff damaged or destroyed 32 miles of trail and over 266 trail structures (water bars, check dams, and grade dips). The Wallow Fire also destroyed kiosks and signage, which needed replacing so users could safely navigate the trail system. Overall, more than 42,000 hours was estimated to be needed to repair and bring the trail back to standard (Pfleiderer et al., 2011). The cost of these hours was not reported.

The Wallow Fire burned through a number of areas that had experienced active forest management and fuels reduction.

The fire was found to have burned at relatively low intensity, for instance, on the Fort Apache and San Carlos Indian Reservations, where thinning and prescribed burning had occurred, resulting in less than 10% mature tree mortality.

The impacts to recreation infrastructure go beyond the physical damage to trails and related infrastructure, as this trail system provided highly valued recreational opportunities for the public, commercial outfitters, and access for range permittees and USDA Forest Service personnel. This damage to recreational infrastructure likely negatively affected local communities that depend on forest and trail-based tourism, although the extent of these impacts remains unknown.



The Wallow Fire burned through Soldier Springs Creek, destroying habitat that harbors a unique population of federally threatened Apache trout. Photo: White Mountain Apache Tribe/for the U.S. Fish and Wildlife Service, © CC2.0. **Inset:** The Apache trout was one of many rare aquatic species impacted by the fire in May and June 2011. Photo: USFWS/© CC2.0

The Wallow Fire burned through a number of areas that had experienced active forest management and fuels reduction. The fire was found to have burned at relatively low intensity, for instance, on the Fort Apache and San Carlos Indian Reservations, where thinning and prescribed burning had occurred, resulting in less than 10% mature tree mortality (Bureau of Indian Affairs, 2011).

A portion of the burn site also coincided with the footprint of the Four-Forest Restoration Initiative, which is a Collaborative Forest Landscape Restoration project.[10] A study of the effects of active fuels management (thinning, mechanical fuels removal and broadcast burning) conducted before the Wallow Fire found that treated areas had less severe outcomes after the Wallow Fire, including lower mortality of large trees, higher remnant understory native herbaceous vegetation, and smaller patches with high-severity burn impacts (Waltz et al., 2014).

This aerial view shows the Wallow Fire burning over a ridge in Arizona to meet forest areas previously managed for fuels reduction. Without dense timber to travel through, wildfires burn slower and with less intensity. Photo: Arizona Department of Forestry and Fire Management

10 https://www.fs.usda.gov/4fri

Las Conchas Fire | NM | 2011

ACRES
156,593

FATALITIES
0

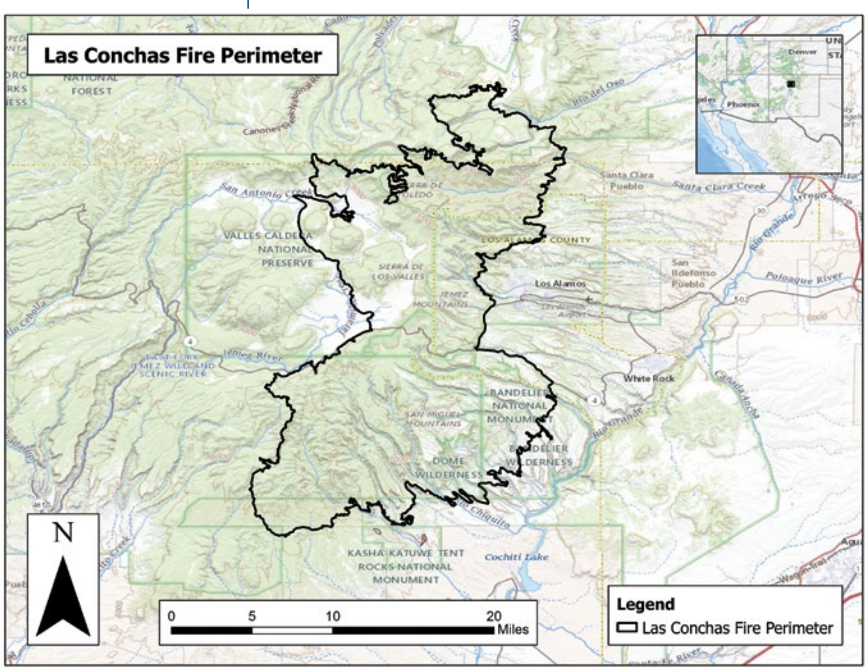
STRUCTURE LOSS
112

IMPACTS
jobs
recreation
water supply
archeology sites

Over 1,500 archaeological sites were impacted by the fire, including several in Bandelier National Monument.

Mandatory evacuations were issued for … the Los Alamos National Laboratory … The shutdown at the National Lab kept 13,000 employees from coming to work for about six days, and was estimated to cost up to $58 million in lost work time.

The 156,593-acre Las Conchas Fire started on June 26, 2011, in the northern region of New Mexico by a tree blown across a powerline in the Santa Fe National Forest. It became the largest fire in New Mexico's recorded history at the time. The fire grew over 44,000 acres in the first 13 hours due to extremely dry conditions and high winds. Despite this intensity and extent, relatively little has been reported on the quantified costs of the incident. The fire destroyed 63 homes and 49 outbuildings in the region (Southwest Fire Consortium, 2014), and severely impacted Santa Fe National Forest, Bandelier National Monument, Santa Clara Pueblo, and the Valles Caldera National Preserve. The fire also impacted 240 square miles of land in the Jemez Mountains, including several archaeological sites, miles of recreational trails, and numerous watersheds. Over 1,500 archaeological sites were impacted by the fire, including several in Bandelier National Monument.



On June 27, mandatory evacuations were issued for Los Alamos and the Los Alamos National Laboratory when a one-acre spot fire burned on laboratory grounds. The shutdown at the National Lab kept 13,000 employees from coming to work for about six days, and was estimated to cost up to $58 million in lost work time (The New Mexican, 2011).

Destructive flooding occurred in the burned area as a result of heavy monsoon rainstorms on August 21.

Sandbagging and other measures were taken to protect buildings from potential flooding after the Las Conchas Fire at Bandelier National Monument in 2011. Photo: Rich Schwab/for the National Incident Fire Center.
Left: The smoke plume from the Las Conchas Fire in the Jemez Mountains, as seen from about 40 miles away in Placitas, New Mexico. Photo: John Fowler/©CC 2.0

Flooding was exacerbated by denuded vegetation and fire impacts to soil (USDOI, NPS, 2012). 15,587 acres of the Las Conchas Fire burned the Santa Clara Pueblo, including lands belonging to Ohkay Owinghe, San Ildefonso, Pojoaque Jemez, Cochiti and Kewa Tribes. Debris flows were expected to have negative impacts on the water supply for Santa Clara Pueblo and a number of recreational lakes, and to potentially affect some major highway bridges and culverts (Tillery et al., 2011). The equivalent of 50 years' worth of normal sediment and debris was delivered to tributaries of the Rio Grande (Bradley, 2017) and to the downstream Cochiti Reservoir in a matter of days, requiring a 66-day shutdown of water withdrawals from the river for Albuquerque. Further, runoff from the burn scars of the Las Conchas Fire caused severe sedimentation and turbidity in surface waters that extended at least 30 miles downstream, posing significant threats for stream health (Dahm et al., 2015).

Deputy Secretary of the Interior Michael Connor toured the tribal lands and the Department of the Interior issued a statement noting, "In the first full year after the fire, significant flooding occurred during the summer monsoon season with estimated flows from 5,000 to 9,000 cubic feet per second, overwhelming the individual dam spillway capacity…this, coupled with the reduced reservoir capacity, resulted in embankment overtopping and dam stability degradation." Additionally, President Obama reached out to tribes to both mitigate and adapt to environmental changes. The pueblo subsequently qualified for FEMA assistance (Indian Country Today, 2014; U.S. Department of Interior, 2014).

A case study of the Las Conchas Fire explored the role of previously burned areas (wildland and prescribed fires) on suppression effectiveness and avoided exposure (Thompson et. al., 2013). Methods included characterization of joint dynamics of fire growth and suppression activities and relative fireline efficiencies inside and outside of previously burned areas. Results indicated that previous large fires exhibited significant and variable impacts on suppression effectiveness and fire spread potential. Most notably, the Cerro Grande Fire (2000) likely exerted a significant and positive influence on containment, and in the absence of that fire the community of Los Alamos and the Los Alamos National Laboratory could have been exposed to higher potential for loss.

Grizzly Creek Fire | CO | 2020

ACRES
32,631

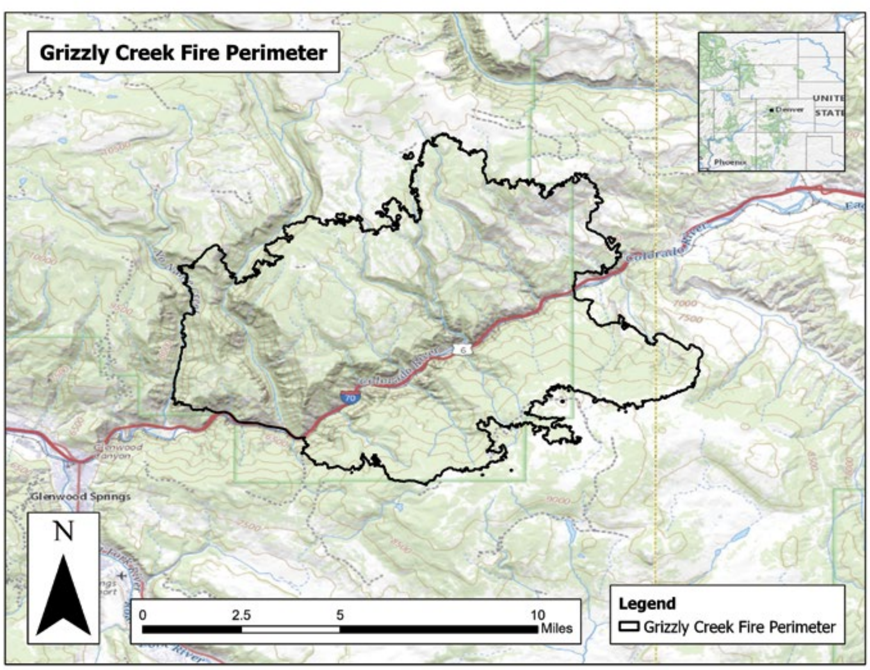
FATALITIES
0

STRUCTURE LOSS
few outbuildings

IMPACTS
supply chain
transportation
tourism
recreation
economy
water supply

Ignited on Aug. 10, 2020, the Grizzly Creek Fire burned 32,631 acres in Colorado, spreading along the Interstate 70 and Colorado River corridor between Glenwood Springs and Gypsum. The fire burned through steep and difficult-to-access terrain, requiring a high level of air support and up to 650 firefighting personnel. Much of the affected land was within the White River National Forest. At the height of the fire, over 1,000 structures were threatened, but only a few outbuildings were destroyed. The BAER report estimated that 12% of the terrain within the perimeter was burned severely, meaning that all or nearly all pre-fire ground cover and organic matter was consumed, resulting in prime conditions for flash flooding in these already susceptible steep landscapes.

This fire represents a case of high impacts to both hydrology and transportation infrastructure. These, in turn, led to severe downstream economic impacts. The fire burned through a narrow choke point along the critical east-west I-70 corridor, forcing the closure of a long segment of interstate from Glenwood to Gypsum for almost two weeks — the longest closure of that stretch of highway in its history. This is an area with extremely limited alternative route options, so this closure created massive accessibility challenges both for local residents and for through-travelers and freight haulers. These transportation woes were extended into the following year when intense monsoon rains led to post-fire mudslides and debris flows on segments of I-70. Between June and August 2021, 19 separate flood events created debris depositions as high as 10 feet, covering all lanes of I-70, and leading to a 100-foot stretch of the heavily engineered highway being nearly demolished (B. Miller, 2021). This led to a second round of interstate closures. These impacts were complicated by geography. The affected section of highway is in a narrow canyon with the Colorado River abutting it. In places, the east- and westbound road sections are stacked at different grades, making access, cleanup, and repair extremely challenging. This complex geography limited alternative routes; some detours, for instance for travelers coming from the Denver region, added close to four hours of travel time.



The impact of these road closures on local economies was severe in both 2020 and 2021, particularly since these events coincided with the COVID-19 pandemic. Closures not only greatly limited access options for residents and increased commute times, but they also undermined local and regional supply chains, which took a heavy toll on local businesses. Glenwood Springs, Carbondale and other communities around the confluence of the Colorado and Roaring Fork rivers are heavily dependent on tourism, with many recreational industries like rafting, fly fishing, mountain biking, and theme parks. Closures made customer access difficult to near impossible for these industries for weeks. It is estimated that restaurants saw sales go down by roughly 25% and lodging was down nearly 50%, while recreational businesses also took a heavy hit. For instance, a single rafting operation saw a reduction of several thousand customers, resulting in over $200,000 in lost revenue (Gilbert, 2021). Likewise, sales tax revenues were estimated to have dropped by about 20%, at least for the 2020 fire event (Weiser, 2021).

Another impact of the interstate closures was the inundation of rerouted cars onto lower capacity detour roads, such as state Highway 82, resulting in massive traffic jams, delays of up to eight hours and heavy wear on roads. This traffic also led to numerous safety issues and limited emergency vehicle access (Weiser, 2021).

The repair costs to the transportation infrastructure are still being calculated as the full extent of the damage of both events is assessed. The Colorado

Numerous post-fire mudslides in 2021 closed sections of Interstate 70, the national transportation route that weaves through Glenwood Canyon in the mountains of Colorado. Some detours added up to four hours for travelers after the interstate was repeatedly shut down following the Grizzly Creek Fire of 2020. Photo: Glenwood Springs Fire Department

Department of Transportation estimated the initial cost of system repairs at $116 million; in addition to interstate repairs and debris removal, this includes millions of dollars to repair traffic impacts to other roads that served as detour routes (Miller, 2021). These repairs were not completed until the end of December 2021.

Other infrastructure was also impacted, including water supply systems. Glenwood Springs gets most of its municipal supply from Grizzly and No Name creeks. Both flow through the burn area and experienced heavy sediment loads that are expected to continue for 3 to 10 years. Glenwood was unable to withdraw water from the creeks for municipal use for 40 days and in 2022 was the process of building sediment removal and mixing basins that will eliminate expected future sediment. While the exact cost is not known, its construction required an $8 million loan from the state (Sackett, 2020), which, in turn, increased water rates by 36%. Overall watershed recovery costs are estimated to be $45 million (Roy, 2021).

Falling rocks damage Interstate 70 during the 2020 Grizzly Creek Fire. Photo: Tom Story/USDA Forest Service Rocky Mountains

Finally, the Grizzly Creek Fire also had direct impacts on natural resource values. Among the highest profile of these was Hanging Lake, a popular scenic hiking destination in Colorado, accessed by a permit-based hiking trail. That trail and lake were closed for eight months because of the fire, resulting in the loss of thousands of visitor days and the economic benefits they bring to nearby communities.

East Troublesome Fire | CO | 2020

ACRES
193,812

FATALITIES
2

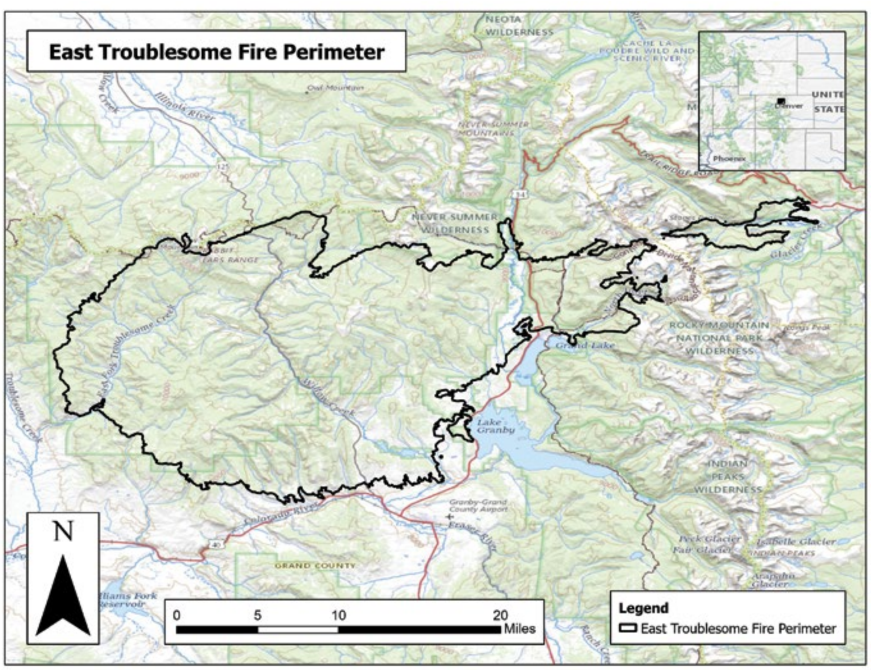
STRUCTURE LOSS
580

IMPACTS
economy
tourism
water supply
housing
transportation

On Oct. 14, 2020, the origin of the East Troublesome Fire was detected northeast of Kremmling, Colorado, in the Arapaho National Forest in Grand County.[11] The fire grew rapidly between October 20-23, from around 18,550 acres to 187,964 acres (BAER 11/23/2020), with highest growth occurring on October 21.

The fire was fueled by high winds, dry grass, brush, and beetle-killed downed and dying pine trees, the combination of which led to unprecedented fire behavior and growth (Janice Coen, pers. comm.). During this period, the area north of U.S. Highway 40 near Granby and extending eastward to Grand Lake and Estes Park had over 7,000 structures threatened, with over 35,000 people under mandatory evacuations. Fortunately, a winter storm occurred from October 24-26, causing a dramatic drop in fire behavior with smoldering and reduced fire spread on both sides of the Continental Divide. In the end, the total fire size was 193,812 acres according to InciWeb, or 171,209 according to the final burned-area report (BAER 11/23/2020).

The East Troublesome Fire was the second largest wildfire in Colorado's history. At the time, it was the costliest fire in Colorado history, according to the Rocky Mountain Insurance Information Association[12], with estimated insured losses totaling $543 million resulting from approximately 1,602 homeowner and auto insurance claims filed. The



Given that the fire burned an area supplying water for nearly a million people, the effects on water quality and infrastructure are of great concern.

fire caused two deaths, and officials reported that 366 homes and 214 outbuildings (e.g., barns, sheds) and commercial structures were destroyed, totaling 580 structures. In addition to destroyed structures, home insurance claims included smoke damage, additional living expenses, and other home damage. The BAER (11/23/2020) identified numerous post-fire threats to off-forest critical values within and downslope/downstream of the East Troublesome burn scar. These included, but were not limited to, threats to municipal water supplies, utility infrastructure, highways, private property, and homes. Several roads were closed due to both the fire and subsequent mudslides, including an important stretch of state Highway 125 which was closed for 18 days.

Given that the fire burned an area that supplies water for nearly a million people, the effects on water quality and infrastructure are of great concern. The fire generated about 30,000 cubic feet of debris, which would have cost of at least $27 million to remove, equating to as much as $50,000 per property (Golden, 2020). The total cost to restore the watersheds affected by the East Troublesome Fire and the nearby Cameron Peak Fire is estimated to be as high as $136 million (Reinke, 2021).

Nature tourism and recreation industries were also heavily affected. This is an important industry sector in the region, given the proximity to Rocky Mountain National Park (RMNP), high-use National Forest lands, and numerous recreational lakes. In 2019, Grand County (where the majority of the fire occurred) attracted more than two million visitors and generated $590 million in local spending, with approximately 80% of jobs in the county depending on the tourism industry (Doedderlein et al., 2021). Hence, an event with a footprint as large as this fire on the landscape is sure to have lasting and significant economic impacts. Some reservoirs have seen disproportionate impacts; for instance, Willow

11 InciWeb (East Troublesome Fire) - https://inciweb.nwcg.gov/incident/7242/
12 http://www.rmiia.org/catastrophes_and_statistics/Wildfire.asp

The smoke plume from the East Troublesome Fire in Colorado is seen 60 miles from the burn. The fast-moving fire ignited near Granby and spread through stands of beetle-killed lodgepole pines affected by the mountain pine beetle outbreak in the mid-1990s. The dense fuel load contributed to the fire moving more than 160,000 acres in two days. Photo: Blair Rynearson/Colorado State Forest Service

Creek Reservoir northwest of Grand Lake was heavily impacted with 90% of its drainages burned in the fire.

Suppression costs for the East Troublesome Fire are reported at approximately $20 million (ICS-209). Statewide, according to the Colorado Fiscal Year 2021-22 Joint Budget Committee Hearing minutes, the estimates for 16 fires qualified as state responsibility (i.e., had some nonfederal land burned, and had exceeded the capacity of the local fire departments and counties) exceeded $278 million, $38 million of which came out of the Colorado state budget. These fires burned over 627,000 acres (511,020 acres [81%] on federal lands, and 116,066 acres [19%] on nonfederal lands), and five of these fires (Pine Gulch, Grizzly Creek, Cameron Peak, Mullen, and East Troublesome) burned for an extended period of time. Those five fires accounted for 594,172 of the total acres burned in Colorado in 2020 (or 95% of the state responsibility fire acres and 84% of the total acres burned statewide), with suppression costing nearly $256 million (or 93% of total suppression costs; with 90% covered by federal budgets and 10% covered by state budgets).[13]

A year after the fire, people who have lost homes and property are still faced with being underinsured, increased building costs, and construction worker shortages. As of early 2022, Grand County has only issued 90 building permits, representing only 25% of homes lost to the fire.

Several electric transmission line were damaged or destroyed by the East Troublesome wildfire. Photo: Ron Burbridge/Western Area Power Administration, ©CC2.0

13 Pers. Comm. - Vaughn T. Jones, Chief, Wildland Fire Management Section, Colorado Department of Public Safety - Division of Fire Prevention and Control (Jan. 27, 2022).

Following a timber harvest in the spring, Oregon Department of Forestry crews created a burn site to test equipment and fire prevention procedures in the Tillamook State Forest. Just months later, on Aug. 16, 2013, regrowth had already begun on the forest floor in the nutrient-rich soils. Photo: Joel Prince/ National Association of State Foresters

LOOKING forward

Conclusions and Policy Implications

While ballooning suppression costs in recent years ($3.65 billion combined federal appropriations in fiscal year (FY) 2020) have garnered national attention, those costs are merely the tip of an iceberg that is orders of magnitude larger.

As this report explains, data on those fully loaded costs is scarce, but the data that exists is sobering. For instance, the total direct and indirect costs of the 2018 wildfire season in California was estimated at $148.5 billion. When compared to $997 million in suppression costs for those same incidents, that yields a ratio of 153:1 of total costs to suppression costs (Wang et al., 2021b). Obviously, 2018 in California was somewhat of an outlier given the magnitude of destruction from the Camp Fire. But less destructive events still yield disturbing ratios.

For instance, when looking at just three categories of nonsuppression costs (structures, debris removal and watershed restoration) for the East Troublesome Fire, the ratio stands at 35:1.

The need for more cost-mitigating investments, like fuel treatments, home hardening, and fire-safe land-use planning, among others, has become increasingly evident as the rate of growth in suppression costs reaches previously unthinkable levels.

Logger Ted Hoffman works in Clearwater, Montana. The 2011 timber sale benefited the Montana public schools system while critical fuels treatment helped lower the risk of future catastrophic wildfires. Photo: Josh Birnbaum/ for the National Association of State Foresters

The focus on suppression costs has sidelined attention away from other types of wildfire costs, which are much larger generally, but imperfectly understood and only partially quantifiable with the sources of information that are currently available. This report is designed to raise awareness of these costs, to highlight the opportunity costs associated with inaction, and to illustrate the benefits of proactive investment.

The need for more cost-mitigating investments, like fuel treatments, home hardening, and fire-safe land-use planning, among others, has become increasingly evident as the rate of growth in suppression costs reaches previously unthinkable levels. However, current mitigation investments remain far smaller than expenditures on suppression (Snider et al., 2006).

For instance, in FY 2020, while federal agency appropriations for suppression were $3.65 billion, funding for fuel reduction was only $590 million and outlays for "preparedness" were $1.52 billion (Congressional Research Service, 2020). By contrast, the actual need for fuel treatments and preparedness was estimated in a study to be a minimum of $5 billion to $6 billion a year (Clavet et al., 2021). Without the public awareness that comes from information on the full costs of wildfire under current conditions, or details about the magnitude of the costs avoided through increased investments in mitigation, it is unlikely that public expenditures will rise to needed levels.

Future Needs

1 National consistency

A national system for consistently and transparently quantifying the full costs of wildfire would be costly and difficult to implement, but its benefits would be enormous.

It would raise public awareness of the magnitude of the problem which, in turn, would motivate both the public and policymakers to support much more aggressive investments in mitigation; it would also help decision makers determine optimal amounts to invest by allowing the magnitude of avoided costs and, hence, return on investment, to be calculated.

2 Develop full-cost formulas

A full-cost accounting system would help governments develop formulas for a more equitable and strategic distribution of aid and compensation after wildfires, addressing acknowledged disparities in how cost burdens are currently borne among different sectors of society.

Research has shown that, in many contexts, the costs of wildfire are experienced most severely by those who can least afford them, such as low-income and elderly populations (Masri et al., 2021). If not addressed, this pattern can not only result in regressive redistributional effects, but also create a self-reinforcing downward spiral for certain communities, leading to generational poverty. It is self-evident that low-income communities have less capacity and fewer resources to prepare for wildfire and respond to its impacts. But less obvious is the fact that many rural communities find themselves with similar limitations, even if they are not classified as low-income. In both cases, there is likely to be a higher than normal proportion of renters and un/underinsured residents, complicating the process of compensation. Further, a lack of public resources in rural communities is likely to limit the ability to repair and rebuild damaged community property and infrastructure.

The more consistently and thoroughly that wildfire true costs are tracked, the more equipped government and private entities will be to direct aid and compensation to vulnerable populations that need it the most, ensuring that no particular group of people or community suffers disproportionate impacts from wildfires.

3 Distribute costs equitably

Address the longstanding question of how to appropriately and fairly share costs of suppression among levels of government and different agencies. Cost-share agreements currently exist for suppression and are mandatory in some cases, where more than one agency is responsible for fire protection within a fire footprint. They often involve formulas for sharing costs by measures such as acres, effort, or flat amount. National accounting of the full costs of wildfire would provide historical data that could be analyzed to assess how costs are experienced locally, regionally, and nationally, from which formulas could be derived to find the appropriate balance for cost sharing. The transparency ensuing from such a system could, in turn, help ensure that nonsuppression budgets of land-management agencies are not commandeered for suppression during an incident, a phenomenon that complicates the ability of land-management agencies to conduct and plan for long-term work aligned with their mission.

Examining Wildfire Costs May Further National Policy

A better understanding of the true costs of wildfires may spur lawmakers to address some of the regulatory barriers that inadvertently slow down the pace of mitigation measures. One of the most complex regulatory issues today revolves around permissions and clearances for prescribed burning, which is a critical — and generally very safe — tool for mitigating wildfire risk and reducing fuel loads. However, a number of regulatory hurdles make it extremely challenging to implement, including air quality regulations (e.g., Fed. Clean Air Act and CA Title 17) and their associated limits on timing windows for allowable smoke emissions, as well as liability laws and required certifications (R. K. Miller et al., 2020). Knowing the full costs of smoke exposure from unplanned wildfires would allow stakeholders to see how much larger they typically are than those for prescribed burns. In turn, this may help reduce opposition to the permitting of these planned smoke emission events.

Development of a consistently and nationally utilized system for tracking the full costs of wildfire is a massive and long-term undertaking. In the interim, there are several steps that can be taken to improve accessibility, understanding and utilization of the full range of wildfire costs to better inform policy and funding decision making. These same steps will also make development of a national system more viable in the long term.

Mechanical thinning is one of many mitigation measures that can help lower the risk of intense wildfire. Yet, costs of such efforts are currently inconsistently reported throughout the West. Photo: Austin Troy/Spatial Informatics Group

Recommended Actions

1 Assess data gaps

A more holistic and granular assessment of data gaps and incongruities is needed. The majority of categories included in this report's cost typology require data that is nationally unavailable, and often only found for a few geographically limited case studies. The needed data for any future national fire cost accounting system would have to come from a wide variety of public sector entities, including municipalities, counties, states, tribes, or utilities. In addition to ensuring needed data exists, it is important to improve its harmonization across entities to enable consistent collection, analysis, and attribution.

2 Enhance research & data

More research is needed to develop modeling approaches to estimate the magnitude of different types of costs attributable to a particular wildfire. This research and modeling must be highly interdisciplinary, involving economists, natural resource scientists, social scientists, planners, and a wide array of wildfire experts.

3 Gather mitigation costs

More complete and accurate estimates are needed to understand the costs of mitigation investments, from fuel treatments, to home hardening, to defensible space, to fire-safe land planning. This research should account for the fact that costs can vary significantly by region or context. Related to this, research is also needed on the effectiveness of different types of mitigation measures. This would aid in better understanding the return on investment for mitigation, allowing for more strategically targeted investments. This research should also incorporate studies of the other benefits from these investments, such as ecological restoration.

This report comes at a time of significant activity in wildfire-related policies and legislation, both passed and under debate or consideration. For instance, the Fire Funding Fix bill signed into law in 2020, addresses the growing costs of firefighting by providing wildfire response funding from an emergency disaster fund, thereby reducing "fire borrowing" from other federal agencies and budgets. It also seeks to encourage fuel treatments less than 3,000 acres through streamlined National Environmental Policy Act (NEPA) requirements. Further, the 2021 Bipartisan Infrastructure Law provided $600 million to increase firefighter pay to boost recruitment and retention, in addition to nearly $3 billion going toward the White House's new 10-year wildfire strategy, known as Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests. This plan calls for the treatment of an additional 20 million acres of National Forest lands and 30 million acres of other federal, state, tribal, and private lands.

How might knowing more about the true cost of wildfire inform these or other future policies, legislation, or best practices?

This is impossible to predict with certainty, but given the jaw-dropping magnitude of these numbers, such information is likely, at a minimum, to prove a highly powerful motivator to the public and legislators.

But, more importantly, it will provide the information needed to take a data-driven approach to wildfire management and mitigation planning, one that enables targeted and cost-effective investments, that directs aid and compensation equitably, and that allows society to measure its return on investment in the fight for wildfire safety.

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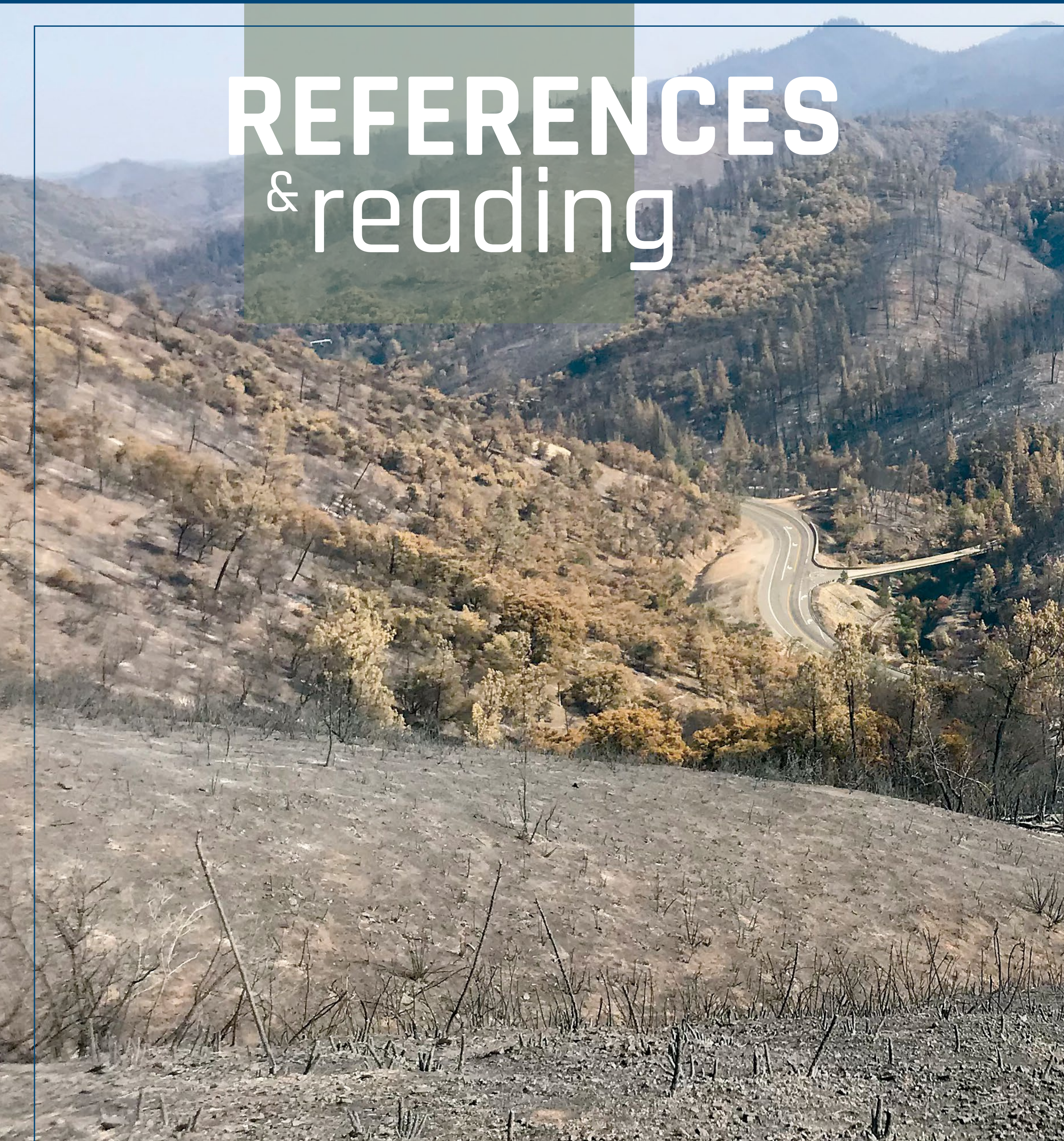

After the 2018 Carr Fire that began inside Whiskeytown National Recreation Area in California, emergency stabilization measures were taken to protect against flooding and landslides as well as to monitor the post-fire landscape. Photo: Ally Reddington/for the National Interagency Fire Center

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