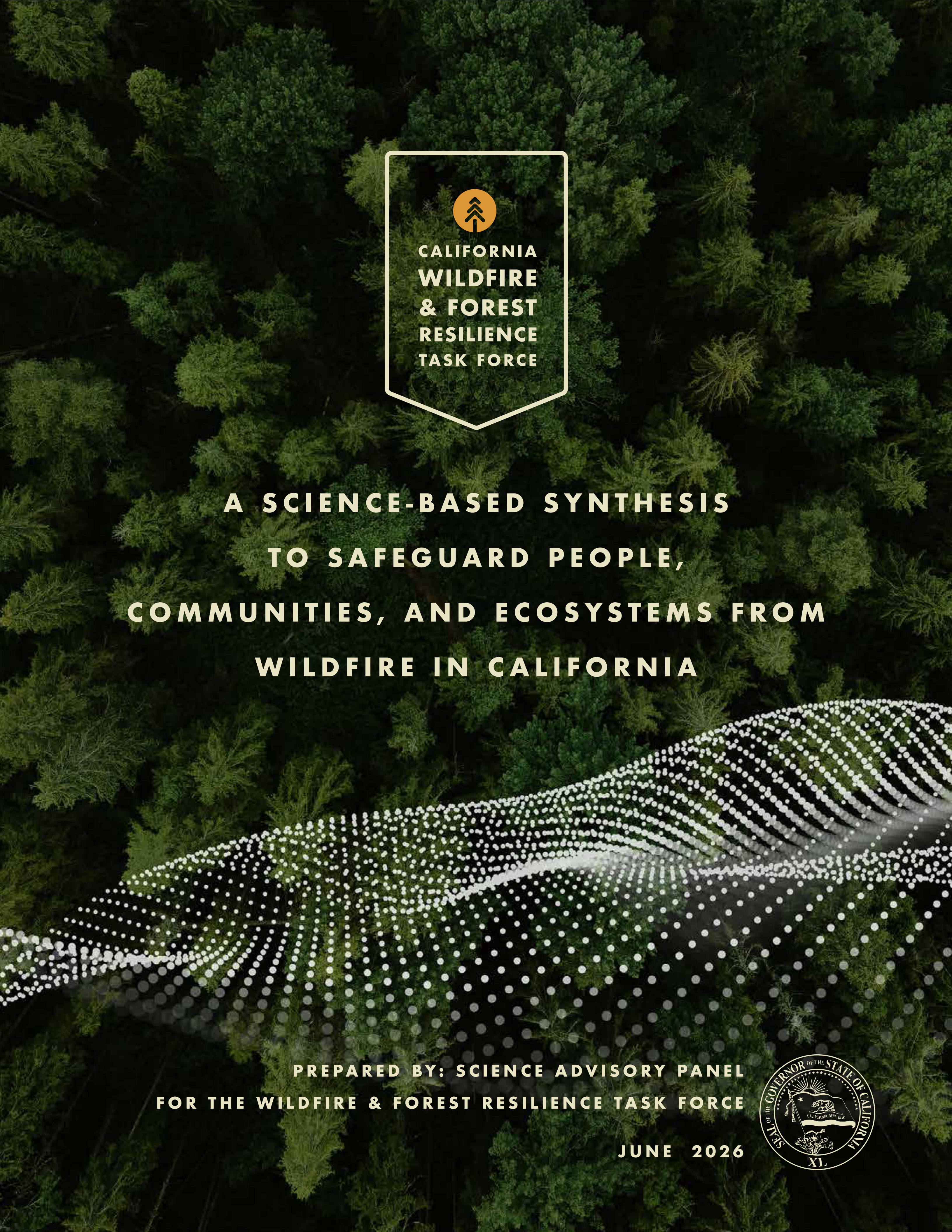

CALIFORNIA
WILDFIRE
& FOREST
RESILIENCE
TASK FORCE

A SCIENCE-BASED SYNTHESIS TO SAFEGUARD PEOPLE, COMMUNITIES, AND ECOSYSTEMS FROM WILDFIRE IN CALIFORNIA

PREPARED BY: SCIENCE ADVISORY PANEL
FOR THE WILDFIRE & FOREST RESILIENCE TASK FORCE

JUNE 2026

SEAL OF THE GOVERNOR OF THE STATE OF CALIFORNIA
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Key Messages of the Science Synthesis

The Wildfire and Landscape Resilience Task Force's Science Advisory Panel (Panel) was tasked with synthesizing topically specific, science-based, and decision-relevant research findings to guide investments and actions to protect human lives and communities and reduce risk to ecosystems and the services they provide from extreme wildfire events in California. The scientific confidence or likelihood of the findings, observations, and projections in this text is indicated using refined terminology from the National Climate Assessment. These calibrated terms describe the levels of confidence (high, medium, or low) and, where appropriate, the assessment of likelihood (very likely, likely, unlikely) associated with the statements in the corresponding text. The key messages of the seven topics in the science synthesis are as follows:

California's Wildfire Crisis: A Brief Overview

During the 21st century, warming, drought, and the legacy of past management have increased the scale and severity of wildfires in California's forests. In both forests and shrublands, recent coincidences of human-caused ignitions with severe fire weather conditions have increased catastrophic losses of human life, property, and ecosystem goods and services across much of the state. Repeat high severity wildfires and uncharacteristically short intervals between wildfires have driven rapid conversions of forests to shrublands and shrublands to grasslands (High Confidence), respectively. Continued housing development in the wildland-urban interface (WUI), where human ignitions are most frequent, will heighten the likelihood of such events, placing more homes in the path of wildfires (Very Likely). Ongoing land development will further alter vegetation composition, with greater potential for invasive species expansions in shrublands (Likely).

Socioeconomic and Public Health Implications of Wildfires

Wildfires have substantial direct and indirect impacts on the health and socioeconomic well-being of the public in California and beyond (High Confidence). Wildfires cause direct losses to life and property, and smoke has far-reaching effects on human health and economic productivity (High Confidence). Fire-related expenditures and losses have ballooned in recent years, with unprecedented spending on fire suppression and billions of dollars of material and health-related losses, and these trends are expected to continue, at least in the near term (Likely). Wildfire smoke is and will continue to be a major driver of health-related losses from fire, contributing to thousands of premature deaths each year in California, as well as undesirable educational and labor market impacts (Likely). Wildfire will continue to have far-reaching indirect effects, including impacts on insurance and housing availability and affordability, utility rates, and natural resource markets (Likely). The economic and health impacts of fire and smoke disproportionately impact vulnerable communities, perpetuating and magnifying social inequalities (Likely).

Protecting Communities from Wildfire Through Land Use Planning and Design

Designing and retrofitting communities to be fire resistant and resilient will lessen vulnerability (Medium Confidence); this includes structure and home hardening (High Confidence). Land use planning that guides where and how development occurs is a critical tool for reducing wildfire risk and exposure (High Confidence). Attention to and investment in community and public engagement is necessary to achieve outcomes (High Confidence). Wildfire impacts to human communities could be reduced through planning that reduces fire exposure and ignition prevention, particularly during extreme fire weather (High Confidence). Defensible space immediately surrounding structures reduces wildfire risk (Likely). The efficacy of planning activities, community engagement, home hardening, and defensible spaces will often improve when efforts are adapted to suit local conditions (Medium Confidence).

Wildfire Impacts to Ecosystems and the Services and Values They Provide

Changes in fire severity, frequency, and size have imperiled ecosystems throughout the state, resulting in altered vegetation structure and degraded ecosystem function (High Confidence). Extreme wildfire events in forests and shrublands can thwart postfire recovery and lead to long-term vegetation change, impacting carbon storage, watershed services, biodiversity, cultural services, and provisioning services such as water (High Confidence). These trends are expected to continue for years to decades (Very Likely).

Applications and Approaches to Reduce Extreme Wildfire Risk and Impact to Ecosystems

Vegetation management, including mechanical treatments and the use of beneficial fire, can reduce wildfire hazard and negative impacts of extreme wildfire events to forests that historically burned with frequent low to moderate severity fires (High Confidence). Fuel treatments, especially the combination of thinning from below and prescribed fire, can effectively reduce wildfire hazard and severity, but effectiveness depends on ecosystem type and declines with smaller treatment units, particularly under extreme burning conditions (Medium Confidence). Strategic fuel breaks facilitate suppression operations and may slow the rate of wildfire spread (Medium Confidence). To align California's conifer and mixed evergreen forests to meet long-term goals of resilience, the pace and scale of fuel treatment implementation, with re-treatment every 10–20 years, should increase (High Confidence).

Post-Fire Recovery, Reforestation, and Management Interventions

Prompt, strategic post-fire management interventions including reforestation and restoration can reduce the likelihood of vegetation type change and secure other ecosystem services (High Confidence). Extreme wildfire events (EWEs) limit post-fire tree regeneration, accelerate forest loss, and denude slopes prone to debris flow (High Confidence). Mitigating post-fire debris flows and land sliding can reduce risk to property and critical infrastructure (High Confidence).

The Value and Role of Data, Modeling, Remote Sensing, and Novel Technological Applications to Address the Wildfire Crisis

To support effective vegetation management, wildfire risk mitigation, and wildfire response, California needs up-to-date, accessible, and integrated spatial data on vegetation, fuels, and infrastructure. To predict the effectiveness of potential management actions in achieving wildfire resilience, California needs ecosystem models, fire models, and scenario planning platforms that fully and seamlessly leverage the latest available data. Current priorities include: (1) improving the accuracy and realism of fuel data and fire behavior models, (2) adopting new mapping technologies that can quickly capture rapidly changing conditions, and (3) expanding the collection and accessibility of ground-based reference data for model training and validation. Data and tools should be delivered through an easy-to-use open-access platform. To guide selection by users and inform future investment, a standardized assessment of existing datasets and tools is urgently needed.

Introduction

The Wildfire and Landscape Resilience Task Force's Science Advisory Panel (Panel) was tasked to produce a synthesis summarizing the best available science to protect communities and increase landscape resilience in the face of the California wildfire crisis. The intent of this document was to form the scientific basis of the 2026 Action Plan. The Panel identified seven topics called "key messages." Each key message in the science synthesis addresses: (1) recent findings in literature related to that key message, (2) decision and management relevant information gaps, and (3) the perspectives on what is needed or required to appreciably realize the optimum outcome per the opinion of the scientific community. This synthesis has been crafted as a resource for decision makers as they set programmatic priorities, develop funding strategies, and advocate for sustained investment in particular management approaches.

Process

The co-chairs solicited input from panel members for the general themes and specific topics believed necessary to capture as part of the synthesis. The co-chairs organized these themes into seven key messages which ultimately formed the basis of individual sections within the synthesis. The structure of the key messages was modeled after the United States Global Change Research Program Fifth National Climate Assessment [1]. Specifically, each section leads with concise takeaway points accompanied by a confidence statement, followed by a supporting narrative with references. Co-chairs assigned a subject matter expert from the panel as lead author to each key message, who then recruited co-authors within or outside the SAP to ensure sufficient expertise and coverage. Early drafts were shared and discussed by the entire panel during a regular quarterly meeting, and then final drafts were submitted to the co-chairs and Task Force leadership for review. After a subsequent round of revision, the synthesis was sent to a five-member external committee for an independent, double-blind peer review. These external reviews were returned to the lead authors for response and revision. The co-chairs independently evaluated the adequacy of author responses and revisions for scientific credibility. The authors provided final drafts of key messages, and the synthesis was copyedited before release to the Task Force. The development of this synthesis followed best practices established by the National Academy of Sciences, Engineering, and Medicine for scientific assessment (NASEM n.d.).

California's Wildfire Crisis: A Brief Overview

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Key Message

During the 21st century, warming, drought, and the legacy of past management have increased the scale and severity of wildfires in California's forests. In both forests and shrublands, recent coincidences of human-caused ignitions with severe fire weather conditions have increased catastrophic losses of human life, property, and ecosystem goods and services across much of the state. Repeat high severity wildfires and uncharacteristically short intervals between wildfires have driven rapid conversions of forests to shrublands and shrublands to grasslands (High Confidence) respectively. Continued housing development in the wildland-urban interface (WUI), where human ignitions are most frequent, will heighten the likelihood of such events, placing more homes in the path of wildfires (Very Likely). Ongoing land development will further alter vegetation composition, with greater potential for invasive species expansions in shrublands (Likely).

Background

Wildfires are a natural part of most California ecosystems, but increased human population pressures, land use changes, vegetation management, fire policies, invasive species, and more recently, the effects of a warmer and drier climate, have altered fire regimes and collectively facilitated the wildfire crisis experienced today. In the last 20 years, 18 of the largest wildfires in recorded state history occurred, with more than 65,000 structures destroyed, more than

100 direct human fatalities, and several thousand human deaths due to complications from smoke exposure [2–4]. In fact, California accounts for most of the recent structure loss to wildfire in the United States [5]. The impacts of some recent wildfires in California have had profound socio-ecological effects, including unprecedented human deaths and health impacts, property destruction, and rapid land cover shifts [6–8]. Importantly, most destructive wildfires are not due to any one issue but result from multiple risk factors aligning in space and time [8–10]. For example, the scale of destruction during the Los Angeles fires in 2025 reflected a combination of antecedent climate conditions, a late start to winter precipitation, and a human-caused ignition adjacent to the city during a severe Santa Ana wind event.

While naturally or Indigenous ignited fires are ecologically important for California's frequent-fire dry mixed-conifer forests, human-caused ignitions (e.g., campfires, electrical transmission lines, arson), are responsible for most wildfires in the state, with disproportionately high human and ecological impacts [11–14]. Importantly, the most frequent human ignition sources differ from the ones that cause the largest area burned, suggesting a need to consider the source, timing, and location of ignitions relative to assets at risk, wind directions, and fire weather [15].

Projections indicate wildfire impacts will continue to increase with climate change and land development [16], albeit differently in different regions of the state [17,18]. For example, climate effects on wildfire are directly related to temperature and precipitation in montane conifer forests; but these variables are less important in coastal California, where prior-year precipitation is the most important climate variable [19]. Simultaneously, impacts to human health, infrastructure, and economies have skyrocketed in response to the increased frequency of extreme wildfire events [20,21] and California's burgeoning wildland-urban interface (WUI) [22–24]. Expansion of WUIs into undeveloped areas or increasing human populations within existing WUIs raises wildfire risk by exposing more communities to wildland vegetation, expanding the footprint of human-caused ignitions, and complicating firefighting efforts [25–28].

Forested Ecosystems

Forests and woodlands cover one-third of the state (~32 million acres) with both natural and human-caused fire influencing ecosystem structure, composition, and function. The historical role of fire in California's forests has varied depending on forest type and region [29], but in many locations was substantially different from that observed today [30]. In the Klamath Mountains, Sierra Nevada, Southern Cascades, and Modoc Plateau, most fires were historically frequent (5–20 yrs. on average between fires) and of low to moderate intensity [29,31,32]. Coast redwood forests experienced fire from natural and anthropogenic sources, with the majority becoming anthropogenic in origin with increasing human settlement [33–35]. Low-intensity fires in oak woodlands were common as Indigenous people made frequent use of fire in their stewardship of California's oak woodlands [36].

Today, wildfires in California's forests are larger, hotter, and more destructive. For example, in 2020, wildfires burned ~4.3 million acres in California, more than twice the previous record. Economic losses exceeded $19 billion and 33 people were killed [37]. The primary causes of increases in wildfire activity in California's forests are clear—warming temperatures, increasing aridity, drought, legacy wildfire suppression effects, past harvesting of large, fire-resistant trees, land use changes and development, interactions with other disturbances, and unintentional human-caused ignitions [5,9,38–40]. In particular, more than a century of wildfire suppression resulted in unnaturally dense conditions in many forest types, which is especially evident in the pine and mixed-conifer forests of the Sierra Nevada, Southern Cascades, and Transverse and Peninsular mountain ranges [32].

Forest loss from non-fire agents, particularly drought and bark beetles, is also increasing [41]. For example, the 2012–2015 California drought was characterized by large precipitation deficits and abnormally high temperatures [42] that incited outbreaks of bark beetles [43,44], which exacerbated tree stress in areas with unnaturally high tree densities. As such, the resulting levels of tree mortality were unprecedented [45]—altering fuels, increasing wildfire risks and impacts, and causing rapid declines in the amount of mature conifer habitat [41], some of which was realized in the 2020 Creek Fire. Future climate projections for California include greater frequency and intensity of drought and overall fuel aridity [46], enabling the likelihood, scale, and severity of future compound disturbances. Increasing fuel aridity has and will continue to increase wildfire danger in California's forests, highlighting the need for proactive management.

Shrubland and Chaparral Ecosystems

Nearly 32% of California ecosystems are shrublands and herbaceous, occupying ~26 million acres. In recent decades, the majority of burned area and losses of homes and other infrastructure have occurred in these vegetation types [20,24,47]. In coastal shrublands, naturally ignited wildfires are rare, and the historical fire regime is characterized by infrequent, large, high-severity crown fires [48,49]. Historical fire return intervals ranged from 30–150 years depending on site conditions, with some wildfires, dating back to the late 1800s, burning 24,000–125,000 ha, especially during annual Southern California Santa Ana wind events [50,51]. High fire severity is beneficial for chaparral recovery and for preventing the expansion of invasive grasses [52,53], and many chaparral species require intervals of 10–30 years between fires to regenerate and re-establish fire-stimulated seed banks. Despite the benefit of maintaining at least 30 years between fires, this interval is difficult to maintain, and the rate and extent of type conversion has been rapid due to frequent reburns [10]. Under extreme wind conditions, wildfires readily burn through young vegetation or mechanically treated vegetation. As such, fuels treatments are not expected to significantly alter fire behavior under these conditions [50,54,55].

Human population growth and expansion of the WUI have increased the distribution and frequency of human-caused ignitions in shrublands such that fire return intervals can be as short as five years [4,56,57]. While these short fire return intervals are common in Southern California, short-interval fires are threatening chaparral ecosystems throughout the state [58]. This shortening of intervals between fires has led to widespread conversion of native chaparral to more flammable invasive grasses [10,53,59], which increases landscape ignitability in a positive grass-fire feedback cycle [60,61]. On the other hand, prior-year precipitation has become an increasingly influential climatic driver in response to proliferation of invasive grasses; in particular, wet years increase herbaceous biomass, which becomes highly flammable during dry years [19]. Prolonged drought events may promote shrub dieback, which in turn can worsen fire behaviors during extreme fire weather conditions [62]. Drought also inhibits post-fire recovery, furthering the rate and extent of conversion of shrublands to grasslands [52,63].

Conclusions

The vulnerability of California’s forests, shrublands, and adjacent communities to wildfire are ecosystem and context dependent. Impacts in forests are primarily driven by seasonal climate effects on fuels, fire weather, land development, and fuel availability, the latter of which is influenced by past management, wildfire suppression, and interactions with other disturbances. Impacts in shrublands are primarily influenced by land development, fire weather, drought, and widespread conversions of shrublands to grasslands by uncharacteristically frequent, severe wildfires. Human-caused ignitions, particularly during extreme fire weather, are increasingly tied to the most destructive fire events in the state.

Ultimately the collective impacts to human life, property, and ecosystem goods and services have a pronounced economic effect that is not fully understood (see *Socioeconomic Implications* and *Ecosystem Risk Reduction Measures*).

Socioeconomic and Public Health Implications of Wildfires

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Key Message

Wildfires have substantial direct and indirect impacts on the health and socioeconomic well-being of the public in California and beyond (High Confidence). Wildfires cause direct losses to life and property, and smoke has far-reaching effects on human health and economic productivity (High Confidence). Fire-related expenditures and losses have ballooned in recent years, with unprecedented spending on fire suppression and billions of dollars of material and health-related losses, and these trends are expected to continue, at least in the near term (Likely). Wildfire smoke is and will continue to be a major driver of health-related losses from fire, contributing to thousands of premature deaths each year in California, as well as undesirable educational and labor market impacts (Likely). Wildfire will continue to have far-reaching indirect effects, including impacts on insurance and housing availability and affordability, utility rates, and natural resource markets (Likely). The economic and health impacts of fire and smoke disproportionately impact vulnerable communities, perpetuating and magnifying social inequalities (Likely).

Direct Impacts of Wildfire

Over the past two decades, people's direct exposure to wildfires in California has grown faster than in any other state in the continental U.S. [64]. From 2017–

2023, California wildfires killed 191 people, including 178 non-firefighting civilians [3]. Total direct property losses from California wildfires are estimated at $9.9 billion annually, based on CAL FIRE data from the 2017–2021 fire seasons [65]. The highly destructive extreme wildfire events (EWEs) of recent years are not anomalies; they reflect a long-term, accelerating trend toward larger and more destructive fires in the state [20]—a trend that is mirrored in state expenditures due to wildfire.

The long-standing fire management paradigm in the Western U.S. based on fire suppression has biased wildfires toward the highest severity and worst outcomes [66], compounding the effects of climate change, fuels accumulation, and other ecological factors [8,67]. Increased development in areas with flammable vegetation [5,27] increased human-related ignitions [68], especially during periods of extreme wind and fuel aridity [5], and the continued exclusion of fire from frequent fire-adapted ecosystems has exacerbated risk (*Wildfire Crisis Overview*). In California, the abundance of structures in flammable vegetation between 2010–2020 marked a 26% increase over the previous decade, and the structure loss rate increased 109% over the same period [5].

In California, wildfires are increasingly affecting more urban areas and socio-demographically diverse U.S. Census tracts, and those communities are disproportionately vulnerable, lacking adaptive capacity to withstand disaster [69]. Exposure of highly vulnerable populations to fire is increasing, up 249% in 2011–2021 compared with 2000–2010 [64]. This exposure can intensify the socioeconomic precarity of already vulnerable groups such as Latino/a, Indigenous [70] and Native American communities [69]. Considerations for Native American communities are multi-tiered, with heightened vulnerability to wildfire, but also to the exclusion of fire and cultural burning practices from ancestral lands, which poses a wide range of ecocultural threats (such as [71,72]).

The Effects of Wildfire Smoke

Although the direct effects of wildfire are significant, indirect economic and social impacts of wildfire in California exceed direct losses by an order of magnitude [65,73], mostly via wildfire smoke. In recent years, wildfires have contributed half of the total airborne fine particulate matter (PM 2.5) in Western regions and 25% of PM 2.5 nationally [74]. Wildfire smoke has undermined many of the air quality improvements from the Clean Air Act [75] and has impacted health, education, agriculture, and the labor market, with a disproportionate burden on vulnerable communities [4].

Key health-related wildfire smoke impacts include respiratory morbidity, adverse birth outcomes [76], increased demand for healthcare and emergency services [77–80], and increased risk of premature mortality [81]. Smoke exposure also negatively impacts the learning outcomes of school-aged children, with a disproportionate burden on students from non-White, economically disadvantaged communities [82]. People with preexisting respiratory conditions, middle-aged and older adults, children, and pregnant women are more susceptible to these effects [2].

Outdoor workers are particularly vulnerable to smoke pollution. This includes firefighters and fire practitioners, who suffer disproportionate exposure to wildland fire smoke and toxins in protective clothing, fire retardants, and post-fire landscapes. Research estimates that wildland firefighters are exposed to a 43% increased risk of lung cancer and a 30% increased risk of cardiovascular mortality [83]. Farmworkers are also a group of critical concern, as the coincidence of harvest season and wildfire season can add to an already high ambient air pollution burden in many agricultural regions in California [84]. The future is likely to bring more air quality impacts to these regions [85], exposing workers to increased wildfire smoke as well as smoke from prescribed burning [86]. However, perceptions of wildfire smoke exposure risk vary among farmworkers and employers, leading to variability in intervention implementation and effectiveness [87].

California wildfire smoke between 2017 and 2021 created an estimated annual mortality burden of between $15-$45 billion [88,89]. There is initial evidence that the labor market impact of smoke due to loss of productivity could be of a similar magnitude [65,90]. Wildfire smoke can also cause economic losses in the agricultural sector; for example, in 2020, the California wine industry suffered $4.2 billion of smoke-related losses [4,91], and the legal cannabis industry lost $1.4 billion [92].

Given the inevitability of wildland fire and smoke in California, it is important to consider tradeoffs of smoke from beneficial fire versus a severe wildfire. Beneficial fire provides opportunity for smoke management planning and strategic health interventions, and it may differ in composition and toxicity from severe wildfire smoke, especially from urban conflagrations. Beneficial fire also reduces burn severity and emissions from future wildfire [93]. And recent research on California's 2020 wildfire season found prescribed fires decreased wildfire burn severity by 16% and led to a net reduction of 14% in smoke emissions [94].

Other Socioeconomic Impacts

Beyond the flames and smoke, wildfire risk creates additional indirect threats to social and economic well-being across California. Insurance availability and affordability have become critical issues in recent years, as mismatches in wildfire risk and allowable insurance pricing have forced many insurers to pull out of California markets, leaving homeowners with limited, costly options and susceptibility to significant financial losses [95]. These conditions may also lead to out-migration from California to other less wildfire-impacted areas. Wildfire and smoke may also negatively impact housing prices [96], natural resource markets [97] and utility rates, as risk mitigation efforts are reflected in utility pricing [98].

It is important to note that concepts and ideas of community wildfire impacts are often framed narrowly as the impacts to people who own property. Fire prevention and recovery efforts should include renters, low-income families, the unhoused, non-English speakers, and others who are also impacted by losses and costs associated with wildfire [99].

Knowledge Gaps and Future Considerations

As wildfires impact increasingly diverse communities in California, there is a need to better understand the full spectrum and potential nuances of impacts and their interactions, including human health implications, housing and insurance availability and affordability, displacement, and gentrification. Our current homeowner-centered approach leaves critical gaps in disaster resilience. There is a need to reexamine notions of community, ensuring that the most vulnerable are considered and included in fire planning, response, and recovery.

On the public health side, there is a need to clarify the extent to which wildfire smoke is a risk factor for cardiovascular health outcomes [78,100,101]; characterize the differing toxicity profiles of wildfire smoke, beneficial fire smoke, and other pollution sources (such as [102]); and parse the potentially differing impact of short- versus long-term exposure profiles [103]. Understanding how behavioral responses may mitigate or exacerbate health impacts from infrequent, high-severity smoke events is important for assessing future impacts [79,104]. These uncertainties currently impede our ability to accurately attribute health and economic costs to wildfire.

There is also a need to understand how smoke exposure interacts with other types of health burdens [105], including environmental exposures like extreme heat [106] and combustion of pesticides during burning [107], as well as respiratory illnesses like Valley Fever [108] and COVID-19 [109]. These concerns are magnified in agricultural regions, where there is a need for improved monitoring networks to better understand air pollution [110], the influence of wildfire smoke on agricultural livelihoods (such as [111]), and the effectiveness of interventions specifically designed to reduce individual farmworker exposure [112]. There is also a need to better understand smoke impacts on crops; for example, smoke exposure in wine grapes is of increasing concern, requiring attention for other potentially vulnerable crops and agrosystems [91].

While there is a broad understanding that certain groups are particularly vulnerable to health impacts from wildfire smoke, more work is needed to clarify vulnerabilities and identify effective interventions. The diversity of California's workforce and communities requires more multilingual and audience-specific messaging around fire and smoke. There is also a need to better develop communication strategies and enforce protections for outdoor workers who face disproportionate risks and impacts [70,113,114]; this necessarily includes firefighters, as the demand for and risks of fire-related work grows in California [83].

Protecting Communities from Wildfire Through Land Use Planning and Design

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Key Message

Designing and retrofitting communities to be fire resistant and resilient will lessen vulnerability (Medium Confidence); this includes structure and home hardening (High Confidence). Land use planning that guides where and how development occurs is a critical tool for reducing wildfire risk and exposure (High Confidence). Attention to and investment in community and public engagement is necessary to achieve outcomes (High Confidence). Wildfire impacts to human communities could be reduced through planning that reduces fire exposure and ignition prevention, particularly during extreme fire weather (High Confidence). Defensible space immediately surrounding structures reduces wildfire risk (Likely). The efficacy of planning activities, community engagement, home hardening, and defensible spaces will often improve when efforts are adapted to suit local conditions (Medium Confidence).

The Planning and Design of Safe Communities and Fire-Resistant Parcels

California has a long history of regulating development in fire-prone areas, including requirements for emergency access, water supply, and vegetation management. Since the 1960s, state policies have shaped how subdivisions are approved, and California Public Resources Code §4291 established defensible space standards. Chapter 7A of the California Building Code (CBC) further strengthened regulations by requiring ignition-resistant construction in high fire hazard areas. These policies represent sustained state investment in land use planning to reduce wildfire risk, but more can be done to ensure consistent implementation, address legacy developments, and proactively guide future growth away from high-risk areas.

Many researchers argue that while large-scale land management efforts, including those focused on forest resilience, are important, they address only part of the challenge in reducing risk in the wildland-urban interface (WUI) [115]. Instead, these challenges are primarily shaped by the built environment, the adjacent landscape, and the local community. The location, pattern, and arrangement of homes are the best predictors of structure loss in California, and this is because fire exposure is the first condition that must be met for fire impacts to occur [116–120]. In general, while per-structure risk of loss is often higher in lower-density, dispersed housing arrangements [117], structure-to-structure ignition becomes a dominant mechanism in very high-density areas, reversing the relationship beyond a certain threshold [121,122]. However, total structure loss is often greatest in interface WUI areas where large numbers of homes are exposed to fast-moving wildfires. Given their potential to prevent fires from reaching assets in the first place, strategies for designing and building new developments with wildfire in mind [123] are critical for reducing future risk. However, because so many homes already exist in fire-prone areas, retrofitting and addressing risks in existing communities remain equally essential [124]. A comprehensive approach will require both forward-looking planning and ongoing investment in adaptation.

Community Planning

While implementing community planning strategies for wildfire resilience can be complex, there is strong consensus around many effective approaches, as outlined in expert guidance and planning frameworks [125]. The greater challenges often lie in securing funding, prioritizing investments, and adapting strategies to local contexts to ensure equitable and sustained outcomes.

To accommodate new housing opportunities that simultaneously reduce exposure to wildfire requires builders arrange structures in ways that reduce the interface between housing and wildland vegetation. Thus, expanding access to housing via urban infill or by expanding urban areas radially has a higher likelihood of reducing fire exposure than creating new leapfrog, dispersed development patterns [123,126,127]. Well-designed road networks are also essential, with roads that are wide, as straight as possible, and interconnected to facilitate both swift evacuation and efficient access for emergency vehicles [128].

If infill or expansion cannot be achieved, housing layout for new construction also plays a critical role in fire resilience, with homes clustered together, on the inner side of perimeter roads, using fire-safe design principles (Figure 1). The physical setting of a community further influences wildfire vulnerability, as developments situated on flat or gently sloping terrain tend to be at lower risk compared to those on exposed ridges or steep slopes [129,130]. New construction is also safer if located in areas without a history of wildfires [116]. Integrating energy resilience into planning is another crucial factor, with localized power sources and underground transmission lines reducing the likelihood of ignition from downed or damaged infrastructure [131]. In areas where development is already in place, targeted vegetation management, such as maintaining clearances under and around powerlines, remains a critical strategy for reducing ignition risk and protecting communities.

Early wildfire detection can further strengthen community safety, with advanced warning systems that incorporate in-situ sensors providing real-time monitoring and rapid response capabilities [132]. In cases where evacuation is not possible, a designated temporary refuge area—centrally located, free of vegetation, and capable of providing a last line of protection—can be lifesaving [133]. These refuge areas could also be public facilities like schools, nursing homes, or hospitals to protect vulnerable populations [123].

However, reducing loss of life requires more than detection and sheltering. Effective evacuation planning must include multilingual alerts, provisions for people with disabilities or medical needs, and support for livestock evacuation. Strengthening social networks and local preparedness can also help ensure that vulnerable populations are not left behind during wildfire events.

Finally, ensuring access to sufficient water sources, including nonelectric and backup supplies for fire suppression, is critical for community resilience [134]. Additionally, larger neighborhoods can benefit from surrounding strategic fuel breaks, particularly in areas bordering wildlands [134–136]. However, it should be noted that strategic fuel breaks require firefighter presence to function effectively [54].

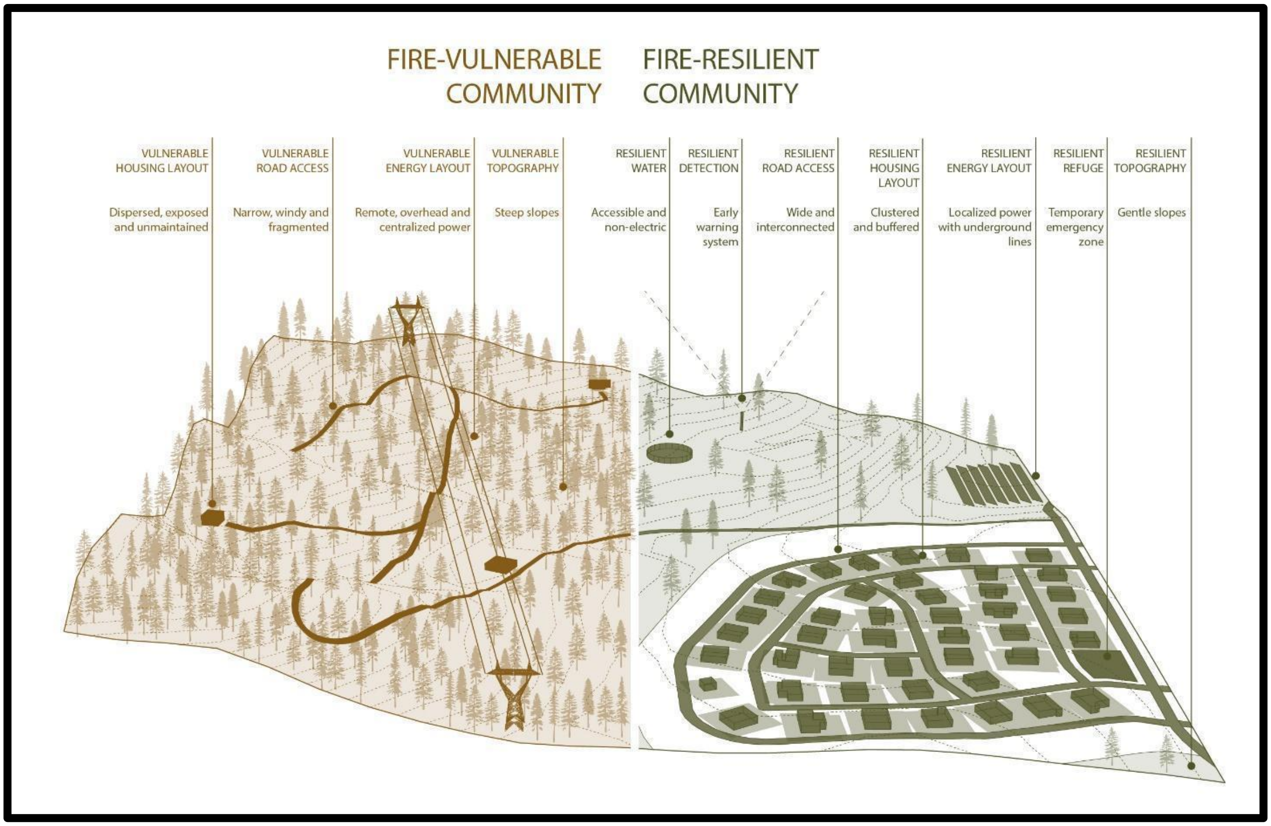

Figure 1. Community planning and design principles. The left half of the figure illustrates measures and characteristics that increase the vulnerability of a community to fire, whereas the right side of the figure outlines key measures that lend to increased community resilience to wildfire.

Homeowner Mitigation Measures

In addition to community design measures that can reduce fire exposure, measures can also be taken within the home ignition zone (HIZ) of existing communities to reduce the severity of fire impacts if a fire does occur. Creating fire-resistant parcels requires a combination of home hardening and defensible space strategies, both of which significantly reduce wildfire risk (Figure 2; [137–139]). Studies have shown home hardening through fire-resilient structural features to be a stronger correlate with structure survival than defensible space [121,140,141] by minimizing ignition risks from wind-blown embers—the leading cause of structural loss during wildfires [142]. To that end, measures most strongly associated with structure survival include closed eaves and soffits, ember-resistant vents, and sealing gaps in the building envelope with fine mesh [140,143–146]. Double- or multi-pane windows are also among the most significant protectors [121,140]. Structural modifications like enclosing eaves and decks, detaching fences, and replacing vulnerable roofs, siding, and single-pane windows can be costly. These expenses can be burdensome, especially for socially vulnerable populations, who are also more likely to experience a wildfire [147]. That being said, research indicates that building a home with enhanced wildfire-resistant features is not significantly more expensive than constructing a standard home that meets CBC Chapter 7A compliance requirements, where the exterior of a structure must be flame-resistant and ember-resistant during a wildfire [148]. Proper site design also plays a critical role in fire resistance, with driveways wide and straight enough for emergency vehicle access and backup water supplies readily available.

Beyond home hardening, defensible space strategies can reduce fire risk to structures by removing combustible vegetation and infrastructure (such as propane tanks, wood fences, and wood piles), creating vertical and horizontal breaks in fuel continuity, or maintaining high-moisture plants that can absorb embers [122,149,150]. Defensible space immediately adjacent and five feet from the structure ("Zone 0") provides the most significant protection, and defensible space beyond Zone 2 or 100 feet adds no significant additional protection [137]. However, it should be noted that defensible space recommendations vary depending on vegetation type; for example, strategies in chaparral ecosystems may differ from those in forested areas due to differences in fuel structure and fire behavior. Lastly, while individual property modifications are essential, wildfire resilience is most effective when property owners collaborate with their neighbors.

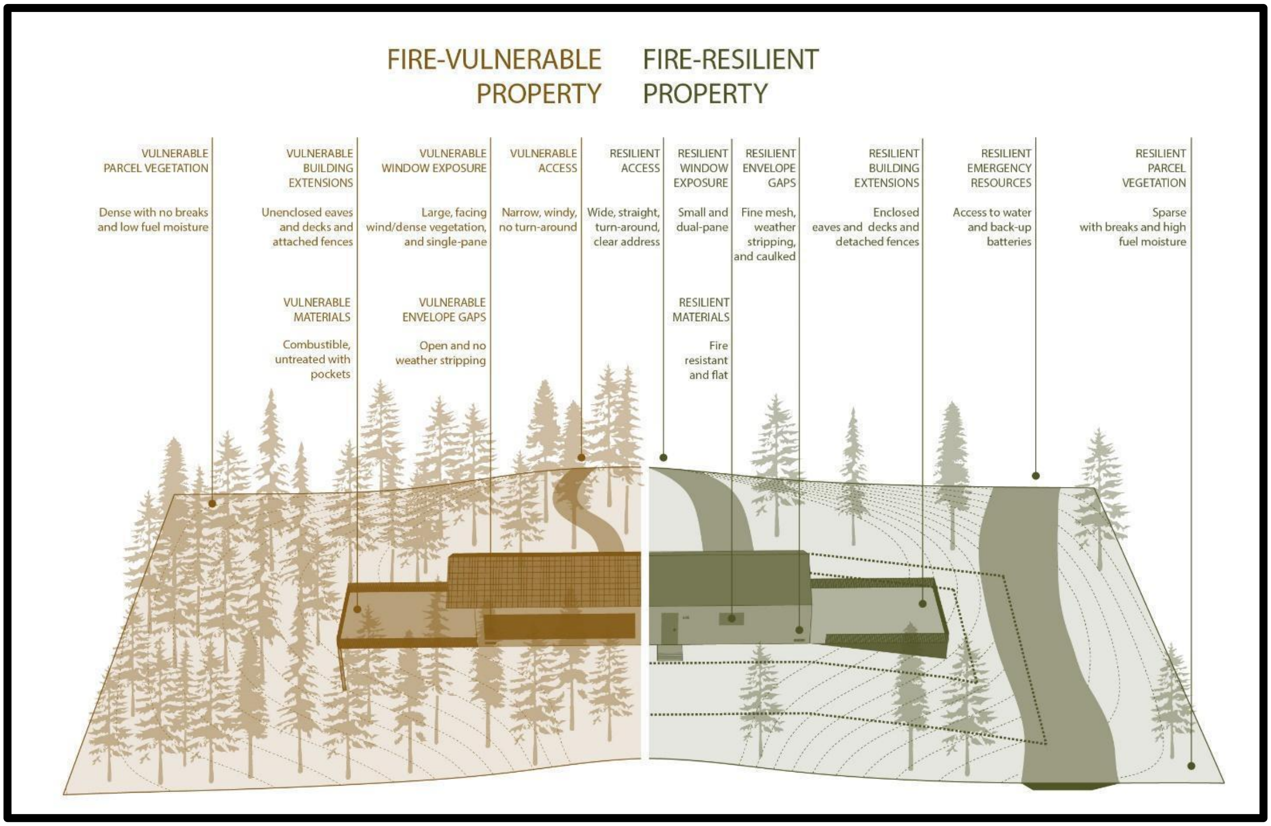

Figure 2. Structural and home hardening principles. The left half of the figure illustrates measures and characteristics that increase the vulnerability of homes and property to fire, whereas the right side of the figure outlines key measures that lend to increased home and property resistance to wildfire.

For thousands of communities already located in fire-prone environments, a variety of risks must be prioritized and mitigated. In these cases, a framework like the Regional Wildfire Mitigation Program (RWMP) takes a comprehensive approach by addressing multiple fire-related risks. The RWMP addresses: (1) retrofitting of the built environment (i.e., structural ignition vulnerabilities, water supply deficiencies, evacuation constraints), (2) buffering the landscape (i.e., less flammable land uses complementing traditional fuel breaks) and (3) training the community (i.e., public education and capacity building to support fire-adapted behaviors and decision-making). The RWMP integrates mapping and risk analyses, ensuring wildfire mitigation efforts are strategically prioritized based on risk rather than convenience or stakeholder influence [124].

Community and Public Engagement

Increasing proactive public action to achieve wildfire resilience is critical because a lack of place-based knowledge, local expertise, community capacity, and shared responsibility can heighten the consequences of fire, especially in highly exposed communities [151]. Ensuring engagement in socially vulnerable communities is particularly important because these groups often face systemic barriers to participation in wildfire mitigation efforts, such as limited access to financial resources, exclusion from decision-making processes, and preexisting socio-economic stressors that make recovery more difficult [69,70,152].

Thus, ongoing engagement must account for (1) trust in information providers and management practitioners, (2) the use of interactive communication processes, (3) the efficacy of actions, (4) the capacity to implement them, and (5) local motivations, values, and barriers [153,154].

Engagement programs tailored for the context of local community conditions are the most effective at building capacity to act and for the potential effectiveness of those actions [154]. Because of the importance of local context, a single program may not be appropriate for all locations. Public engagement plays a key role in encouraging risk-reducing actions—such as defensible space maintenance, evacuation planning, and home hardening—particularly when designed in partnership with the community. Engagement to drive uptake of risk-reducing actions is especially important for community members who face heightened risks during evacuation and recovery, such as older adults and people with limited mobility.

Knowledge Gaps and Future Considerations

A forward-thinking approach to designing fire resistant and safe communities involves developing effective land-use planning, implementing effective building codes for new developments, and prioritizing policy measures focused on retrofitting existing homes to ensure long-term community resilience.

Several knowledge gaps exist at the structure and community scale, both before and after a wildfire. Before a fire, specific strategies and guidance for how closely to cluster new structures and how to safely build on slopes are needed. At the community scale, an improved understanding of how different land use and development practices may increase or decrease wildfire risk is also needed. Determining a mitigation threshold (e.g., what proportion of homes must be effectively hardened to reduce risk) could also guide effective planning for existing communities. Importantly, given the geographical variability of wildfire across the state [18], research is needed to understand the extent to which the effects and effectiveness of different resilience measures vary from region to region. Additionally, future research could explore how to modernize water infrastructure in older, nonconforming communities and the long-term implications of shifting responsibility for road development from public to private entities, particularly in terms of maintenance and standards [124].

Insurance availability and affordability is another critical area for further study, especially as coverage increasingly depends on how homes are built, maintained, and located in relation to wildfire risk. A better understanding of how design and mitigation efforts affect insurance markets could help align homeowner incentives with fire-resilient planning and construction. Equally important is providing clear guidance on how individual homeowners can prioritize investments—such as home hardening, defensible space, or backup power—based on their budget, parcel characteristics, and surrounding landscape context. More applied research is needed to match specific mitigation strategies to setting, and to evaluate which combinations yield the greatest risk reduction and insurance benefits.

After a fire, building (both rebuilding and construction of structures that were not present prior) presents an opportunity to change home construction and community layout, but because public and political pressure to build back quickly is strong, planning for how to respond after a fire must occur before the fire [120]. Understanding how communities successfully balance the pressure between rebuilding better and the need to rebuild quickly would be beneficial. For instance, strengthening existing building codes or extending building codes like CBC Chapter 7A beyond wildland-urban interface fire areas and fire hazard severity zones, while challenging, could encourage homeowners to rebuild more safely.

Despite the many benefits of community outreach and engagement of the public in relation to building trust and capacity, demonstrating the benefit of outreach and engagement to reduce wildfire risk is difficult. More data on the efficacy of proactive community mitigation actions are needed. Future research could also explore effective strategies for engaging socio-economically vulnerable communities in wildfire resilience efforts, particularly those without established leadership structures [124]. Additionally, there is a need to expand community-based beneficial fire, overcome potential workforce limitations, increase incentives, and decrease liability concerns [155]. Understanding how communities achieve these goals while ensuring their work and mitigation actions are economically sustainable, given their local context, is necessary to further increase community involvement.

Wildfire Impacts to Ecosystems and the Services and Values They Provide

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Key Message

Changes in fire severity, frequency, and size have imperiled ecosystems throughout the state, resulting in altered vegetation structure and degraded ecosystem function (High Confidence). Extreme wildfire events in forests and shrublands can thwart postfire recovery and lead to long-term vegetation change, impacting carbon storage, watershed services, biodiversity, cultural services, and provisioning services such as water (High Confidence). These trends are expected to continue for years to decades (Very Likely).

Ecosystem Structure and Integrity

Changes to forest structure and composition, coupled with a warming climate and its effects on aridity [156], have led to significant increases in burn area and severity in forested ecosystems across California [157]. Mature and old-growth stands in seasonally dry, fire-adapted forests in the Western U.S. are at particularly high risk of loss, due to long-term lack of fire, heavy fuel loadings, and high live fuel continuity [41,158]. Forests in California that burn in extreme wildfire events (EWEs) may lack living seed sources and are often replaced by shrublands that greatly impede natural or artificial forest recovery [159], potentially leading to reburn by high-severity wildfire [160]. Where severe burning has occurred more than once within a decade or two, shrubs or non-native grasses may replace forest cover, producing higher fire hazard and degradation of multiple ecosystem services [7] (Box 1).

In shrubland ecosystems, especially chaparral, sagebrush, and sage scrub, increasing fire frequency due to human-caused ignitions is driving vegetation type conversion to highly flammable grasslands dominated by non-native annual species [58,161]. Shrubland dieback and conversion is also influenced by drought [62,162], with postfire drought playing a particularly important role [163]. The resultant dynamic is referred to as the "grass-fire cycle" and can permanently prevent landscapes from supporting dense woody shrub cover or furnishing the ecosystem services they once provided [28,164,165] (Box 1).

Water and Watershed Services

Watersheds provide ecosystem services that sustain lives and livelihoods in California. Watershed degradation is one of the ways that EWEs threaten the health and resilience of California's ecosystems (see [166]). After the combustion of vegetation and litter on the soil surface, wildfires can result in increased water runoff and limit groundwater recharge [167,168]. However, the magnitude and persistence of this effect vary by the severity and size of the wildfire [168–170], aridity [168,171], changes in subsurface storage [172], and postfire vegetation recovery and structure [166].

Wildfires are a major driver of soil degradation, nutrient loss, and alteration (e.g., creation of a hydrophobic or water-repellent layer), impacting ecosystem productivity and diversity at the burn site and downstream [167]. Because of EWEs, soils typically experience reduced water infiltration and increased runoff; areas burned in these events pose a significantly higher flood hazard relative to unburned areas [173], causing additional constraints on already stressed reservoir operations. While increased runoff can augment hydropower [174], increased sedimentation may be a major threat to hydropower and other critical built infrastructure such as reservoirs and roadways [175–177]. Post-fire sediment and debris flows can also devastate communities located downslope from the fire footprint (see *Post-Fire Recovery*).

At higher elevations, wildfires may alter snow accumulation and melt due to changes in canopy shading and snow reflectivity. The resultant conditions can facilitate more snow reaching the ground, but trend toward lower peak snowpack levels, shorter snowpack duration, and faster and earlier melt out [178,179]. Lastly, wildfire smoke can have profound implications for cold-water organisms, amphibians, and aquatic species in lakes, even in regions far away from fires [180].

Carbon Storage

California's wildlands play a critical role in carbon storage and cycling (Box 1). Wildfires within the historical fire regime can preserve landscape carbon stocks by stimulating seed germination, replenishing soil nutrients, maintaining habitat diversity, and thinning overly dense forests to encourage open stand structure, thereby reducing risk of EWEs [9,181,182]. As in many other parts of the world where increased fire severity and magnitude threaten carbon stocks [183], it is generally accepted that California's landscape carbon storage will decline throughout the 21st century due, in part, to limited forest recovery following EWEs (see *Post-Fire Recovery*).

In forests, EWEs drive change in carbon uptake and storage by limiting tree seedling recruitment and slowing postfire regeneration [184–186]. Paci et al. [65] estimate wildfires between 2017–2021 will result in an average loss of 39% of California forests' carbon storage capacity at 20 years postfire, even with partial regeneration. In shrublands, EWEs lead to loss of landscape carbon storage when woody shrubs are replaced with other vegetation types such as annual non-native grasses, which have a lower capacity for carbon storage (see *Wildfire Crisis Overview*; [59,119]).

Wildfire emissions and their subsequent impacts on vegetation productivity are a major driver of the carbon balance on natural lands in California. In years where wildfire extent is extensive (e.g., 2008, 2020, 2021) the state's natural and working lands become a net emitter of carbon [187]. The contribution of wildfires to emissions is strongly related to both the area burned and the fraction burned at high severity. Contrasting wildfire emissions to other sectors illustrates the scale, though the comparison is imperfect because the original carbon sources differ. In 2022, a mild fire year in which 300,000 acres burned, California wildfire emissions (9 MMT CO2e) were equivalent to 6.5% of emissions from transportation (140 MMT CO2e), the largest emitting sector. In a record fire year such as 2020, where 4.1 million acres burned, wildfire emissions (107 MMT CO2e) were equivalent to 79% of transportation-sector emissions (135 MMT CO2e) [188,189].

This level of CO2 emissions has an estimated annual social cost of $12.3 billion, excluding the health impacts of wildfire smoke [190]. Forest losses from wildfire also complicate California's carbon offset markets. Beyond releasing stored carbon into the atmosphere, large wildfire events erode the financial and environmental logic of credits tied to forest carbon stocks [191].

Biodiversity

The combination of California's diverse climate, geology, topography, and disturbance regimes (e.g., wildfire) supports more native biota than any other state in the U.S. [192]. Many species in California are adapted to fire, in some cases requiring fire to persist, but even fire-adapted species are threatened by EWEs [181]. In California, spatial and temporal changes in landscape-scale patterns of fire (i.e., size, severity, season, and postfire recovery) can have significant impacts on biodiversity [181,193]. These impacts vary based on factors such as a species' range, niche breadth, sensitivity, population size, and co-occurring stressors that include climate change, land use change, and the presence of invasive species [192,194].

In forested ecosystems, studies have shown EWEs have negatively affected the habitat and associated population dynamics of species across all taxonomic groups [181,195–197]. Forest species with small, discrete populations and limited distribution, like the giant sequoia [198,199], California spotted owl [200], and bigcone Douglas-fir [201] are particularly vulnerable to large-scale, stand-replacing wildfires. For example, a single fire in 2020 killed 7,500–10,600 large-diameter (>4 ft) giant sequoias. This mortality event represents a loss of 10% to 14% of all large-diameter giant sequoias in California, whose natural range is limited to the western slope of the Sierra Nevada mountains [202].

Biodiversity in shrublands and woodlands is threatened by the increasing frequency of fires, which can inhibit habitat recovery and the recovery of wildlife populations that depend on them. Of particular concern are habitat specialists such as the California gnatcatcher [203], Hermes copper butterfly [204], or obligate seeding shrubs like those in the genus *Ceanothus* spp [205]. Because shrubland, woodland, and grassland ecosystems cover more acres in California than do coniferous forests [47], fires in non-forested ecosystems are likely to affect a larger number of endemic species, degrade areas of high species richness, and burn adjacent to human communities where postfire recovery may be more challenging [206].

Impacts to Cultural and Resource-Provisioning Ecosystem Services

EWEs that alter ecosystem structure and function also impact the provisioning services they supply like food, fresh water, timber, fuel, fiber, and other goods. Between 2018 and 2021, timber losses due to large fires in California’s industrial timberlands (>10,000 acres) were valued at approximately $12.6 billion [207]. Similarly, loss of forage for livestock and wildlife can persist for years following a fire; high-severity fire can cause losses of more than 75% of forage for at least three years postfire, with impacts to rancher livelihoods and the health of rangeland ecosystems [208,209].

EWEs impact cultural ecosystem services including recreation; the aesthetic and cultural benefits offered by landscapes including a sense of place, spiritual enrichment, and cognitive development [210,211]. While the presence of smoke in recreation areas does not generally deter visits in the Western U.S. [212–214], wildfires can yield disadvantages to recreation, especially after large crown fire patches or in areas with complete vegetation loss [215]. Migration rates into U.S. counties with high levels of environmental and recreational amenities may be disproportionately impacted by extreme heat and wildfire events [216], potentially leading to economic downturns associated with attracting residents and visitors. Within the U.S., rates of roadway exposure to large fires are highest in California, with an increase of 80 miles per year from 2000 to 2019; damage to roadways from fire can inhibit access to recreation and other societal services [217]. However, people's experiences of recreating in burned landscapes are not always negative and depend on the recreational amenities they seek (e.g., hiking trails versus picnic areas) [215,218].

Importantly, the effects of both fire suppression and vegetation type conversion resulting from EWEs can negatively impact Indigenous groups' gathering of materials for food, medicine, and fiber from both forests and shrublands in California. Such practices are an important expression of biocultural sovereignty for these groups [219–221].

Knowledge Gaps and Future Considerations

A top management priority for California's diverse landscapes is conserving ecosystems and ecosystem services that have not yet been impacted by EWEs. Efforts to protect landscapes that are both vulnerable to wildfire and support key ecosystem services (e.g., cultural, natural, and biological assets) can offer the greatest opportunity for desirable outcomes (e.g., [222]) to both ecosystems and communities that are increasingly being impacted by wildfire [223]. Standout opportunities include:

- The production of reliable and up-to-date structural datasets for forest and non-forest vegetation (e.g. tree density by size class, surface fuels, and shrub architecture) is instrumental to identifying vulnerability (see *Data and Technologies*). This can be achieved by incorporating LiDAR and canopy height modeling technologies with existing data to improve mapping products. With regular updates, such efforts can help quantify biomass and carbon storage changes over time.
- Research and mapping products that deepen our understanding of wildfire impacts on key ecosystem services and their recovery, including the preservation of biodiversity and at-risk taxa [206] as well as cultural values will help to develop ecosystem-specific stewardship and adaptation strategies throughout California.
- To preserve shrubland ecosystems, effective ignition reduction strategies that reduce the likelihood of frequent repeat burns, especially in areas of high human populations are greatly needed.

In ecosystems already degraded by EWEs, restoration and reforestation efforts aimed at restoring the integrity of ecosystem processes are critically needed (see *Post-Fire Recovery*). To do so, the development of statewide vegetation type conversion maps, and the development of corresponding restoration objectives as they relate to ecosystem function including water provisioning, carbon storage, biodiversity, and cultural uses are essential. Further research into tipping points and thresholds associated with biodiversity loss is also needed. Continued studies of postfire recovery dynamics of different ecosystems (e.g., plant physiological responses), coupled with a better understanding of climatic influences on regeneration, will help inform where ecosystems may recover without intervention and where restoration may be both necessary and successful (such as [159,224]).

In all cases, conservation and restoration efforts in California should focus on retaining biodiversity and ecosystem function in locations that rank high across multiple services (i.e., hotspots). An important approach to motivate action is programming that connects the public to ecosystems recovering from fire, educates about the benefits and challenges of fire, and demonstrates the need for postfire management action to secure long-term ecosystem persistence (see [218], *Post-Fire Recovery*).

Box 1. Fire Effects on Forest and Shrubland Ecosystems

The forests and shrublands of California evolved under starkly different historical fire regimes: many of the state's forests experienced frequent fires of low or moderate severity, whereas shrublands typically experienced infrequent fires of high severity. Today, the fire regimes of both ecosystems are significantly altered, which has contributed to changes in the structure, composition, and diversity of species, and, as a result, the services these ecosystems offer. To mitigate the impacts of current fire regimes, managers of both forests and shrublands need high-quality spatial data to track and prioritize areas in need of treatment, as well as resources to pursue restoration and ignition-reduction efforts.

	California Forests	California Shrublands
Vegetation Description	• Conifer forests cover 17% of land in California; hardwood forests cover 5% (1) • Historical fire regimes: short-interval, low-to-moderate severity fires	• Shrublands (chaparral, sage scrub, and sagebrush) comprise 13% of land cover in California (1) • Historical fire regimes: long-interval, high severity fires
Characteristics of Current Fire Regimes	• Fire deficiency and fuel accumulation, especially of small-diameter trees • Vulnerability to large scale, high severity burns	• Excess human-caused ignitions, resulting in too much fire • Vulnerability to short-interval fires
Ecosystem Impacts from Current Wildfire Regimes	• High fuel continuity across landscapes • Loss of conifers and forest cover, conversion to shrubs • Potential for high severity reburns • Loss of wildlife habitat and impacts to biodiversity	• Loss of native shrubs and conversion to nonnative, fire-prone vegetation • Development of fire-grass cycle • Loss of native species richness and diversity
Current Wildfire Impacts to Ecosystem Services (Both Types)	• Carbon storage on landscapes reduced • Erosion and debris flows more likely • Watersheds and water quality degraded • Economic losses (e.g. timber)	• Cultural uses and aesthetic value impacts • Recreation opportunities altered • Infrastructure exposure (e.g. roads, powerlines)
What is Needed to Mitigate Current Wildfire Impacts (Both Types)	• Develop high quality spatial data statewide (e.g. vegetation, carbon, watershed services, biodiversity) to identify areas already impacted and areas most in need of protection • Increase ignition reduction efforts, particularly in shrublands • Undertake active reforestation, forest restoration, and restoration of shrublands	

(1) California Department of Forestry and Fire Protection's Fire and Resource Assessment Program. Forests and Rangelands Assessment (2025, DRAFT).

Applications and Approaches to Reduce Extreme Wildfire Risk and Impact to Ecosystems

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Key Message

Vegetation management, including mechanical treatments and the use of beneficial fire, can reduce wildfire hazard and negative impacts of extreme wildfire events to forests that historically burned with frequent low to moderate severity fires (High Confidence). Fuel treatments, especially the combination of thinning from below and prescribed fire, can effectively reduce wildfire hazard and severity, but effectiveness depends on ecosystem type and declines with smaller treatment units, particularly under extreme burning conditions (Medium Confidence). Strategic fuel breaks facilitate suppression operations and may slow the rate of wildfire spread (Medium Confidence). To align California's conifer and mixed evergreen forests to meet long-term goals of resilience, the pace and scale of fuel treatment implementation, with re-treatment every 10–20 years, should increase (High Confidence).

Societally critical ecosystem services, such as water, carbon sequestration, energy generation, and mature-forest wildlife habitat [41] are under threat by extreme wildfire events (EWEs; *Impacts to Ecosystems*). Across California, restoring fire as a keystone process on its own is rare, but Yosemite and Sequoia-Kings Canyon National Parks are notable exceptions. In many cases mechanical fuels reduction is first needed to both guard from EWEs and allow for future reintroduction of fire to maintain an ecological resilient condition [8]. There is scientific consensus that the scale of the management challenge cannot be addressed with the level of current action [225] and in the face of increased ecological stress from climate change (i.e., warming, atmospheric drying, and drought) [46,226].

Value of Vegetation Treatments and Beneficial Fire

Planning vegetation treatments to reduce wildfire hazard requires careful consideration of site-specific conditions (e.g., vegetation type, topography) and landscape-level considerations (e.g., potential control features and adjacent treatments to contain fires and the benefits of fuel treatments outside of treated areas; [227–229]) to optimize human safety and ecological integrity. Planning efforts are important, but increasing the pace and scale of implementation is critical for creating resilient landscapes in frequent-fire adapted ecosystems [225,226,230]. To maintain effectiveness, every new acre treated in forests or woodlands requires retreatment every 10–20 years in perpetuity [231], which could be accomplished with the occurrence of low- to moderate-severity fire. The state's current goal of treating 1 million acres/year is a good beginning, but more will need to be done to increase the resilience of California's ecosystems and human communities (Table 1).

Table 1. Potential acreage treated and re-treated under a 1M acres/yr. implementation target

Treatment Time Frame	Goal: 1M acres treated/year	Acres Burned Historically [30]
New Acres Treated (2025 - 2040)	16M	67M
Acres Re-treated through 2040 (15-year interval)	2M	8.4M
Total Acres Treated	18M	75.4M

Note: Historical acres burned include all California forests, woodlands, grasslands, and wetlands (no shrublands or deserts). The historical acreage burned serves as a reference point rather than a target; [30] reports fire return intervals by ecosystem type.

In conifer forests, combined mechanical thinning from below (cutting and removing the smallest trees while leaving the largest trees) followed by prescribed fire is the most effective strategy to reduce wildfire hazards [232–235] and to increase forest resilience [236]. Prescribed fire alone can be an effective tool when ladder fuels (smaller trees) are reduced along with surface fuels [233,234]. While burning in high-density forests is possible, it can be operationally challenging [237–239], particularly in the wildland urban interface (WUI) [240,241]. Furthermore, meaningful reductions in density of moderate sized trees (> 18 inches in diameter) with prescribed fire alone is difficult since they have developed thick bark and tall crowns. When fuel reduction treatments do not integrate beneficial fire, they rarely mimic the broad beneficial role of wildfire [242], which performs many beneficial functions such as nutrient cycling, facilitating tree regeneration, and promoting valued cultural and aesthetic resources [243]. As a result, areas treated using mechanical fuel treatments alone will not fully restore fire-adapted ecosystems, but they still can achieve important fuel reduction and drought resistance goals [229,236].

Fuel treatments can improve initial firefighting response when fires start within or near treated areas [244,245] and facilitate continued firefighting as fires spread. Treatments also support evacuations and can be used for firing operations or contingency lines [244]. They can improve resilience of forests to future fires, droughts, and bark beetle attacks, and post-wildfire, they can reduce recovery costs and reforestation needs by lessening tree mortality (see *Post-Fire Recovery*; [233,234,246]). Treatments can also reduce the chance for EWE behavior when areas burn that previously experienced severe tree mortality from drought and bark beetles [247].

Wildfires managed for resource benefits can also improve forest resilience [246,248–251], water resources [252], and drought resistance [229]. Beneficial fire, a treatment type that includes prescribed burning, cultural fire practices, and managed wildfire, should be encouraged to increase the resilience of forests and oak woodlands while mitigating fire risk.

In Southern California shrublands, however, increased use of beneficial fire is not recommended in large areas, as fires in many areas are occurring too often [56]. Frequent disturbance, including wildfires and fuel treatments, can lead to ecosystem degradation and invasion by non-native flashy fuels that are readily ignitable [58,119,253,254]. In these areas, reducing human ignitions is particularly essential (see *Wildfire Crisis Overview*) and the Southern California Ignition Reduction Program is managing non-native roadside vegetation to reduce ignition potential.

Treatments in shrublands reduce fuels, which can aid suppression actions to limit fire extent, but often introduce non-native plants to the ecosystem and risk converting shrublands to non-native grasses [255–257]. The recent California Department of Conservation report on managing risk in Southern California thoroughly summarizes key issues [258] and professionals with wildfire experience in this region can also offer insights (Box 2). In grasslands and woodlands, prescribed fire can moderate wildfire behavior, but longevity is relatively short, at two to three years [259,260]. Livestock and targeted grazing can be effective at reducing annual grass fuels and therefore, fire hazard [261–265].

Strategic Fuel Breaks

In forests, shaded fuel breaks reduce wildfire behavior [266], but they must be a part of a suppression response to be most effective. Fuel breaks must cover a wide enough footprint to effectively reduce wildfire behavior and provide adequate space for safe firefighting operations [267].

In shrublands, particularly in the wildland urban interface in Southern California where wildlands are adjacent to communities, fuel breaks are crucial for suppression operations, although their effectiveness diminishes under high wind conditions [54]. Firefighter access is a key component in determining fuel break effectiveness and can be enhanced by regular maintenance and placement of fuel breaks near existing roads [268,269]. Targeted grazing may be a solution to manage herbaceous plants, but additional treatments are necessary to control woody and non-native vegetation [262].

Knowledge Gaps and Future Considerations

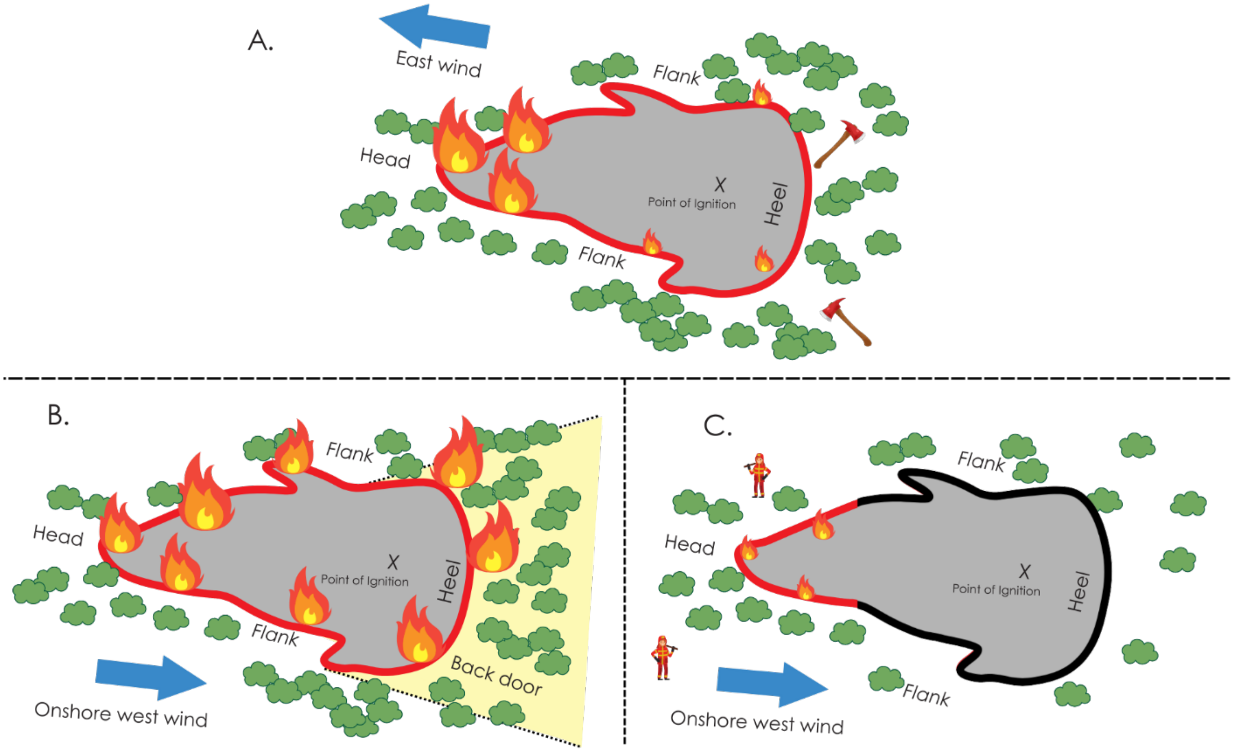
Improvement to fire models to better predict EWE behavior in developed areas [270] is needed. It is also important to know future levels of vegetation management required to safeguard California from EWEs and the amount of maintenance treatments needed annually. Research is needed to study how fuel treatments at the landscape scale benefit areas outside of treated areas [271]. Also necessary to increase the pace and scale of stewardship and restoration are new policy initiatives that allow Indigenous communities to efficiently lead stewardship projects [272]. Other solutions, such as identifying new markets and products (e.g., engineered wood) from forest fuel reduction waste would further enable landscape resilience projects and carbon sequestration while reducing emissions and impacts from pile and broadcast burning.

Box 2. Closing the Back Door During Wind-driven Fire in Southern California

by Thom Porter (Retired CAL FIRE Director and State Forester)

An often-overlooked reality of wind-driven wildfires in Southern California is that the fire's heel and flanks account for the bulk of the fire perimeter. During the initial, often east-wind-driven run, the head of the fire is relatively focused, moving downwind with little opportunity for suppression efforts to check its progress. During this period, fire activity at the heel and flanks is low enough that firefighters can take effective suppression action, even under extreme conditions. Suppression action on the heel and flanks is significantly aided in areas where fuel modification or other disruptions in fuel bed continuity have occurred.

Suppression and control of the heel and flank portions of the perimeter becomes critical when the wind switches to onshore west-wind-driven conditions. If firefighters have the opportunity to "close the back door" by controlling the heel and flanks, there is no fire to spread and focus can switch to control of the remaining perimeter. The effectiveness of fuel modification on wind-driven head fire can be debated. However, fuel modification provides firefighters a better opportunity to contain wildfire at the heel and flanks of a wind driven fire perimeter and effectively close the back door.



(A) During the initial wind-driven run, suppression activities focus on the flanks and heel. **(B)** When the conditions switch to onshore west-wind-driven, the intensity on the heel and flanks increases. If fuels are continuous, suppression activities may not be enough and the fire may spread "out the back door". **(C)** However, fuel modification can greatly aid suppression activities and may allow firefighters to "close the back door" and focus on controlling the rest of the perimeter.

Post-Fire Recovery, Reforestation, and Management Interventions

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Key Message

Prompt, strategic post-fire management interventions including reforestation and restoration can reduce the likelihood of vegetation type change and secure other ecosystem services (High Confidence). Extreme wildfire events (EWEs) limit post-fire tree regeneration, accelerate forest loss, and denude slopes prone to debris flow (High Confidence). Mitigating post-fire debris flows and land sliding can reduce risk to property and critical infrastructure (High Confidence).

Context Prompting Post-Fire Attention

Increases in wildfire severity and frequency, warming temperatures, greater climate extremes, and limited reforestation capacity are driving changes in post-fire restoration, reforestation, and debris flow dynamics. High-severity fire is an important driver of these changes and, particularly for recent wildfires (last ~10 years), is occurring in increasingly large, contiguous patches [157,273]. In forested systems, these patches have sizable interiors beyond the seed dispersal distance of most Western U.S. conifers. Even when seedlings become established through reforestation efforts or natural recruitment, hot droughts have significantly increased mortality [274,275]. In shrubland systems, increasing fire frequency is leading to conversion from native shrub species to highly flammable grasslands (see *Wildfire Crisis Overview*). Unless replanted and fuels managed, these large, burned patches are prone to type conversion and severe re-burns [7,160].

Considerations for Post-Fire Restoration

Given the extent and intensity of current wildfire and drought events [247], a science-based, strategic planning approach supports effective restoration and remediation of impacted forests and shrublands. Post-fire restoration frameworks ensure individual, local projects contribute to rebuilding ecosystem integrity and habitat connectivity, while protecting communities [276,277]. Landscapes are partitioned into practical units where management interventions can: (1) maintain or improve desired conditions in areas of positive or neutral fire effects, (2) restore desired conditions in areas with negative fire effects, and (3) evaluate anticipated future conditions in areas of negative fire effects where traditional management actions (e.g., maintaining pre-fire tree densities through reforestation) are impractical [276,277]. This framework mirrors other climate adaptation approaches such as RRT (resistance, resilience, and transition) and RAD (resist, accept, direct) [278–280]. The restoration framework uses the historical range of variation (HRV), traditional ecological knowledge, and science-informed benchmarks to evaluate where ecosystems have been improved or degraded [276,277]. Recognizing variable fire effects, it breaks the landscape into manageable units for integrated restoration efforts (e.g., prescribed fire, cultural burning, mechanical treatments including salvage harvest). This includes post-fire fuels reduction to minimize type conversions (see [7]; *Impacts to Ecosystems*).

Reforestation Applications

Conventional reforestation practices are well established [281]. These intensive practices are widely used in private industry, given their success at rapidly growing saw logs and biomass. In mixed-conifer forests, before planting, site preparation involves mechanical removal or burning of fuels and controlling competing vegetation. Conifer seedlings, predominantly pine, are then planted in a gridded pattern (e.g., 15' x 15' spacing or approximately 200 trees/ac) to minimize competition and boost growth rates. Developing shrub cover may be reduced with herbicide, mastication or manual removal [282]. Pre-commercial and commercial thinning are used to reduce tree density and maintain rapid growth in the remaining trees until their harvest at 60–80 years old.

On public lands and small private ownerships, conventional practices are often modified due to different management objectives as well as supply and budget constraints (i.e., seedlings and workforce) that greatly outstrip available resources [283,284]. For many ownerships with limited funding, follow-up treatments reducing competing vegetation and tree density are increasingly rare [285]. There is also concern that gridded planting, an agronomic approach without an analog in natural forest ecosystems, reduces biodiversity and resilience to fire and drought [286–288].

Given these constraints, recent research suggests three principal changes to reforestation practices: lower planting densities, resilient planting patterns responsive to microsite conditions, and early use of beneficial fire. To conserve seedlings and reduce costly thinning treatments, planting densities should be lowered to roughly 1.2–1.5 times the density found in mature historical forests with a frequent, low-severity fire regime [289] (i.e., 60 to 160 seedlings/ac). Planting should mimic spatial patterns found in active-fire forests [290], a mix of Individual trees, Clumps of trees, and Openings (ICO) that improves forest resistance to severe fire [291–293] and drought [294]. In contrast to a regular grid, strategic planting should focus on wetter, less fire-prone locations [285], where the number, species composition, and spatial configuration vary with microsite condition [295–297]. Once seedlings are 10–15 years old, young plantations could be burned to reduce fuels and favor individuals with more fire-tolerant characteristics, such as thick bark and higher crown base [230,239,298] or treated with variable density thinning and fuel removal to increase young stand resilience [227].

Protection from Post-Burn Debris Flow Impacts

Post-fire debris flows (PFDF) frequently impact human safety, private property, natural resources, and essential infrastructure [299] across a wide range of forested and shrubland slopes. Wildfire reduces vegetative cover and surface roughness, thereby impeding infiltration, causing rainfall to quickly convert to runoff [300]. Research shows PFDFs are commonly runoff-induced and form as flow is bulked with sediment and debris cascading downslope [301,302]. PFDFs are triggered by short-duration, high-intensity rainfall, and are insensitive to antecedent moisture [303–305]. Additional factors increasing PFDF likelihood are steep slopes burned at moderate or high severity, changes in canopy cover, and soil erodibility [306]. Recent research has focused on predicting PFDF magnitude as a function of peak discharge [306] and volume [307], and using hydraulic models to predict potential flow paths [308–310]. Runoff-induced PFDFs most frequently occur one to two years following fire [306], with a transition to landslide-induced PFDFs three to five years post burn [311]. PFDFs are prevalent in the steep chaparral-covered slopes of Southern California [306] but also occur on forested central and Northern California slopes [305,312].

Given the documented risk of PFDFs on steep burned slopes, postfire response efforts emphasize rapid slope stabilization and erosion control to reduce runoff and sediment delivery. Common practices include mulching, erosion barriers, and emergency seeding, and, where applicable, culvert replacement or improvement. The goal of these measures is to reduce the likelihood of PFDFs during the first years following fire, when risk is highest [313]. However, in shrublands that have burned too frequently, the longer- term solution may require active restoration to re-establish native shrub cover and ecosystem function [314].

Knowledge Gaps and Future Considerations

Reforestation applications. Substantial knowledge gaps include understanding when and how facilitation amongst tree seedlings and between seedlings and shrubs benefits early tree survival and growth, and when competition becomes more dominant. Optimizing ICO patterns for different locations and forest types will require experimentation and identification of microsites with the greatest chance of seedling survival. Robust models that identify which tree species can continue to grow and persist under changing climate conditions are needed. Potential mismatches between changing climate conditions and local seed [111,315] need to be tested with field trials to determine if outbreeding depression reduces transplanted seedling vigor [316]. To hasten wider adoption of these new practices, increases in the timeline and desired outcomes for evaluating reforestation success must be expanded from initial survival to long-term forest resilience.

Post-fire debris flows. Significant knowledge gaps limit our ability to predict PFDF occurrence, magnitude, and run off across California's wide range of physiographic conditions. To better assess PFDF hazards, develop plans, and design standards, we need to: (1) build a comprehensive PFDF database including location, timing, triggering rainfall, peak discharge, total volume, and inundation extent; (2) leverage remote-sensing technologies, such as LiDAR and satellite products, to identify better prediction metrics; (3) develop hydrologic and hydraulic models predicting postfire runoff and inundation; (4) better understand landslide-induced PFDFs and their impacts; and (5) provide design guidance for flood control and highway infrastructure resilient to PFDFs.

Post-fire shrubland management. Research and restoration management of shrubland ecosystems including chaparral, coastal sage scrub, and sagebrush steppe, is frequently conducted at fine scales (i.e., several acres), whereas wildfire impacts are often at coarser scales (hundreds to thousands of acres). A critical knowledge gap is how to effectively expand new science-based approaches to restore native plant cover (via seeding or planting) and minimize non-native grass invasions in burned ecosystems. Managers need sound information evaluating the effectiveness, feasibility, and socioeconomic barriers of scaled-up restoration in California's shrublands [317].

Increasing the resilience of recovering ecosystems to intensifying fire and drought requires combining successful restoration practices with ecologically informed approaches and developing better predictive models of unstable slopes. Holistic, large-scale assessment tools for post-fire remediation, resilient reforestation, and debris flow prediction are now available. These science-based approaches to post-fire restoration will continue evolving in response to rapidly changing climate conditions and disturbance regimes.

The Value and Role of Data, Modeling, Remote Sensing, and Novel Technological Applications to Address the Wildfire Crisis

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Key Message

To support effective vegetation management, wildfire risk mitigation, and wildfire response, California needs up-to-date, accessible, and integrated spatial data on vegetation, fuels, and infrastructure. To predict the effectiveness of potential management actions in achieving wildfire resilience, California needs ecosystem models, fire models, and scenario planning platforms that fully and seamlessly leverage the latest available data. Current priorities include: (1) improving the accuracy and realism of fuel data and fire behavior models, (2) adopting new mapping technologies that can quickly capture rapidly changing conditions, and (3) expanding the collection and accessibility of ground-based reference data for model training and validation. Data and tools should be delivered through an easy-to-use open-access platform. To guide selection by users and inform future investment, a standardized assessment of existing datasets and tools is urgently needed.

Foundational Data for Vegetation Monitoring and Treatment Assessment

Data on landscape conditions, infrastructure, and treatments, at appropriate spatial resolutions, are fundamental to understanding the value of vegetation management investments. For example, the effects of treatments on wildfire severity may be inferred by comparing vegetation characteristics in treated and untreated areas after a wildfire [251,318]. Landscape conditions can be understood via ground-based sampling and/or processing of aerial and satellite remote sensing data. Ground-based data generally have high accuracy and, despite limited spatial extent, are critical for the development and evaluation of remote sensing-derived datasets. Remote sensing datasets, in turn, support vegetation assessment across broad spatial extents, though often at the expense of some local-scale accuracy. However, increasing availability of satellite and airborne remote sensing systems (e.g., ESA Sentinel-2 and NAIP) and advances in machine learning and artificial intelligence [319,320] are significantly improving broad-extent monitoring capabilities at relevant time intervals. Uncrewed aerial vehicles (UAVs) are emerging as a potential low-cost option for high-resolution vegetation mapping at the project scale [321–323], while airborne LiDAR offers promise for mapping at broader extents [324,325]. In addition, there are several existing and emerging state and federal programs that compile records of completed and planned vegetation treatments (DOI WFIT, USDA FACTS). In California, the Interagency Tracking System compiles geospatial treatment records across land ownerships. Together, vegetation characterization and treatment tracking programs can be used to assess treatment effectiveness.

Predicting Future Disturbance Risk and Treatment Impacts

Modeling and data compilation support project planning and prioritization by predicting disturbance effects and treatment impacts, thus enabling a form of scenario planning [326]. Academics, NGOs, state and federal agencies, and the private sector have made marked progress on these fronts over the last half decade. For example, the Center for Ecosystem Climate Solutions (CECS) combined ecosystem modeling and remote sensing to create a geospatial dataset for approximately 20 resilience-related metrics spanning the state's wildlands from 1985–2023 and added them to the California Landscape Metrics (CLM) statewide compilation. Separately, and with less interproject integration, researchers have developed quantitative models and tools to predict climate-driven vegetation conversion [327–330], natural post-fire regeneration outcomes [224,274,331,332], reforestation outcomes [333,334], and fuel treatment effects on fire severity [271,327], and to optimize reforestation seed sourcing [335,336].

Synthesizing Data to Develop Management Strategies

Decision support tools (DSTs) can expedite and standardize assessments of risk and benefit to management objectives related to fire suppression operations and fuels reduction efforts (e.g., WFDSS and IFTDSS), as well as wildlife habitat and forest refugia conservation (e.g., ForSyS). A valuable decision support tool is one that assists land managers to (1) set planning goals, (2) assess conditions using spatial depictions of landscapes, (3) develop alternative action plans, and (4) facilitate decisions through rational, logical rulesets or social approaches. Decision support tools range from simple geographic information system (GIS) workflows to highly developed web apps, with some already in use by land managers (e.g., ForSys) and others under development by external parties (e.g., Wildfire Resilience Platform) or through interagency partnerships (e.g., Planscape). Of particular value are DSTs that account for the effects of fuel treatments on fire behavior and fire effects not just inside, but also outside, the treated areas (the "treatment shadow effect") [271] (see also *Impacts to Ecosystems*). Such a system is currently in development through a broad collaborative effort [318].

Knowledge Gaps and Future Investments

Data Standardization and Publication

The vast existing and emerging data collection and synthesis efforts—including field and remote sensing landscape condition data, treatment records, and DSTs—tend to be independent of each other, follow incompatible protocols and delivery formats, and/or involve significant access restrictions, hampering analyses that span jurisdictional boundaries. As a result, there is a need to develop products that are meaningfully standardized, integrated, validated, cataloged, and released publicly with minimal restrictions. To accommodate the increasing number of stakeholders using open-source software [337], geospatial datasets should be delivered in a common, non-proprietary format. A centralized open database with modern graphical and programmatic interfaces could facilitate greater data discovery, access, and contribution. To succeed, such an effort would need to be supported by data curation and end user services.

Assessment of Existing Datasets and Tools

The recent proliferation of landscape condition datasets (e.g., maps of aboveground biomass), disturbance hazard datasets (e.g., maps of predicted fire severity), and DSTs has created a need for an unbiased comparison of existing options. Such an evaluation would inform land managers of dataset and DST strengths and weaknesses and help dataset and tool creators improve their offerings. In the near term, an evaluation could consist of a user-friendly visualization platform for comparing datasets to each other and to available basemaps. A panel of experts could rapidly assemble a set of public "curator notes" identifying apparent strengths and deficiencies of each resource under relevant use cases. Evaluation of DSTs could include assessments of the sensitivity of tool outputs to embedded and user-supplied assumptions [338]. Eventually, formal validation against ground-reference data would provide the gold-standard form of evaluation for key metrics such as fuel loading and vegetation type. The California Air Resources Board is currently conducting such an evaluation for soil carbon and forest biomass carbon datasets, specifically [339]. Qualitative evaluation and quantitative validation of datasets and tools will accelerate progress toward improving accuracy, enhancing credibility, and informing continued data and tool development investments.

Next-Generation Fuel Data and Fire Models

Wildfire simulation models are valuable for treatment prioritization, but the most widely used models have limited accuracy because they rely on low-fidelity, infrequently updated satellite-derived fuels data [340,341] or very rough categories for field observations (such as [342]). For example, the broadly used Rothermel-based fire spread models are in a strong position for improvement as they cannot accept detailed field-based fuels data without extensive local calibration [343,344]. Fuels data themselves also pose a major bottleneck for accurate fire modeling given the difficulty of observing understory fuels via over-canopy (e.g. satellite, aerial) remote sensing. New methods including physics- and process-based models (such as [327,345]), along with emerging 3D fuel data collection and synthesis methods (such as [346,347]) are positioned to overcome this limitation with continued investment. More realistic fire models will help in the creation of DSTs that account for the effects of fuels treatments both within and beyond treatment footprints [157,271,348,349]. Improved modeling would translate to direct improvements in tracking key performance metrics such as wildfire risk to communities, wildlife habitat, ecosystem resilience, and local economic indicators.

Emerging Technologies for Foundational Data Collection

Traditional data sources for vegetation management planning necessitate choosing between high accuracy (i.e., field surveys) and high spatial coverage and frequency (i.e., remote sensing). Several emerging "proximal remote sensing" technologies, including airborne and terrestrial LiDAR and UAV imaging, promise to fill this gap by providing broader coverage than field surveys and higher accuracy than satellite observations [157,325,350–355]. Investing in development of these data collection methods along with enhanced data processing and analytics (e.g., computer vision and other machine learning methods) would enable more accurate broad-scale prioritization, planning, and monitoring. Airborne LiDAR data acquisitions, in particular, are too infrequent to support rapid adjustments of management plans following disturbances like wildfire, but expanded investment may resolve these shortcomings. To support the development and validation of these burgeoning methods for rapid, high-resolution vegetation mapping, a targeted and modernized reference database of existing and newly sampled ground plots (¼ acre or larger) with open-access location data and individually mapped trees is required.

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