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CHAPTER 23

Wildfire Risk, Resilience, and Adaptation in a Burning World

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Learning Objectives

1. Examine the relationships between climate change and wildfire risk.

How is anthropogenic climate change impacting natural wildfire regimes and changing risks to humans? You will learn the basic components needed for fire, and how long-term climate variability influences those components. This lays the foundation for understanding how human-caused climate change is altering the frequency, seasonality, and severity of fires across the globe.

2. Understand how ecosystems are naturally resilient to wildfire and the role humans have played in modifying this resilience.

What strategies have ecosystems evolved to survive fire? You will explore the ways that different species, particularly trees, interact with fire, and the ways that postcolonial forest and fire management abolished natural ecological resilience. This loss can both be reversed through proactive forest management and inform human pathways for fire resilience.

3. Understand the unique role fire plays in human evolutionary history and how wildfire negatively impacts humans both directly and indirectly.

How has this role changed to produce contemporary wildfire disasters? The relationship between humans and fire has evolved substantially over the last century, leading to the contemporary wildfire disaster. Understanding how disasters are a product of both biophysical risk and social vulnerability is critical to identifying solutions that will effectively mitigate wildfire disasters.

4. Identify key features of successfully mitigating wildfire disasters.

What does it look like to live successfully with wildfire? You will learn about the broad range of mitigation and policy solutions that can help to prevent wildfire disasters. We will always have wildfire across much of the globe, and recent case studies have demonstrated the effectiveness of different types of activities in helping us live with wildfire.

Overview

Humans have a unique relationship with fire. We are the only species on the planet that can create fire, carry it with us wherever we go, control the quantity of energy it produces, and use that combustion energy to meet our needs. Anthropologists think that human ancestors regularly used fire for cooking, personal defense, warming, and a host of other activities from ~300–400ka. The ability to make fire, and especially to cook food with it and change the chemistry and availability of nutrients in raw food sources, set our human ancestors on a unique and solitary evolutionary trajectory that separates us from all other species on Earth today.

Over time, our relationship to fire has drastically changed. We became very good at controlling fire and identifying the most abundant fuel sources that could be most easily burned efficiently to produce high amounts of heat and energy. However, colonization and imperialism fundamentally changed landscapes adapted to fire and, coupled with contemporary anthropogenic climate change, produced the modern wildfire disaster. This chapter explores the relationships and feedbacks between humans, wildfire, and the climate system, including the flux of carbon between the land and the atmosphere. It highlights how climate change is altering environmental conditions to make them more conducive to destructive wildfires, and what we can do to make ourselves and the ecosystems we depend on more resilient to wildfire. It describes the natural fire resilience of ecosystems and how we humans can learn from and enhance that resilience. It explores our historical relationship to fire and what aspects of the built environment are most vulnerable to wildfire and why. Finally, it asks how we can change our social systems to mitigate wildfire disasters and relearn how to live with wildfire.

23.1 Wildfire Risk and Climate Change

Fire arrived on Earth much earlier than humans. Almost as soon as vascular plants appeared in the geologic record, charcoal also appeared, providing evidence that those plants burned. As we humans are comparatively only a very recent entry to Earth's history, we have lived with fire for our entire existence. Ever since we discovered how to do so, we have also ignited fires for most of our history.

To understand how climate change impacts fire, we first need to understand how fire burns. Fire is the result of combustion, itself a physical and chemical process. This process requires three components to co-occur, the so-called **fire triangle**: oxygen, fuel, and an ignition source (Figure 23.1.1). Oxygen became abundant in Earth's atmosphere starting around 1.7 billion years ago, and fuel in the form of plant biomass arrived approximately 400 million years ago. Heat is required to ignite **pyrolysis**, or the heating of fuel in the absence of oxygen, and to sustain the chemical reaction **combustion**, which then converts oxygen and the

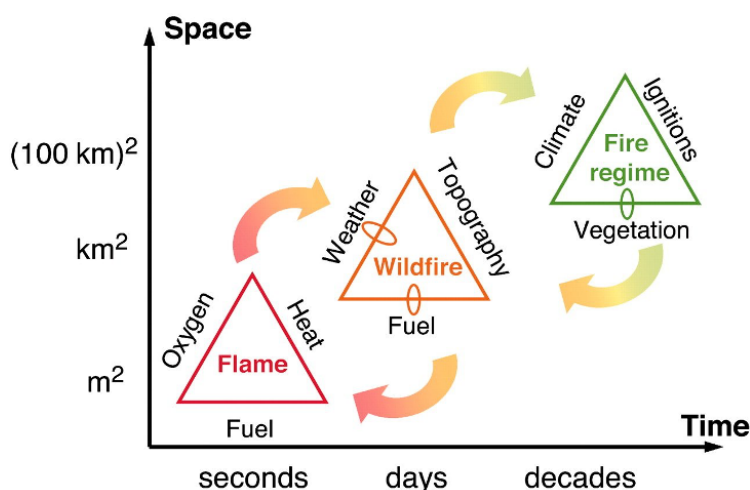


FIGURE 23.1.1 Fire triangles at different spatial and temporal scales determine how flames burn, how individual wildfires burn, and how fire regimes burn. From Moritz et al. 2005.

sugars and alcohol polymers that make up plant cellulose and lignin into three primary products: carbon dioxide (CO₂), water vapor (H₂O), and more heat energy. The naturally occurring sources of heat to ignite early fires were an abundance of lightning across the globe and occasionally a volcanic eruption. Once our early human ancestors arrived and learned to make fire, they too became a source for wildfire ignitions.

As the Earth's climate has varied across the millennia, it has always naturally changed how frequently and where wildfires burned by affecting two legs of the fire triangle: fuel and heat. Climate controls both the amount and type of fuel arranged across the landscape, as well as the availability of that fuel to burn at a given moment. The amount and type of vegetation that grows in different places across the terrestrial surface is determined by the average climate of a location. The hottest and driest places, like the Sahara desert, have no vegetation at all, so there is nothing for a wildfire to burn. Wetter, more temperate climates support greater amounts of plant life, especially big trees, so there is a high level of biomass in those regions. The frigid Arctic and high alpine environments support mostly grasses, shrubs, and very small trees thanks to short growing seasons and frozen soils. Over thousands of years, naturally changing long-term climatic conditions controlled the gradual transitions between different biomes (Figure 23.1.2).

At much shorter time scales of months to years, climate controls when fuel is available to burn, a concept that is familiar to anyone who has tried to start a campfire with wet wood. During hotter and drier seasons and years, fuels have lower water content and are able to more easily produce the heat energy required to sustain the chain reaction of combustion (Figure 23.1.3). During cooler, wetter seasons and years, combustion may fizzle out due to insufficient heat energy. Since lightning is the primary natural ignition source for wildfires, the amount of dry lightning (that is, unaccompanied by rain) and the probability of a given lightning strike igniting fuel on the ground are also affected by climatic variability. Thus, **fire regimes**—the patterns of fire across space and time—are primarily controlled by climate.

Anthropogenic climate change from fossil fuel combustion and greenhouse gas emissions has altered the spatial and temporal patterns of wildfires in several key ways. First, as global temperatures warm and

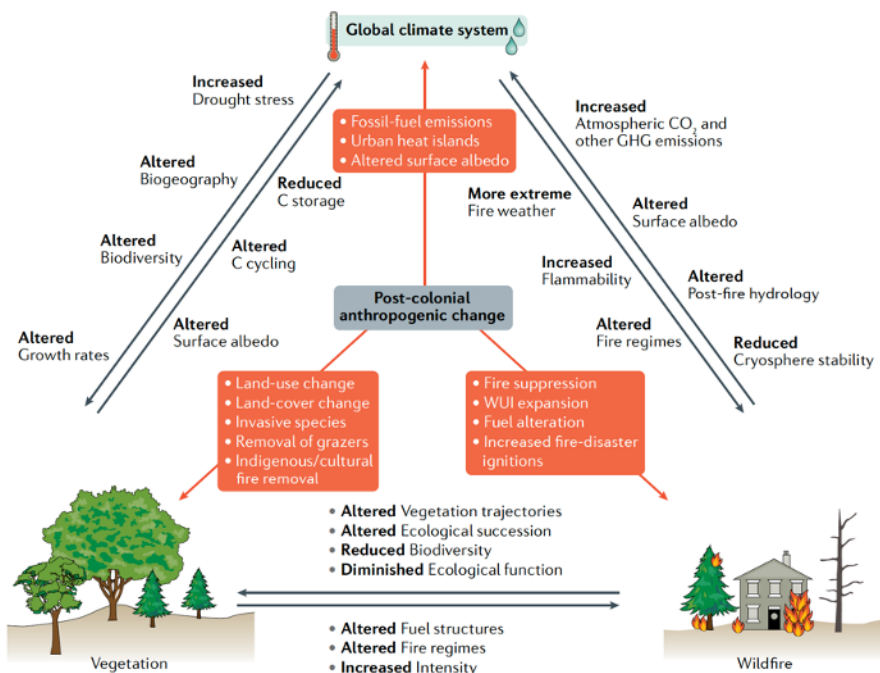


FIGURE 23.1.2 The complex relationships between Earth's global climate system, vegetation, and wildfire were substantially altered by European colonization and contemporary human activity stemming from ideas around land use, natural resource extraction, and Manifest Destiny in North America. From Bowman et al. 2020.

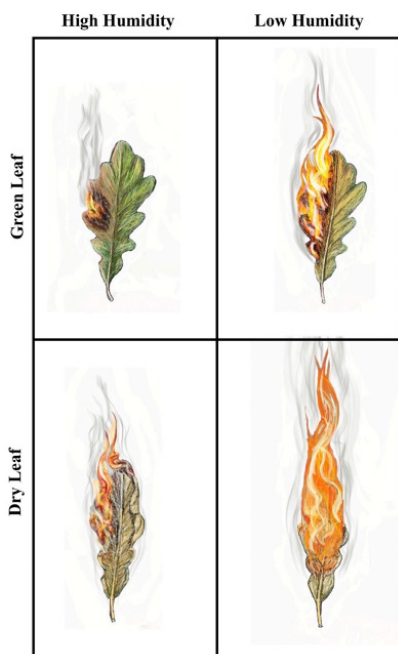


FIGURE 23.1.3 Weather and climate naturally control the heat energy produced by combustion, based on how much water content a piece of fuel (like a leaf) has. A living leaf with high water content will not readily burn, while a dead leaf that has been drying in the summer heat will easily burn. From Morrill 2019.

weather patterns shift, vegetation growth patterns also change, altering where and how much fuel is available to burn. Over longer time scales, drought conditions have caused huge numbers of trees to die and become readily available firewood. Second, key weather patterns have intensified, producing more extreme fire behavior. On extremely hot and arid days, which are occurring more frequently, vegetation dries out and burns more easily. The nights are staying warmer and drier, so plants don't recover their moisture levels as well as they used to, and fires can burn more readily and release more energy. That energy not only makes it much more difficult for firefighters to control the flames, it also can create a situation where very large fires create their own weather. Smoke columns on very hot fires form **pyrocumulonimbus clouds** ("fire thunderclouds"; Figure 23.1.4) more frequently, and extreme fire behavior results when these clouds collapse and release downdraft winds in all directions.

Climate change is also changing the seasonality of wildfires. Like most places, California had well-defined fire seasons that generally

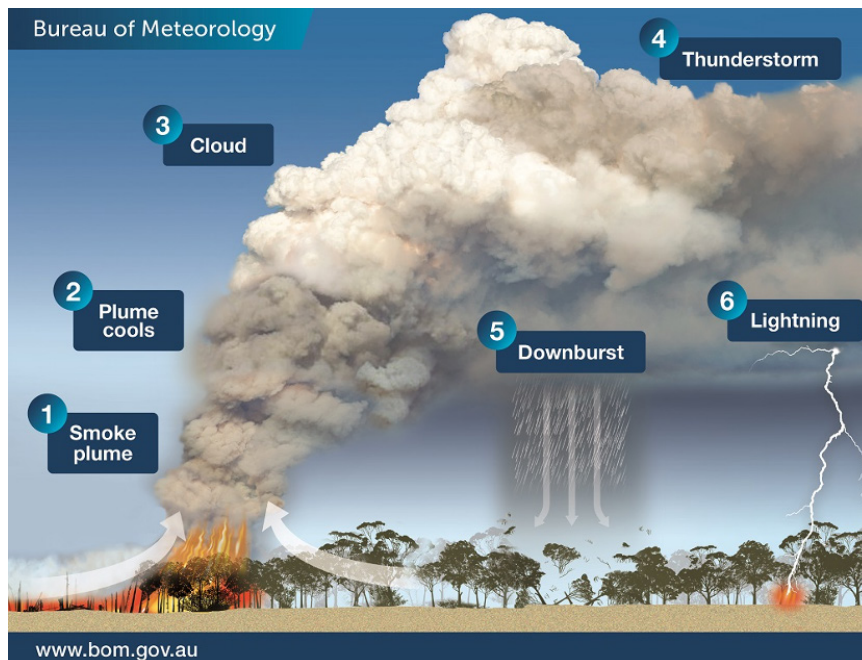


FIGURE 23.1.4 Pyrocumulonimbus clouds form over extremely hot wildfires that produce high amounts of heat energy, creating extreme fire behavior conditions. Reproduced from Commonwealth of Australia, Bureau of Meteorology.

began in late spring at low elevations, and then expanded to the mountains in late summer to early fall. Historically, by October or November fire season had ended across most of the state, with only Southern California waiting to see if rain would arrive to wet everything down before the dry, hot Santa Ana winds the region is known for in winter arrived. Usually the rains came by October, or November at the latest. But with climate change, the autumn rains are increasingly delayed or do not come at all, leaving the region parched all winter long. This has transformed the fire regimes of California, and large fires can now burn year-round under the right conditions.

Across North America, fires that escape initial suppression efforts also burn longer and over a much larger area. Researchers who created scientific models of wildfires and climate change have shown that anthropogenic climate change doubled the forested area burned by wildfire in the western US from 1980 to 2015 (Figure 23.1.5). This is partially because the period of high fire danger, when the most fire growth happens because of high temperatures and arid conditions, has increased by over a month in the last few decades. Scientists have further traced 37% of the area burned from 1986 to 2021 directly to the top 88 fossil fuel companies, the first time such a direct connection has been made.

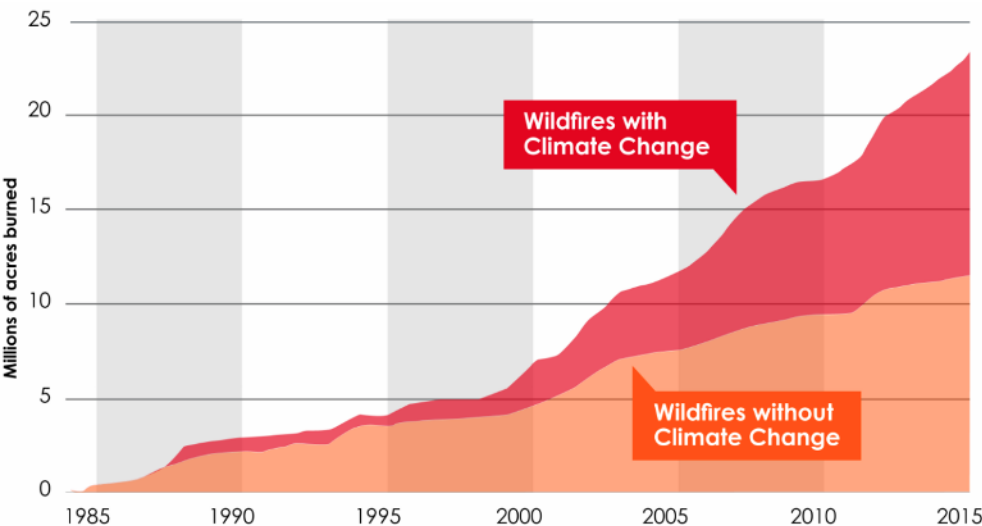


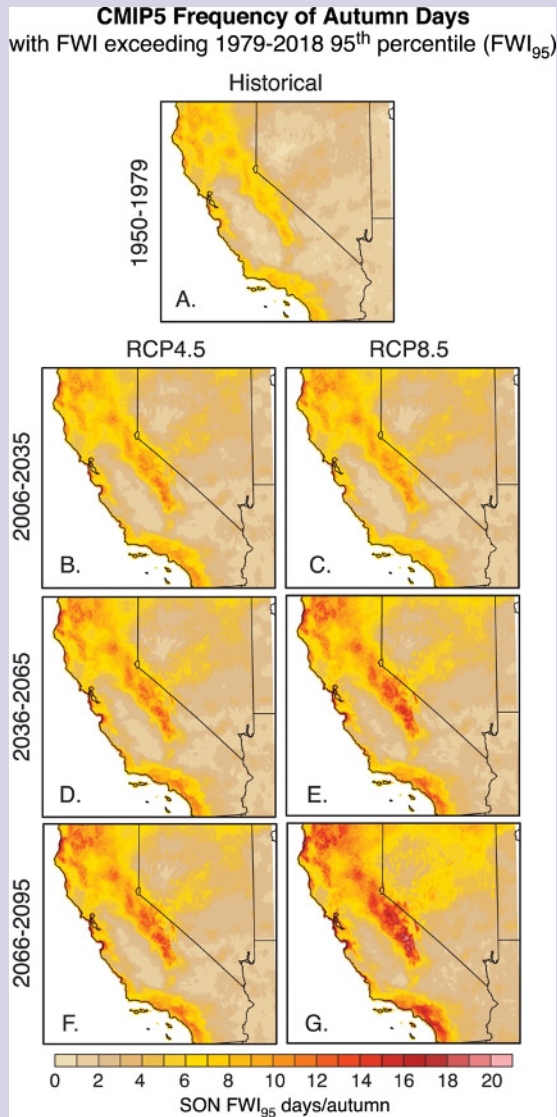
FIGURE 23.1.5 The amount of wildfire area burned attributed to human-caused climate change (red) compared to without (orange) 1985–2015. Adapted by Union of Concerned Scientists from Abatzoglou and Williams 2016.

Box 23.1.1

The period when California has the most destructive wildfires is the autumn (September, October, and November), when most of the state has not had any rain in 4 to 6 months. The vegetation is extremely dry, and around mid-October the changing of seasons produces conditions for strong downslope winds from the north or east across large sections of the state. These winds go by many local names (Santa Ana, Diablo, Mono, Jarbo), but they are all associated with high pressure in Nevada and low pressure along the Pacific coast, creating a very strong gradient that forces air over mountains and through narrow canyons. Thanks to the friction and compression that cause **katabatic heating**, these winds become extremely hot, turning a giant hair dryer on across the state. If a fire ignites, it is often catastrophic, and nearly all of California's greatest wildfire disasters in terms of loss of life and homes have occurred during these events.

Historically, using 1950–1979 as a baseline reference, much of California's forests and wildlands experienced approximately a week of very high fire danger days as determined using the top 5% of observed Fire Weather Index (FWI) values, or FWI exceeding the ninety-fifth percentile (FWI_{95}). A research team modeled the number of FWI_{95} highest fire danger days into the future using two different climate emissions scenarios called RCP4.5 and RCP8.5 (*RCP* stands for “Representative Concentration Pathway,” and the 4.5 scenario is an intermediate one, while 8.5 is a worst-case scenario where humans do nothing to limit increasing emissions). They looked at three future periods of time: 2006–2035, 2036–2065, and 2066–2095. Even by the middle decades, some places in California could have 2 weeks of FWI_{95} days each year and, by the end of the century, a few locations could see up to 3 weeks of extreme fire danger when the most destructive fires burn.

Wildfires can burn anywhere where there is vegetation growing to create fuel, including across most of the US. Even places where there have not been many wildfires in recent decades have a greater probability of experiencing the type of extreme weather that supports fire ignitions and growth under climate change. This has led to numerous disastrous and fatal wildfires across the country in recent years, but it



BOX 23.1.1 Number of days in the autumn months when the Fire Weather Index exceeds the historical 95th percentile threshold for the historical (1950-1979) period and both the middle-of-the-road (RCP4.5) and worst-case (RCP8.5) greenhouse gas emissions scenarios for three future periods, based on projections from global climate models for 2006-2025, 2036-2065, and 2066-2095. From Goss et al. (2020).

is especially true in the flammable Mediterranean biome of California. Nearly every scientific model of future wildfire activity under continued climate change agrees that these trends will only continue—that hotter and drier conditions lasting for longer periods of time will continue to support both extreme fire behavior and longer fire seasons across much of the western US. In California, fire danger will be higher in the future across all four seasons, but particularly in the autumn months (September–November) when some parts of the state could see double the number of the highest fire danger days when the most disastrous wildfires occur (Box 23.1.1). For humans, this means that we will be exposed to more intense and potentially fast-moving wildfires more frequently. How we respond to this increased exposure, however, and whether we enact mitigation strategies at multiple spatial scales, will determine how the increased fire exposure ultimately affects us. While it is easy to be concerned that there is nothing we can do, we need only look to nature to understand there are adaptation strategies for living with fire, and some of these strategies can potentially inform human mitigation efforts.

23.2 Ecosystem Resilience to Wildfire

Ecosystems have evolved with wildfire since it first appeared on Earth; this has led to a diverse array of response strategies across biomes and species. Some species thrive in places with frequent fire; others occupy ecological niches where fire is absent for centuries to millennia. Generally, however, flora and fauna fall into four primary categories of **fire resilience**: avoidance, adaptation, dependence, and sensitivity.

Fire avoidance

Fire avoidance is the strategy adopted by nearly all terrestrial fauna, from insects to birds to mammals. It is a simple strategy: when fire burns, species either run away or hide underground or in **fire refugia**, places where flames can't reach them. In plants, fire avoidance is slightly more specialized, since they cannot physically move. Instead, fire avoidance in plants manifests as a reallocation of critical resources, particularly the starches and sugars needed for making new leaves, into the underground root system. Fire avoiders stop growing new leaves as the dry and hot season advances, and instead they move the carbon produced from ongoing photosynthesis back down into their roots, banking it for later. Then these plants wait, either for fire or for rain, whichever comes first. If it is fire, the aboveground, mostly dormant portion of the plant burns, killing all of the existing photosynthetic equipment in the leaves. But within only a few weeks after the fire—even before the rains come, in many species in California—the plant taps into its underground savings account and rapidly begins to grow new leaves from its basal buds (Figure 23.2.1).

Often known as resprouters, the most widespread grasses, shrubs, and even several tree species (such as eucalyptus) in California utilize this strategy to live through repeated fires. Perennial grasses and flowering herbaceous plants that regrow from the same root system each year, like the ubiquitous California poppy, are particularly well adapted



FIGURE 23.2.1 Eucalyptus trees resprouting, only 2 months after a severe wildfire, from the basal buds that make them so resilient. Photograph by Crystal Kolden.

Box 23.2.1

Redwoods are found throughout coastal regions of Central and Northern California and thrive in places where moist fogs support their growth. However, these forests burn regularly under prolonged dry conditions, scorching the flammable needles, trunk, and branches of the tree. Within only a few weeks after burning, however, redwoods do something remarkable. Small buds emerge from beneath the blackened bark and unfurl new needles and small branches so that photosynthesis can restart (see figure). The result is that burned redwoods look like fuzzy green columns with black bare branches sticking out at odd angles. The redwood cluster (redwoods always grow in groups with interconnected roots underground) then works to simultaneously drop seeds on the newly cleared soil and send up new sprouts from the roots to begin the next generation.

to avoid fire by sending all of their resources to their roots. A particularly unique form of resprouting is found in trees that sprout new leaves from epicormic buds in the bark (rather than basal buds at the base of the plant near the roots). Perhaps the most famous epicormic is the California redwood, also known as the world's tallest tree (Box 23.2.1).

Fire adaptation

Fire-adapted species are widespread globally and include many of the most iconic California trees, such as giant sequoia and ponderosa pine. Most fire-adapted species have evolved with special characteristics that make them particularly resilient and able to survive (or even thrive with) lower-intensity fire that stays on the ground. When they are young saplings, fire-adapted tree species are particularly susceptible to fire and will die in a low-intensity burn. But as they grow, the morphology (or structure and form) of these trees changes in three key ways.

First, they begin to develop thick bark that insulates them from the heat of a fire and acts like an armored plate against the flames, protecting the xylem and phloem that carry water and nutrients to and from the roots to the needles and leaves at the ends of branches. The bark can be several inches to more than a foot thick! Second, as the tree grows, it drops its lower branches by cutting off water to them until they shrivel



FIGURE 23.2.2 A mature giant sequoia (*Sequoiadendron giganteum*) and the sugar pine (*Pinus lambertiana*) to the right of it are both fire-adapted species that grow thick bark and drop their lower limbs to create a huge gap between the forest floor and the canopy, which prevents fire from easily climbing into the crown. Photograph by Crystal Kolden.

and eventually fall off or burn off during a low-intensity fire. Removing lower branches is critical to protecting the crown of the tree, as lower branches serve as a “ladder” that allows fire to climb from the ground into the canopy and kill the tree (Figure 23.2.2).

Finally, fire-adapted species develop special reproduction characteristics that allow them to capitalize on a postfire landscape. Giant sequoias, for example, develop serotinous cones that are covered by a thin layer of wax. This wax melts when heated by the flames, allowing the cone to open and the seeds to drop to the newly cleared forest floor. Other types of plants, including many herbaceous species, have seeds that will only germinate when they have been damaged, or scarified, in some way, including by fire.

Fire dependence

Species that have evolved to be fire dependent do so in order to achieve a key goal: dominance of a landscape for generations to come. Such species grow in such a way as to support higher-intensity crown fires every couple of centuries: they grow as a monoculture, densely populating an area and producing substantial amounts of seed that builds up in the soil and is resistant to burning. Unlike fire-adapted trees, fire-dependent trees have thinner bark and do not drop their lower limbs. Rather, they maintain a dense crown so that each tree is touching its nearest neighbor to more easily facilitate fire spread. In the western US, lodgepole pine trees are the classic example of a fire-dependent species that carpets cooler and wetter regions at higher elevations, such as along the spine of the Sierra Nevada in California or across the Rocky Mountains from Canada to Colorado. When two-thirds of Yellowstone National Park in Wyoming burned in lightning-ignited fires in 1988, lodgepole pine was the dominant forest type consumed in massive conflagrations that were only extinguished when the snow fell. Within only a few short years, however, dense carpets of new lodgepole seedlings covered the burned land, shutting out light and capitalizing on the available nutrients before the seeds of any other plants could get established in the soil. Thirty years after the 1988 fires, a visitor to Yellowstone is challenged to tell where the old (unburned) forest ends and the new forest begins (Figure 23.2.3). In the natural world, survival of the species is more



FIGURE 23.2.3 The only indications of the 1988 wildfires in Yellowstone are a few remaining prefire lodgepole pines that survived, and several standing and downed trunks of dead trees. The rapidly regrowing forest is already 20–40 feet (6–12 meters) tall in most places. Photograph by Crystal Kolden.

important than survival of the individual, and fire-dependent species use flames to accomplish this goal.

Fire sensitivity

Species that have no resilience to fire at either the individual or community level are characterized as fire sensitive. These are species that have no long-term survival related to fire because they generally grow in places that burn either not at all or with very long intervals between burns, generally on the order of many hundreds to thousands of years. Among plants, they are also generally species whose reproduction relies on seeds dispersed from a parent.

Across the world, there are many places where it is generally too wet to burn, for decades to centuries on end: rain forests (both tropical and temperate), wetland environments, coastal regions where humidity from fog constantly envelops the forest and sustains spongy mosses and fungi, and high alpine regions where plants grow very slowly and often far apart due to the cold, the persistent snow, and the strong winds. Fire is rare in these places, so the plants have not evolved with it and are highly sensitive

FIGURE 23.2.4 Tasmania waratah (*Telopea truncata*), a Gondwanan paleoendemic found only in Tasmania and a symbol widely used in Tasmania to reflect its unique wilderness. Photograph by Crystal Kolden.



to it. When fire does occur in such places, usually due to humans in the modern era, fire-sensitive species are erased from the landscape and will not return unless a remnant or wayward seed takes hold.

In California, there are few places that meet such criteria and, thus, there are few native trees and plants that are truly fire sensitive. Even the verdant rain forest that carpets the northwest corner of the state and the ancient bristlecone pine forest that clings to rocky crests of the White Mountains along the Nevada border have evolved with infrequent fire. In other parts of the world, however, truly fire-sensitive species are disappearing as humans today burn places that our ancestors did not. On the island of Tasmania, Australia, for example, there are stretches of forest full of **paleoendemics**: species that are from a much earlier time in Earth's history (paleo) and only found in that location (endemic). A hundred million years ago, Tasmania was part of the Gondwana supercontinent, a giant land mass that eventually broke into Antarctica, Australia, India, and southeast Asia. Tasmania became isolated from mainland Australia during the last ice age (about 12,000 years ago) and became a refuge for species whose ancestors have existed on the island for millennia and are found nowhere else in the world (Figure 23.2.4). Unfortunately, these species are fire sensitive, and recent wildfires during the hot and dry years that are becoming more common with climate change destroyed thousands of acres of paleoendemic forest that will never return.

Restoring fire-resilient ecosystems

Over the last two centuries, the impacts of western imperialism have fundamentally altered the relationships between fire and ecosystems.

The California gold rush of the 1850s jump-started a century of intense clear-cut logging that removed over 90% of the ancient forests that had survived with fire for millennia. Before widespread logging, most of the fire-adapted forests in California were composed of primarily large trees that were widely spaced across the land, with patches here and there of younger trees and seedling nurseries. Regular fire cleared brush from the surface. The forests have been described as “park-like” due to the relatively clear understory that allowed early explorers and settlers to pass through easily. Logging of old-growth trees took out the giants, and as the seedlings grew into saplings, fire suppression removed the natural thinning and clearing process that previously kept the tree density low. By the late twentieth century, one could no longer pass easily through a cleared forest understory, or even see through it. Instead, the forest had become dense thickets of smaller trees and brush, with dead logs lying in a tangle throughout. As the climate has warmed, the number of trees dying during droughts has increased, and the forest that once burned frequently and with low intensity and flame lengths now burns as an unstoppable raging crown fire.

Scientists call these forests “unhealthy.” Regular fire acts like a vaccination for the forest, bringing the flames in small doses that take out excess vegetation and leave the strongest trees to grow stronger. Without regular fire, and with the stressors of climate change, the forest has grown sick and much more vulnerable to disease, bark beetles, and high-intensity conflagrations that burn tens or even hundreds of thousands of acres at once.

Humans are not helpless in this scenario, however. Forest health can be restored, and science is also learning that healthy forests, where forest managers have taken key steps to actively return the forest density and composition to a mix that resembles what was there 200 years ago, are even resilient to the effects of climate change. There are four primary activities undertaken by forest and fire managers to restore forest health and resilience: reducing fuel density in fire-adapted forests, restoring regular low-intensity fire, facilitating the success of nature-based solutions, and monitoring the change in fire dependence.

In California, forests today are up to ten times more dense than they were a century ago. This means that for a given piece of land, there are

ten times more trees than when fire regularly burned on the landscape. Even outside of the forests, in the oak woodlands that dominate the foothills at lower elevations, the loss of regular fire has produced a dense mass of shrubs and trees carpeting the landscape. To reduce this density, and the attendant increased fire hazard, forest managers either reduce or remove biomass entirely (Figure 23.2.5). They thin the forest by cutting down and removing smaller trees and shredding (or “masticating”) shrubs and saplings. They increase the vertical gap between the forest floor and the remaining tree crowns by removing the lower limbs of remaining larger trees. They make large piles of both the debris from these activities and the downed dead trees that litter the forest floor like giant toothpicks and burn the piles when winter rain and snow provide safe conditions for doing so.

Returning fire to these ecosystems is a key piece of restoring resilience. Thinning and pile burns are a first step, but across much of California and the western US, precipitation is plentiful enough to support rapid regrowth. Unless this growth is regularly removed, it will contribute to high fuel density again, and regular fire is one of the best ways to remove it—and the primary way it was regularly removed before colonization. **Prescribed fire** is fire that is ignited intentionally under weather conditions that will produce the fire behavior desired to meet objectives for fire effects. In much of California, it is usually low-intensity fire: relatively short and slower-moving flames, lower heat temperatures, and a limited number of tree crowns catching fire and torching, killing the tree. Low-intensity fire is easily controlled by people using it, with fewer of the embers that can be carried over a control line and start a fire around a house or somewhere else it is not supposed to burn. Although such “escaped” prescribed fires happen less than 0.01% of the time, they are high-profile events that terrify the public and often cause a moratorium on prescribed burning throughout the US. In 2022, the Calf Canyon wildfire began from a midwinter pile burn that persisted under snow, and the Hermits Peak wildfire began as an escaped spring prescribed burn. The two fires ultimately merged to become New Mexico’s largest wildfire and destroyed over 900 homes. This disastrous outcome produced calls from politicians and others to stop all prescribed



FIGURE 23.2.5 (Left) Before a fuel reduction treatment in the Angeles National Forest of Southern California, there was substantial shrub density, with growth well over 10 feet (3 meters) tall (see the yellow-clad person for scale). Photograph from USFS. (Right) After the fuel reduction, piles were burned and a clear understory with low density of trees remains. Photograph by Crystal Kolden.

burns. However, prescribed burning is critical for avoiding even larger and more disastrous wildfires.

How do we know that prescribed burning and regular fire are so critical? In California, forest ecologists have been studying the benefits of thinning and brush removal both with and without subsequent prescribed fire for several decades. They have found repeatedly that when thinning and brush removal occur without prescribed burning, there is still a substantial amount of biomass in the forest that is fuel. When such areas have burned in subsequent wildfires, they burn hotter and with greater tree mortality, and the biodiversity of such areas is lower both before and after the wildfire. By contrast, when prescribed fire is applied either after thinning and brush removal or even by itself, it increases biodiversity, reduces subsequent wildfire behavior (Box 23.2.2), returns critical nutrients to the soil, and reduces competition for water and scarce nutrients, allowing the remaining mature trees to thrive. It also improves carbon sequestration in large trees, a critical component of offsetting carbon emissions from fossil fuel burning. Regular prescribed fire in oak woodlands and grasslands in California is particularly important for restoring and maintaining oak savannas and providing forage for wildlife.

Box 23.2.2

We have ample evidence that prescribed fire is very effective at reducing subsequent fire intensity, even with the more intense fire behavior occurring with climate change. In 2021, the Caldor Fire started in the pine forests of El Dorado County, California, west of Lake Tahoe. Over several weeks, the wildfire burned steadily east toward the crest of the Sierra Nevada, destroying over 1,000 buildings, despite the best efforts of thousands of firefighting resources. Just outside of the Kirkwood Ski Resort, however, the Caldor Fire ran into the Caples Creek Watershed Ecological Restoration Project (Caples Project), and the fire behavior changed. The Caples Project covered over 8,700 acres and had included thinning, brush reduction, and landscape prescribed burns on over 5,000 acres in 2017 and 2019. In 2021, despite high winds and a drought, the Caldor Fire burned across the Caples Project at low intensity, with flame lengths of less than 8 feet (2 meters) that did not kill any large trees. By contrast, outside of the Caples Project, the Caldor Fire burned so intensely that it killed millions of trees across more than 40% of the fire area.

Another way humans can enable greater ecosystem resilience to fire is to support nature-based solutions. There are many nature-based solutions, but one of the easiest to understand is the role of wetlands in mitigating wildfire risk. For much of US history, settlers and the US government sought to drain wetlands and swamps in order to convert them to rich farmlands (as well as reduce the massive swarms of mosquitoes that thrive in such places). We further reduced wetlands by eradicating the engineers responsible for wetland construction and maintenance across much of western North America: the beaver. Fur traders killed beavers nearly to extinction in order to send their pelts to Europe for clothes and hats, and farmers have kept them at bay due to the damage they can cause to culverts and drains on farms. However, beaver-engineered wetlands provide an amazing refuge for flora and fauna during a wildfire because they are simply too wet and cool to burn, and some complexes are extensive enough to actually stop wildfires from advancing (Figure 23.2.6). Scientists have found that supporting beaver reintroduction into habitat they once occupied is as easy as building beaver

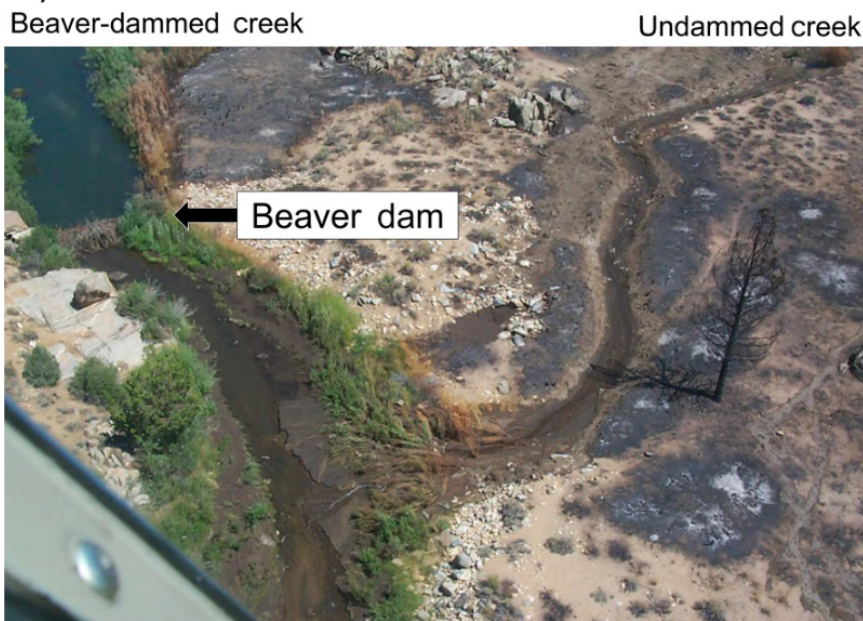


FIGURE 23.2.6 A simple beaver dam on the left fork of the creek produced a fire refugium where vegetation was too wet to burn, while the right fork of the creek, with no beaver dam, was completely burned. From Fairfax and Whittle. 2020.

dam analogues (artificial partial dams that beavers will be keen to build on top of), and once beavers are established, they can restore wetlands in just a few short years, breaking up the landscape and reducing the potential for high-intensity wildfire.

Finally, as climate change continues to alter meteorological patterns and the conditions under which fire burns, it is critical that we monitor changing fire regimes and intervene when necessary to mitigate the worst climate change impacts across all types of fire resilience. Even forests that are fire dependent, such as the high-latitude boreal forests of the US, Canada, and Russia, can have too much fire. Normally these forests have long intervals (several hundred years) between fires, and fires are allowed to burn unchecked because of how remote they are and because they start primarily from lightning. But as the climate warms, boreal fires are reburning at shorter intervals and covering much larger areas. This is particularly problematic because of the vast amount of carbon stored in boreal forests and peatlands and raises questions about whether northern countries should try to actively manage and

suppress these fires. Similarly, while the giant sequoia trees of California are fire adapted, recent high-intensity fires have killed hundreds of ancient monarch trees (the oldest and biggest ones) and led fire managers in the Sierra Nevada to consider special interventions protecting them. Monitoring fire-resilient ecosystems for signs of reduced resilience allows us to prioritize the ecosystems that are the most vulnerable to changing wildfire behavior and also to implement interventions when they can still be effective, rather than when it is too late. The same applies to humans.

23.3 Social Resilience to Wildfire

Humans, and even humans living in California, weren't always so vulnerable to wildfire. Anthropologists estimate that early humans learned to regularly utilize and create their own fire approximately 400,000 years ago. This is not to say that our ancestors didn't occasionally use fire before this, but the best evidence that it was integrated into daily living is for only within the last half-million years. Humans carried fire with them as they spread across the Earth, including into North America, and they eventually developed a broad array of uses for fire, including cooking, hunting, production of tools, agricultural and medicinal uses, ceremony, communication, travel route maintenance, and broader land stewardship. Fire was one of the best tools Native people possessed to impact the land in a way that maximized the productivity of resources they needed and desired. Using fire proactively made early humans resilient.

In what is now California, Indigenous people across a number of tribes used fire extensively, shaping the landscape and vegetation across the state. However, the Spanish colonizers who began to settle in Southern California in the mid-eighteenth century were not accustomed to fire use on landscapes and feared it. More importantly, they quickly realized that banning fire use, as it was so ubiquitous among the Native people, was a critical part of an extensive cultural extermination campaign. The Spanish, with the full backing of the Catholic Church, banned the intentional use of landscape burning almost immediately and arrested and enslaved Native people for continuing the practice.

Colonialism and the war on fire

In the first half of the twentieth century, Americans became truly afraid of wildfire. This permanently altered our relationship with fire, making us less resilient to wildfires. When early European colonizers arrived in eastern North America, wildfire was not a widespread threat, thanks to the wetter climate and the regular use of fire by Native people in

northeastern forests. It was not until Europeans began to log the extensive forests across what is today the northeastern US and eastern Canada that enough slash accumulated to fuel wildfires. The 1825 Miramichi Fire in New Brunswick killed several hundred people and destroyed towns across the region. This was only the first of a series of disastrous wildfires that followed the timber industry on the frontier across the Great Lakes region, including the deadliest fire in US history in 1871 near Peshtigo, Wisconsin. The Peshtigo Fire, occurring the same October day as the Great Chicago Fire, killed at least 1,500 people and likely many more whose remains were never found. Subsequent wildfires in 1881 (Thumb Fire, Michigan; 282 fatalities), 1894 (Hinckley Fire, Minnesota; 418 fatalities), and 1918 (Cloquet Fire, Minnesota; 453 fatalities) led to increased public fear of the raging wildfires portrayed in newspaper headlines. Then, in 1910, the Big Burn torched 3 million acres in Idaho and Montana, killing 87 people. The nascent US Forest Service promptly responded by vowing to put out every new wildfire by 10 AM the next morning, spawning a century of fire suppression in the western US. Further, local fire bans were enacted to prevent immigrant settlers from using fire to clear the forest so they could homestead land claims in the nineteenth century. The timber barons, powerful men who owned vast tracts of virgin timber and had substantial influence over Congress, successfully pushed to ban the regular use of fire both to control the impoverished immigrants (whose abandoned homesteads and timber they then often bought for pennies) and to protect their own vast timber holdings across the West from being torched by wildfires.

Throughout the twentieth century, Americans became increasingly fearful of wildfire both in response to how it was portrayed in newspaper headlines and due to a concerted government branding campaign. During World War II, the government reinforced the idea that wildfire was the enemy by equating forest fires with the Axis powers (Nazi Germany and Japan) in posters and flyers (Figure 23.3.1). Disney made an animated film about a little deer named Bambi who barely escapes a forest fire started by careless humans. Smokey Bear told citizens, “Only YOU can prevent forest fires.” The messaging was consistent: fire was the enemy, and the US had declared war upon it. This cultural shift in just over a century, from fire being a helpful and mostly benign tool of



FIGURE 23.3.1 Caricatures of Adolf Hitler and Prime Minister Hideki Tojo on US Forest Service propaganda posters were designed to make the public scared of starting wildfires, which was seen as aiding the enemy during WWII, when the normal firefighting forces were overseas fighting the war and timber was critical to the war effort. Reproduced from Library of Congress.

land stewardship to being a highly feared enemy, had disastrous consequences for the future social vulnerability of the western US to wildfires. The US Forest Service became incredibly effective at suppressing wildfires with military precision. Most fires were kept small, with only the occasional large or catastrophic forest fire making the news.

Fire disasters in the wildland urban interface

This initial firefighting success had a two-fold outcome that influenced modern disasters. First, as described in the previous section, it allowed forests to grow dense and fuels to accumulate across all landscapes where wildfire and Indigenous fire use previously regularly removed them. Second, it allowed Americans to build increasing numbers of homes and small communities in rural areas closer to and within the wildlands. This interface where rural homes and towns nestled into forests and shrublands became known as the **wildland-urban interface (WUI)**. The US Forest Service had successfully convinced Americans that it could quickly contain fires and that it was safe to build in increasingly rural areas away from crowded and polluted cities.

Between 1990 and 2010, the WUI extent grew by one-third across the US, while the number of homes in the WUI area increased by 41%. The greatest growth in the WUI was in the western and southeastern



FIGURE 23.3.2 The town of Bend, Oregon, is a classic wildland-urban interface where the forest integrates into the city, with thousands of homes situated among tall trees and plenty of fuel for wildfires. Photograph by Crystal Kolden.

states, with Arizona, Colorado, Florida, and Nevada seeing the greatest increases in homes and people living in the WUI (Figure 23.3.2). In California today, 12 million people live in the WUI and one-third of all housing units are located there. This number continues to rise as California seeks to address a decades-long shortage of affordable housing by growing into semirural areas. This trend was only amplified after the COVID-19 pandemic began in 2020, allowing more people to work remotely and seek the affordability and access to the outdoors that they could not find in cities. For Californians, however, this trend of increasing homebuilding coinciding with climate change in the WUI has had disastrous wildfire consequences.

California leads the US in wildfire disasters. Since 1990, wildfires in California have destroyed over 50,000 homes and forced hundreds of thousands to evacuate for days to weeks, unsure if their homes would still be standing when they returned. Over 200 people have died in California wildfires, with the greatest loss of life occurring during the

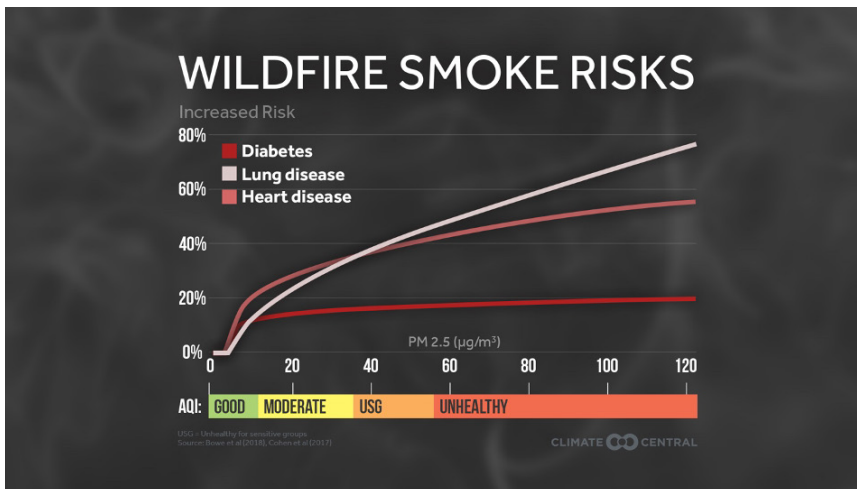


FIGURE 23.3.3 As wildfire smoke exposure increases and people spend extended amounts of time breathing in tiny particles (also called PM2.5) that lodge deep in their lung tissue, their risk of correlated diseases, particularly heart and lung disease, increases substantially. Reproduced from Climate Central.

2018 Camp Fire that consumed much of the town of Paradise and surrounding rural communities in Butte County, killing at least 85 people. Potentially hundreds or even thousands more have died from the indirect impacts of fires, including the heavy smoke that inundates cities and towns throughout the state and triggers asthma attacks, heart attacks, respiratory infections, and other major health problems that ultimately result in premature death (Figure 23.3.3). Such secondary fatalities are often difficult to track but are globally estimated to produce at least ten times the fatalities of the actual flames.

Social vulnerability to wildfire

Beyond the initial death and destruction, wildfires in California ultimately trigger a cascade of consequences, including subsequent debris flows, floods, and contamination of municipal water supplies due to the melting of plastics. Evacuations close schools and businesses, impacting education and job security. Smoke damages crops and affects the health of the laborers who grow and harvest those crops. Burned forests contribute sediment, ash, and charcoal to rivers and reservoirs, reducing habitat for critical cultural species like salmon, altering storage potential

in reservoirs where the burned debris settles, and ultimately reducing water availability during drought years. The loss of housing raises rents and home prices locally, further exacerbating the housing crisis across the state. Over the last decade, numerous regional and national insurers have simply stopped insuring homes in high-fire-hazard areas across California, driving up insurance prices and adding to the already high cost of living.

The harmful impacts of wildfires are not distributed equally across the population, as highlighted in recent wildfire disasters that show some people are more vulnerable to wildfire disasters than others. For example, most homes lost in wildfires are mobile homes, despite constituting only 4% of California's housing units. Mobile homes, however, are often the only affordable housing option for individuals with low incomes, those on fixed incomes (for example, disability or social security checks), and especially those residing in rural fire-prone areas where housing precarity is an ongoing problem. Seniors and individuals with mobility limitations are among the most vulnerable to wildfires. From 2003 to 2021, individuals more than 60 years old composed 76% of California's wildfire fatalities. As many seniors are also on fixed incomes and live in 55+ mobile home parks, the combined vulnerabilities place older and mobility-limited individuals at higher risk of fatalities, loss of homes, and potential for permanent displacement from wildfires.

Marginalized populations consistently bear the brunt of the worst impacts of wildfires, including smoke exposure, subsequent disasters, property loss, and long-term displacement. These communities often face barriers that limit their ability to prepare for, adapt to, or mitigate the negative effects of wildfires. Limited financial resources hinder necessary home upgrades to reduce building flammability, and the high housing prices in less fire-prone areas make it difficult for vulnerable individuals to relocate to safer regions. Indigenous peoples are particularly affected, as their homelands are among the most flammable areas in California. Historical colonization practices banning intentional fire use for preventing disasters have contributed to the vulnerability of these communities. Additionally, transportation challenges, such as limited access to cars and public transportation, further hinder evacuation efforts and increase the risk for vulnerable populations.

Education also plays a crucial role in mitigating the impact of wildfires, as many marginalized individuals lack the knowledge and awareness of appropriate actions to take during fire incidents. Language barriers compound these challenges, as wildfire information is primarily provided in English, neglecting the needs of non-English speakers. This is particularly significant in California, where over one-third of the population speaks a language other than English as their primary language.

Occupational vulnerability is another concern, particularly in professions that rely on temporary employees, such as agricultural workers, day laborers, landscapers, child care providers, house cleaners, and more, who suffer job loss and income reduction during wildfire events. These individuals often lack benefits, paid leave, or accommodations to deal with smoke exposure. Migrant and undocumented workers face additional fears of deportation when seeking time off or requesting accommodations. Once a wildfire ends, vulnerable and marginalized populations face significant challenges in terms of recovery. Job loss and difficulty finding employment during the rebuilding process lead to financial strain, unpaid bills, loss of health insurance, and depleted savings. The scarcity and increased cost of housing after wildfire contribute to homelessness or displacement among these populations.

Recovery efforts are often hindered by the lack of accessible and multilingual information on resources from agencies like FEMA, insurance companies, and state organizations. The expectation that individuals have computer access and can navigate complex forms creates further barriers for those in desperate need of assistance. The bureaucratic nature of the systems can delay aid and prioritize fraud detection over supporting those most in need.

Approximately 40 million people in the US are living in the regions of highest wildfire risk, accounting for over 10% of the national population. Among them, nearly a million families live in poverty, and over 6 million are over the age of 65 or have disabilities, making them more susceptible to wildfire-related harm. Additionally, almost half of these populations identify as Hispanic or people of color, who routinely experience discrimination and marginalization. Language barriers, lack of transportation, and limited access to resources further compound their social vulnerability to all natural hazards, not just wildfire.

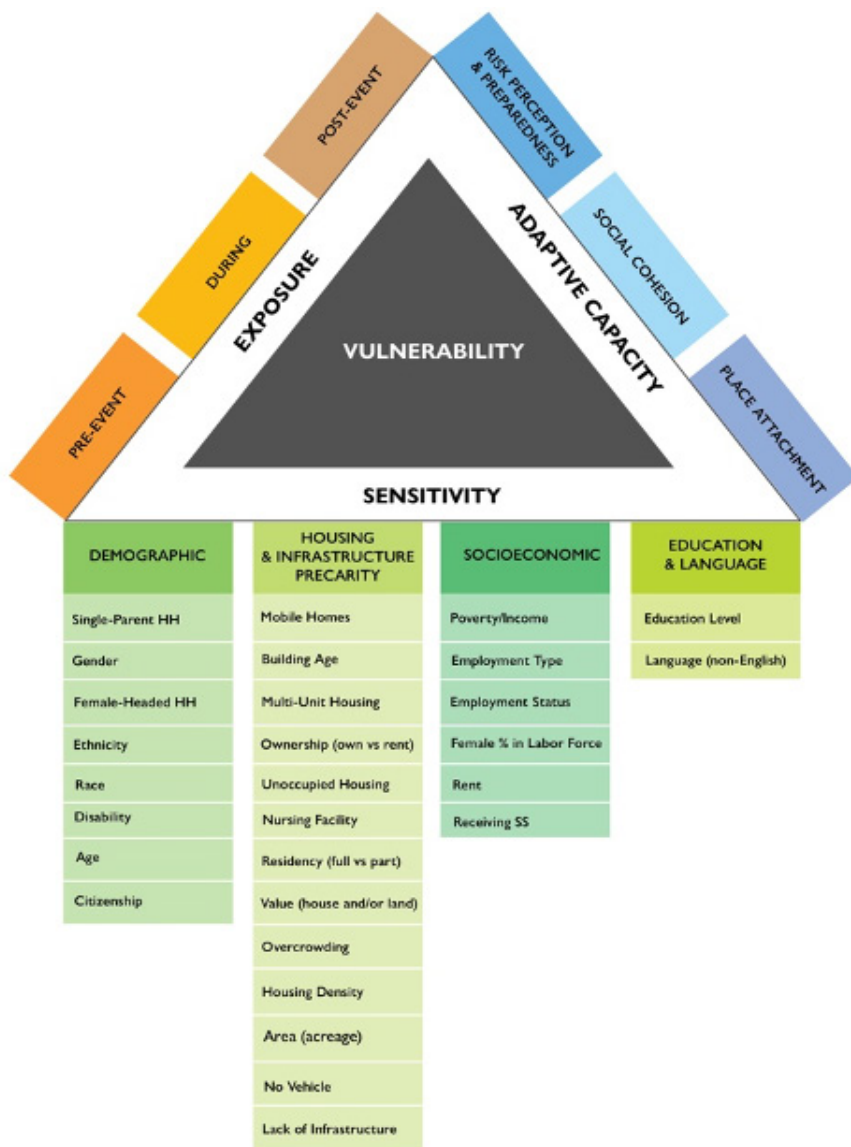


FIGURE 23.3.4 Vulnerability to wildfire disasters is a function of the biophysical risk of fire, the sensitivity of people being exposed to fire, and the ability of communities to adapt and be resilient. Climate justice requires addressing the social inequities that make people sensitive to hazards like wildfire. From Lambrou et al. 2023.

In natural hazards science, vulnerability describes how three characteristics interact: exposure, sensitivity, and adaptive capacity (Figure 23.3.4). Exposure describes the probability of humans being exposed to the physical hazard itself, the wildfire. Sensitivity describes the set of demographic and community characteristics that make someone more susceptible to a negative outcome, like someone with an immune deficiency that is more susceptible to becoming sick. Adaptive capacity describes the ability of people to prepare for hazards ahead of time so they can more easily overcome harmful effects.

Understanding social vulnerability is essential for building resilience as a society. To become truly resilient, it is crucial to identify the most vulnerable populations and prioritize strategies that mitigate their specific vulnerabilities. Our collective strength relies on the well-being of the most vulnerable among us. Developing partnerships between experts in wildfire hazards and those who work with socially vulnerable populations is crucial. These partnerships aim to mitigate the negative impacts of fire and prevent wildfire disasters, rather than solely focusing on fire suppression.

An excellent example of such collaboration occurred during the 2021 Caldor Fire near Lake Tahoe. As the fire approached the city of South Lake Tahoe, evacuation plans were put into action for the entire population of over 20,000 people, plus additional thousands of tourists on vacation. However, a significant concern arose regarding the hundreds of unhoused or otherwise stranded individuals within the city. The Tahoe Coalition for the Homeless partnered with law enforcement agencies and the Tahoe Transportation District to locate and evacuate these vulnerable individuals, ensuring their safety and well-being during the wildfire event. This collaborative effort effectively mitigated potential disaster and protected a highly sensitive population from harm, including the adverse health effects of smoke and potential fatalities.

23.4 Living with Fire

Over the last half century, it has become increasingly clear that trying to suppress all wildfires or even stop ignitions is simply not a viable option. No matter how much money firefighting agencies burn through or how many firefighters they send to the front lines, wildfires will continue to burn as long as there are plants and trees on the landscape, and we definitely need plants to photosynthesize oxygen for human survival. Fire science increasingly points to the need for us to learn to live *with* wildfire, and focus on stopping wildfire disasters, rather than trying to stop all wildfire. But what does it actually mean to live with wildfire? First, it is important to recognize that there is no single solution or quick fix to wildfire resilience. Instead, a combination of strategies and actions is necessary to mitigate wildfire disasters. It took over a century of removing widespread Indigenous fire, suppressing wildfires, and building homes and communities into the wildlands to get where we are today, and it will take time and substantial changes across many fronts to avert future wildfire disasters.

We can't prevent wildfire

In order to avoid disastrous wildfire outcomes, it is essential to account for both where and when fires occur, but also fundamentally change how humans relate to wildfires in the modern era and address the needs of the most socially vulnerable people. One common misconception is the idea that all fires can be prevented. California experiences a substantial number of lightning strikes, igniting hundreds of wildfires annually. Approximately 15% of all California wildfires are started by lightning, but these fires burn 33% of all wildfire area burned in California. Lightning fires burn a disproportionate amount of area because they are often more remote than human-ignited fires and a single lightning storm can start hundreds of fires at the same time across portions of the state,

overwhelming fire suppression. Accidental ignitions by humans are also nearly impossible to prevent entirely. Climate change further complicates the situation, making it unsafe and often impossible to extinguish wildfires quickly, even when it seems like it should be possible to do so. Many wildland firefighters have died trying to fight fires in unsafe conditions, so today firefighting is still aggressive but with key rules in place to prevent firefighter fatalities. All of these factors contribute to a reality where we will always have some wildfire. The actual solution is to better prepare for it so we can avoid disasters, instead of simply hoping wildfire won't happen.

Another commonly proposed solution to the wildfire problem is to simply stop living in wildfire-prone areas. While this may initially sound like a logical solution, it has some key flaws. First, any place with vegetation can burn under the right conditions, and nearly all of California had fire historically and will eventually burn again. Millions of Californians would have to find somewhere else to live under this proposal. Second, since smoke harms far more people than direct flames do, this solution would not mitigate the smoke-induced health outcomes of wildfire. Finally, this solution is not justice oriented; it exacerbates existing inequities across the population by worsening the ongoing housing crisis. Further, since many Indigenous tribes in California live in fire-prone regions, such a proposal continues a centuries-long removal of Native people from their homelands and erasure of Indigenous culture.

Nature-based solutions to mitigate wildfire

So what does work, to mitigate wildfire disasters? First, we can learn from ecological resilience and employ the principles of **biomimicry**, mimicking or learning from nature to solve a problem, to human settlements. What do fire-adaptive species tell us about how to survive wildfire relatively unscathed? Mimicking nature's adaptive strategies can help communities develop resilient approaches to living with wildfire. For example, ponderosa pine trees grow thick, flame-resistant bark to protect their cambium, they drop their lower limbs to create a gap between their crown and flames on the ground, and they have even developed a symbiotic relationship with a specific species of ants that build a nest in the root systems around the tree. These same ants actually remove

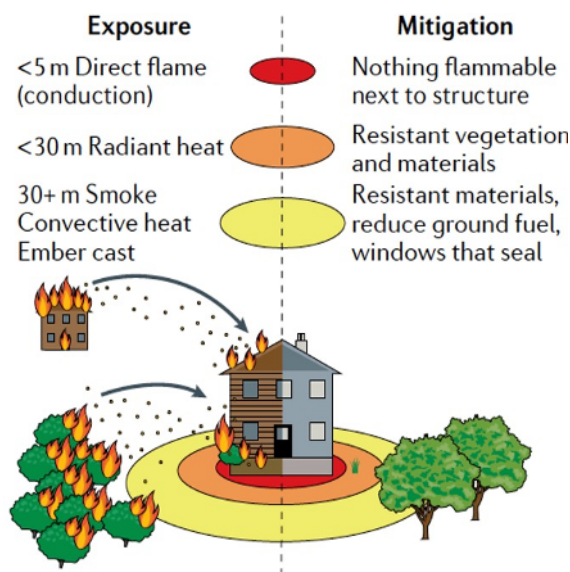


FIGURE 23.4.1 Defensible space and home hardening with nonflammable materials both reduce the number of embers falling onto a home and the potential for those embers to ignite the structure. Adapted from Bowman et al. 2020.

sticks and pine needles that fall to the ground, creating a 2-foot-wide ring of no needles or branches (or anything else that can burn) right around the bole of the tree, protecting it from direct flames.

Humans can replicate this zone of nothing flammable around their homes. A no-fuel zone is one part of creating **defensible space**, a widely promoted system that protects homes from wildfires by reducing more and more flammable vegetation the closer you get to a house. In California, defensible space around the home is meant to be coupled with making the structure itself fire-resistant, a process known as **home hardening** (Figure

23.4.1). Just as a ponderosa pine or giant sequoia grows thick, fire-resistant bark, homes should have nonflammable exteriors made of stucco or fiber cement boards, metal or tile roofs, metal gutters, and nonwood decks and steps. Since 2007, new homes in the highest wildfire hazard areas of California are required to be built to more fire-resistant standards according to Chapter 7A of the California Building Code, and these newer homes have had substantially higher survival rates in recent wildfires, especially when homeowners maintain defensible space around them.

Biomimicry extends beyond individual homes, though. In wildfires there is naturally about 20% to 25% of the area within the perimeter that doesn't burn at all or burns at very low intensity. These areas are called fire refugia by ecologists. These refugia are places where wetlands or streams keep it too wet to burn, or places where trees are spaced far enough apart that fire cannot leap from crown to crown. In communities, we can mimic this spatial pattern by placing homes far enough apart to minimize house-to-house ignitions, and strategically using irrigated

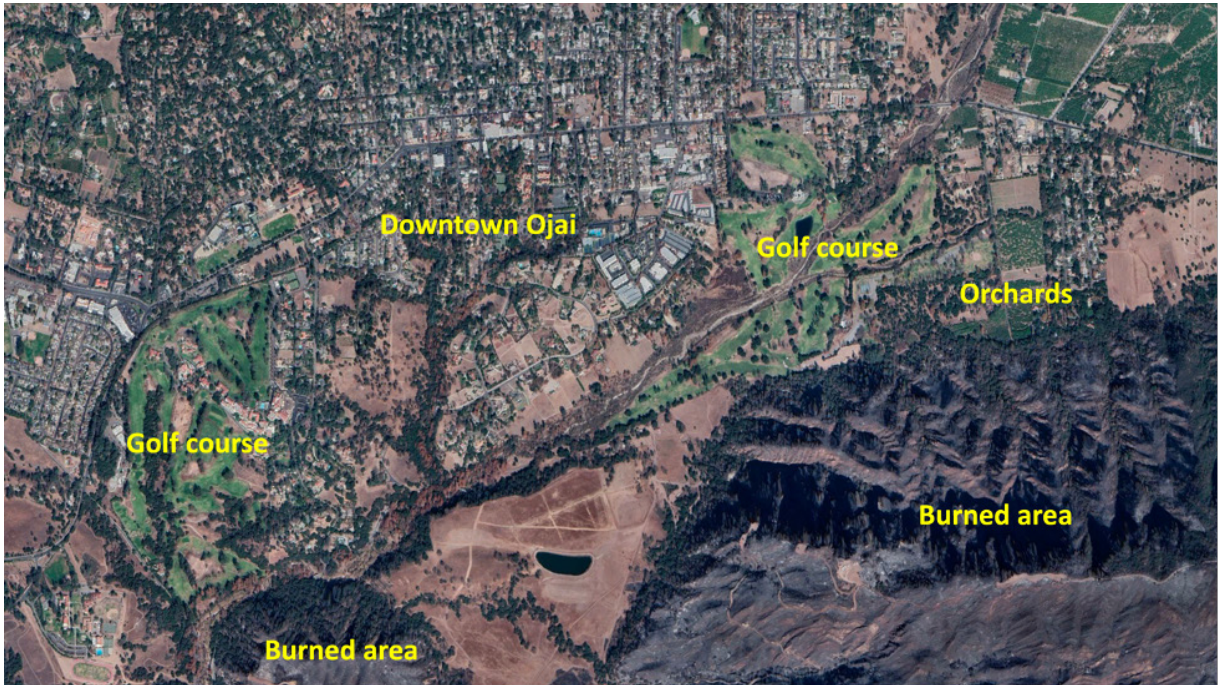


FIGURE 23.4.2 The town of Ojai, California, was partially protected from the devastating 2017 Thomas Fire (black, charred areas) on the south and east sides by two golf courses and extensive orchards that were all irrigated. Adapted from Google Earth 2017.

areas like golf courses and orchards to protect communities. Irrigated golf courses are an ongoing topic of debate in the water-limited western US, but they have repeatedly helped save communities from burning down by acting as barriers to advancing flames (Figure 23.4.2), and irrigated avocado orchards were highly effective in limiting fire spread in the 2017 Thomas Fire in Santa Barbara County, California.

Learning from success stories

Examining success stories helps us to identify where biomimicry and other activities that induce fire resilience can work, and success stories provide valuable lessons and guidance so that we can replicate the most effective practices in other areas. Grazing is a nature-based solution that is increasingly and successfully used across California and other states to reduce fuel for fires, particularly in areas near homes and other places

where it is challenging to use prescribed fire or mechanical means of reducing fuel. The California state capital, Sacramento, has been using goat herds for many years to reduce the amount of grass and shrubs in city parks and on other parcels of land owned or managed by the city. Goats are particularly effective because they are less selective eaters than sheep or cattle, and they will eat invasive species such as noxious weeds.

Indigenous knowledge plays a crucial role in mitigating wildfire disasters. Indigenous people have long understood and managed wildfire risks through cultural burning practices and land management techniques. Recognizing and supporting Indigenous fire stewardship is essential, and efforts to acknowledge the wrongs of the past, promote positive media coverage of Indigenous fire use, educate the public about cultural fire practices, change public policies to remove barriers for Indigenous fire practitioners, and support land back movements are steps in the right direction. In California, key policy changes and increased positive media coverage in recent years have promoted more Indigenous cultural fire use. In 2021, California passed Assembly Bill 642, an omnibus fire bill, that specifically acknowledged cultural fire practitioners as qualified to conduct cultural burns without needing to go through the state or federal prescribed burn boss training programs. The bill also highlighted the need to elevate cultural fire more broadly, identifying key areas where the state should partner with tribes to reduce the risk of wildfire disasters. At the same time, the state passed Senate Bill 332, which changed liability for conducting prescribed burns so that only persons acting in a grossly negligent manner could be held liable for damages from an escaped prescribed fire. This was paired with Senate Bill 170, which created a \$20 million accidental damages fund for persons conducting prescribed burns in accordance with laws and best practices.

All of these legal components have set the stage for substantially increased Indigenous cultural fire, and media and public education are furthering efforts. Courses at UC Berkeley and UC Davis teach students about cultural fire. The state is evaluating opportunities to return ownership of public lands to tribes, and it is providing grants to tribes to increase cultural burning in partnership with private landowners (Figure 23.4.3). Such actions are slowly moving the needle toward climate



FIGURE 23.4.3 Students from the UC Davis “Keepers of the Flame” course learn from tribal partners conducting a cultural burn. From Adlam et al. 2022.

justice for Indigenous people who have repeatedly experienced some of the most harmful outcomes of wildfire.

However, fully addressing wildfire social vulnerability in a climate justice context across California and the western US more broadly requires broader systemic changes. Many of the solutions described above are based on personal responsibility and an agency and ability to change one’s situation, something that many socially vulnerable populations do not have. For example, defensible space and home hardening assume homeownership; however, 45% of Californians are renters and do not own their homes. Mobile home owners may own their home, but they do not necessarily own the land on which it sits, as those living in mobile home parks rent their spaces. Prescribed fire use and grazing is limited to landowners and requires a substantial investment of time and money, something many small rural landowners do not have, particularly if they inherited land but live near or below the poverty line. When smoke events occur in cities, public health officials often suggest that people either stay indoors and run air conditioning or leave town for a few days, luxuries that many low-income and marginalized populations simply

cannot afford. Evacuation planners frequently assume that everyone can drive and has access to a vehicle, but the unhoused population, elderly and disabled people, and low-income families that rely on public transit are left out in such scenarios.

Climate justice and wildfire

In order to address climate justice, wildfire solutions must aim to break down structural inequalities and prioritize social equity. Affordable housing that incorporates fire-resistant design features, particularly in high-fire-risk areas, can enhance community resilience. Safe and accessible evacuation options, including nearby locations within walking distance, are crucial for socially vulnerable populations. Ensuring clean water as a human right and safeguarding municipal drinking water supplies from wildfire toxins is essential. Providing fire information and support services in multiple languages and through various channels, rather than solely online, promotes inclusivity. Empowering agricultural workers with safety measures, paid time off, and worker protections during smoky days contributes to their health and well-being. Universal health care can address the long-term health impacts of smoke exposure, particularly for children. Developing reliable and low-cost public transit systems that reduce pollution and carbon emissions while also serving as evacuation resources during wildfires is crucial.

Socially just wildfire planning requires four key steps: (1) community engagement, partnerships, and empowerment; (2) education and outreach; (3) infrastructure and land management; and (4) early warning systems and evacuation planning. First, community engagement, partnerships, and empowerment are essential to overcoming social vulnerability to wildfire and living with wildfire in California. By involving residents in decision-making processes, fostering collaboration, and building partnerships, communities can develop effective strategies for preparedness, response, and recovery. Engaging community members, including marginalized populations, in wildfire education and awareness programs helps identify the specific needs of marginalized populations and ensures that everyone understands the risks and knows how to take appropriate actions. Empowering individuals to actively participate in

creating fire-adaptive communities fosters a sense of agency and ensures that the socially vulnerable are not overlooked in the planning process.

Education and outreach initiatives are vital for overcoming social vulnerability to wildfire and fostering a culture of living with wildfire in California. Providing accessible and comprehensive information about fire risk, prevention measures, evacuation procedures, and available resources is crucial. Outreach efforts should consider the diverse needs of the community, including language accessibility, cultural sensitivity, and communication channels. Collaborating with local schools, community organizations, and government agencies can help ensure that wildfire education is integrated into curricula and community events, reaching a broader audience and promoting long-term awareness and preparedness. In California, public school children for decades have learned what to do in the event of an earthquake, and they practice getting under desks during the US Geological Survey's annual Great ShakeOut program. There is no equivalent program for wildfire, even though California school children have a far higher likelihood of experiencing a wildfire than an earthquake.

Infrastructure planning that addresses social vulnerability and includes implementing and enforcing fire-resistant building and land management codes is crucial for reducing social vulnerability to wildfire. This includes incentivizing construction of affordable *and* fire-resistant housing and retrofitting homes and apartment buildings with fire-resistant materials, disclosing wildfire risk to prospective tenants, and requiring landlords and absentee homeowners to maintain defensible space around structures. Community-level efforts can focus on implementing zoning regulations and building codes that prioritize fire-resistant construction in high-risk areas; protecting critical community infrastructure, like municipal drinking water supplies, from wildfire; and identifying “clean air” shelters during smoke events, like the warming or cooling centers that open to the community during heat waves and cold snaps. Encouraging responsible land management practices, such as controlled burns and vegetation management, through incentives, education, and partnerships with local fire departments and land management agencies is key to enhancing community resilience.

Finally, establishing robust early warning systems and implementing effective evacuation planning are critical components of overcoming social vulnerability to wildfire and living with wildfire in California. Alert systems like reverse 911 automated notification systems, that are mandatory rather than optional, can disperse accurate information more rapidly to everyone in an affected area. Backup siren systems can be installed for when cell phone towers and power grids fail. Evacuation planning should prioritize the needs of vulnerable populations, including those without personal transportation, by identifying transportation alternatives, clearing roadside trees and brush to ensure evacuation routes stay open, and developing local last-resort evacuation locations that are the equivalents of local bomb shelters that were built across the US in the mid-twentieth century in the event of nuclear war.

The community of Montecito, California, near Santa Barbara, is one of the most expensive places to live in the entire state. Yet, it still has socially vulnerable residents. Beginning in the 1990s, the Montecito Fire Protection District began working in partnership with residents to plan for the next big wildfire. They developed a variety of programs, including neighborhood chipping of trees and shrubs removed from properties, free defensible space inspections, prescribed burning, home hardening grants, road widening and brush removal on evacuation routes, and an evacuation preparedness education campaign so residents would be prepared to evacuate quickly when the time came.

In December 2017, Montecito faced one of the most harrowing days of the massive Thomas Fire, when sundowner winds exceeding 70 miles per hour drove flames downhill out of the national forest and into town. Remarkably, the community was relatively unharmed, despite the extreme fire behavior observed. There were no fatalities and only a few homes lost. Firefighters were able to protect homes and stop the Thomas Fire from overrunning the town despite the extreme winds, specifically because 20 years of preparatory work had been done. Interviews and mapping of community efforts revealed that landowners had created defensible space in an almost unbroken line along the northern edge of town, and firefighters were able to safely attack the fire in these areas. It was an incredible outcome, particularly given that planning models had projected that up to 500 homes would potentially burn down in such

extreme conditions, and it was the outcome of a strong partnership between multiple fire agencies and the residents of the community.

A similar type of outcome was seen in the 2021 Caldor Fire when the fire reached South Lake Tahoe. The Caldor Fire burned under such extreme conditions that it marched across the Sierra Nevada mountain range, burning hundreds of homes along the way, with fire suppression efforts futile to stop it. However, when it reached the east side of the Sierra and descended into Meyers and South Lake Tahoe, something incredible happened. A multiagency partnership had spent over two decades conducting prescribed burns, thinning out smaller trees, limbing larger trees, and removing brush around South Lake Tahoe, effectively removing so-called ladder fuels across thousands of acres of forest. These same agencies launched massive education campaigns and grant programs for residents living along the edges of the forest to develop and maintain defensible space and harden their homes against embers and flames. Evacuation plans were developed that centered the needs of the socially vulnerable, and agencies came together to prepare for the worst-case scenario. The result was that while hundreds of homes were lost in the Caldor Fire, the area around South Lake Tahoe was virtually unharmed. Keeping the fire completely out of South Lake Tahoe's core protected the vulnerable portion of the population that likely would have become climate refugees if that core burned, as affordable housing would have been completely consumed and housing prices would have soared.

23.5 Summary

Climate change is increasing the potential for wildfire disasters in California. This is occurring due to an increasing number of days of extreme fire danger, both during the summer when record heat events make vegetation incredibly flammable and during the autumn when downslope winds and dry fuels combine to create conditions for some of the most destructive wildfires in California history. Historically, California ecosystems were fire resilient and evolved many adaptations that allowed species to avoid, adapt to, or even depend upon fire to survive and reproduce. As our relationship to fire changed and we saw it as the enemy to be defeated, the health of our ecosystems declined and we increased the potential for catastrophic wildfires. Today, we can learn from ecosystem adaptations and apply nature-based solutions to restore the health of California forests and mitigate wildfire disasters to communities. There are many examples of communities that have adopted a range of solutions to mitigate fire disasters, and these examples show us that wildfire resilience is complex. The challenge moving forward is to identify place-based solutions that work for a given location and protect the most socially vulnerable populations in order to achieve climate justice. Addressing social vulnerability and achieving wildfire resilience requires comprehensive approaches that consider ecological factors, social vulnerability, learning from success stories, Indigenous knowledge, and community partnerships. By integrating these strategies with a focus on justice and equity, California can work toward a more resilient future in the face of increasing wildfires.

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- Figure 23.2.1: Photograph by Crystal Kolden.
- Box 23.2.1: Photograph by Crystal Kolden.
- Figure 23.2.2: Photograph by Crystal Kolden.
- Figure 23.2.3: Photograph by Crystal Kolden.
- Figure 23.2.4: Photograph by Crystal Kolden.
- Figure 23.2.5: Photographs from US Forest Service (left) and Crystal Kolden (right).
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- Figure 23.3.3: Graphic from Climate Central. <https://www.climatecentral.org/climate-matters/wildfire-smoke-waves-2018>.
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- Figure 23.4.2: Adapted from Google Earth. Image date December 30, 2017.

Figure 23.4.3: Adlam, C., et al. 2022. Keepers of the flame: supporting the revitalization of Indigenous cultural burning. *Society & Natural Resources* 35(5), 575–590.

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Chapter Glossary

Following is a list of terms and acronyms used in the chapter.

TABLE 23.1.1 **Glossary Items**

Term	Definition
Fire triangle	Heat, oxygen, and fuel are the three components needed for fire to burn. These make up the fire triangle.
Pyrolysis	The heating of fuel in the absence of oxygen, deconstructing the polymers.
Combustion	A chemical reaction between fuel and oxygen that produces heat and emissions. When this reaction is sustained, the visual by-product is a fire.
Fire regimes	Patterns of fire across space and time. Attributes of a fire regime describe the frequency, intensity, severity, size, ignition source, timing/seasonality, location, and effects of fire.
Pyrocumulonimbus clouds	Thunderstorm clouds that form due to the high amount of convective energy during a wildfire, sufficient to enter the lower stratosphere.
Katabatic heating	Heating of air that moves from high to low pressure, often from higher to lower elevation, heating as it is compressed and from friction with the surface.
Fire resilience	The ability of an ecosystem or landscape to recover from the detrimental impacts of fire to prefire functionality.
Fire refugia	Locations on the landscape where fire either does not burn or has very minimal fire effects due to either a lack of fuel or flammability, such as in wet meadows or bogs.
Paleoendemics	Species that are from a much earlier time in Earth's history (paleo) and only found in that location (endemic).
Prescribed fire	Fire that is ignited intentionally under weather conditions that will produce the fire behavior desired to meet objectives for fire effects.
Wildland-urban interface (WUI)	Interface where rural homes and towns are nestled into forests and shrublands.
Biomimicry	Mimicking or learning from nature to solve a problem.
Defensible space	A buffer around a structure where fuel for a fire has been reduced or removed entirely. It is considered defensible because firefighters are able to safely defend a structure from advancing flames.
Home hardening	The removal or replacement of flammable materials or components on a home with nonflammable materials. For example, roofs, siding, decks, and gutters that are made of plastic vinyl or wood are replaced with metal, fiber cement board, stucco, tile, or other nonflammable materials.