Chapter 10
Fire and People

Learning Outcomes
After reading this chapter, you should be able to

1. Build a table of costs and benefits of fires and then describe in your own words how you think those can be balanced to inform people making decisions about fires,
2. Articulate how smoke can compromise human health and name several strategies for reducing the vulnerability of people to smoke from fires,
3. Develop three short statements you can use to inform people about fire, and for one of them how you will adapt them to communicate with people from different perspectives within wildland-urban interface communities, and
4. Explain, based on the fire science you learned in this and previous chapters, one strategy for protecting fire fighters and other people and their homes and communities from fires long-term.

10.1 Introduction

Humans have long used, valued, and feared fire. Fires have been part of the Earth's system for millennia (Fig. 2 in Introduction to this textbook), and people have long influenced how fires burn. People often aggressively suppress fires, usually out of fear of how fire will affect them or those people and resources they care deeply about. People also ignite fires, sometimes accidentally and sometimes on purpose,

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and people make tremendous efforts to control fire and fire effects. In all human cultures, fire is a symbol of power, warmth, and renewal.

“Fire is a bad master but a good servant”. This old saying, and similar sentiments deeply rooted in many different languages, reflect the complex realities of fire. Fires can threaten people and property, yet people can use their understanding of fire to mitigate such threats. People are often affected by fires and smoke, yet people also value the ecosystem services that fires often maintain and sometimes enhance. For instance, fires consume fuels that otherwise accumulate and can lead to future high-intensity fires. Many plants and animals survive and thrive after fires. However, fires can also have negative impacts on the things people value.

Living with fire depends on taking action based upon a sound understanding of fires behavior and effects. Some people suggest that we learn from Indigenous cultures about fires (See Sect. 10.5 and Case Study 13.7). As climate changes, both traditional knowledge and scientific knowledge about fire and ecosystems can help people coexist well with fire (Moritz et al. 2014; Schoennagel et al. 2017).

Fires are what people make of them, and fires will reflect how people perceive them. Thus, although fires are biophysical processes, they are influenced by the social, political, economic, and cultural context in which they occur. The success of fire suppression policies and tactics to protect people and homes can paradoxically lead to the accumulation of fuels that can increase the intensity of subsequent fires. Thus, the fear of negative consequences of fires has led people to make policies and take actions that can lead to fires that adversely affect people. Integrated fire management (see Chap. 13) seeks to increase positive and decrease negative impacts of fires. This often involves balancing the need to protect people and property from fires with the ecological imperative of fires burning.

How do people value the costs and benefits of fire, including ecosystem services? How are people affected by and what will protect fire fighters and other people from heat during fires? How can people reduce the likelihood that their homes will burn in wildfires? The smoke that commonly spreads far from the flames can endanger human health, so how can we manage smoke while using fire proactively and effectively? How might individual people and the communities we live in become fire-adapted so that we can live well with fire? How can we reduce vulnerability and increase the resilience of social-ecological systems to fires? How might we learn together, and how can traditional ecological knowledge complement science to help people? We address these questions in this chapter. We don’t review all of the ways fires and smoke affect people. Instead, we highlight important concepts and how they are linked to fire behavior (Parts I and II, including Chaps. 1–5, 7, and 8), and ultimately to fire effects (Chap. 9), fuels management (Chap. 11), changing fire regimes (Chap. 12) and integrated fire management (Chap. 13).

10.2 Different Perspectives About Fire

The relationship between fire and people can be complicated because there are different perspectives. Much active research in social science and environmental economics is devoted to this topic. Here we present different perspectives, starting from those emphasizing the adverse effects of fire, focusing on wildfire damages and other changes due to fire, to those including the beneficial effects of fire under a more comprehensive perspective.

10.2.1 Fire as a Disaster and Change Agent: Vulnerability, and Resilience

This perspective of viewing wildfire only as a hazard is common to the approaches used for other natural hazards, like floods or earthquakes. Many of the concepts and terminology agreed upon internationally provide a common understanding for use by the public, authorities, and practitioners (UNISDR 2009) and allow for the development of indicators to measure global progress in implementing the Sendai Framework for Disaster Risk Reduction 2015–2030. The perspective of fire as a disaster focuses on the negative effects of wildfires. Extreme wildfires represent disasters when they lead to human, material, economic, and environmental impacts. However, this perspective typically does not take into account the possible benefits that fires can also provide. Alternatively, we can view fires as agents of change that can have both positive and negative effects.

Fires change system values, as fires affect people, infrastructures, and ecosystems. The degree to which the system is affected depends upon its exposure and vulnerability. The fraction not affected is the resistance of the system to the event. The accumulated change is a function of the value of the system, its exposure and vulnerability to the event, and the recovery time (Fig. 10.1). Resilience is the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazardous event in a timely and efficient manner (UNISDR 2009).

The vulnerability of people to fires varies widely. Vulnerability to wildfire and peoples' ability to adapt to fire often varies with race, ethnicity, and economic capacity (Davies et al. 2018). Wildfire vulnerability increases when and where large fires result in large areas burned with high severity. Both social factors and fire behavior and size influence the vulnerability of both individuals and the communities they live in. Older adults are especially vulnerable to both fire and smoke, as is anyone who is not very mobile and has limited financial and social resources.

Resilience depends on the adaptive capacity of people to prepare for, live through, and recover from wildfire (Holling 1985). Resilience will be different for different people and places. Globally, 55% of the world's people live in urban areas, as many people have left many rural areas (UN 2018). North America is mostly urban (82% of all people live in cities), while Africa is mostly rural (43% of people live in urban areas). Abandoning marginally productive agricultural lands increases fuels and fire hazard in many places. Many poor people are so vulnerable that wildfire events can be both devastating and difficult to recover from. Resilience depends on socioeconomic resources, including insurance. Families who rent rather than own their homes may not be eligible for the federal and state funding designed

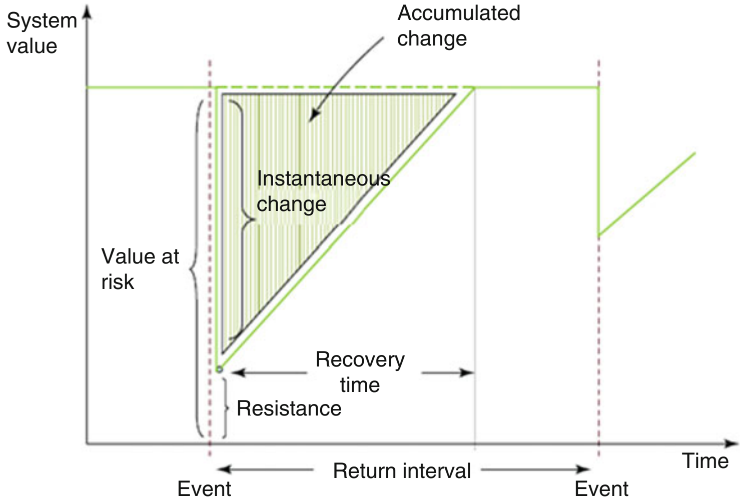


Fig. 10.1 Fires result in changes in system values. The accumulated change (shaded area) depends on the instantaneous change and the recovery time. The recovery rate (instantaneous change/recovery time) is a fundamental indicator of the capacity of the system's resilience. The fraction changed is an indicator of its vulnerability. Originally developed for fire as a damaging agent, we adapt this perspective to recognize that fires can have both positive and negative effects. Then, vulnerability and resilience are evaluated relative to change due to fires, whether those are positive, negative, or both. (Adapted from Rego and Colaço 2013)

to help people recover from fires (Davies et al. 2018). Sadly, many Native Americans, especially those living on reservations, are vulnerable to fire. Early settlers of central North America learned about fires from Native Americans, and many tribes now are innovative in their use of fires. White people of higher incomes are more likely to live in communities with adaptive capacity for fires. Some rural areas, often described as "amenity communities", are growing fast because they are attractive for recreation and second and third homes.

Recognizing, adapting, and mitigating risks are critical for increasing the resilience of social-ecological systems to fires (Smith et al. 2016). For communities to become more resilient, Schoennagel et al. (2017) emphasized the concept of "adaptive resilience" based on recognizing both the potential and the limitations of fuels management, acknowledging the vital role of wildfire in maintaining many ecosystems and ecosystem services, and embracing new strategies for living with fire. Understanding fire and smoke can help communities develop local strategies to become fire adapted. Outreach advisors working with communities long before and long after fires can aid preparations and recovery and share the messages that fires have benefits as well as costs. Communicating in ways that are meaningful depends on recognizing and appreciating who is listening and when. People vary in their attitudes about fire and protection strategies. Engaging people effectively depends on listening well, understanding, and messaging.

10.2.2 The Economic Perspective: Costs of Pre-suppression, Suppression, and Net Value Changes

A second perspective about fires comes from the economic models used to evaluate wildfire management programs. Sparhawk (1925) focused on minimizing costs and losses due to fire. Optimal program levels were based on the trade-offs between pre-suppression costs (fire management costs before fires), suppression costs (during fires), and losses due to fires. According to this model, the optimum pre-suppression budget is the value that minimizes total cost plus losses due to wildfires (Fig. 10.2).

This Least Cost plus Loss model has many drawbacks that limit its practical use. In particular, it is challenging to estimate wildfire damage, or even area burned, only as a function of the pre-suppression budget. The assumptions of the models are difficult to verify and many other factors are involved in the outcome. In the USA, area burned has increased in recent decades with increases paradoxically paralleling investments in fire suppression (Fernandes et al. 2020, Fig. 10.3). Further, while these analyses may indicate how much pre-suppression resources are optimal, the approach does not guide allocating to the many pre-suppression activities that can take place. Although this model has evolved through time (e.g., Gorte and Gorte 1979), in its initial formulation the possible benefits from fires were not considered.

The recognition that some effects of wildfire can be beneficial (e.g., fuel consumption and ecological benefits) led to the development of more comprehensive economic models under the concept of Cost plus Net Value Change (C + NVC) model (Donovan and Rideout 2003). The Net Value Change (NVC) is the difference between losses and benefits to the resource resulting from the fires. The pre-suppression and suppression costs are considered as independent inputs, whereas only pre-suppression was independent in the previous model. The economic analysis of the efficiency of fire management programs is now generally evaluated by this C + NVC model (e.g., Thomas et al. 2017) with resources allocated accordingly (Fig. 10.4). Still, determining the optimal mix of fire-fighting resources for a given fire management program is a necessary condition for identifying the

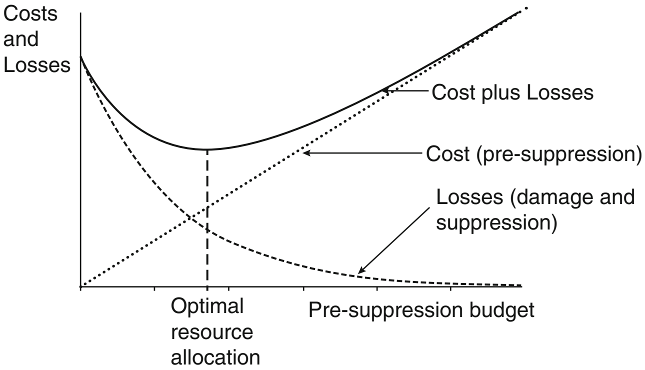


Fig. 10.2 Least Cost plus Loss model for fire management (Sparhawk 1925). The optimal resource allocation for the pre-suppression budget minimizes total Cost plus Losses

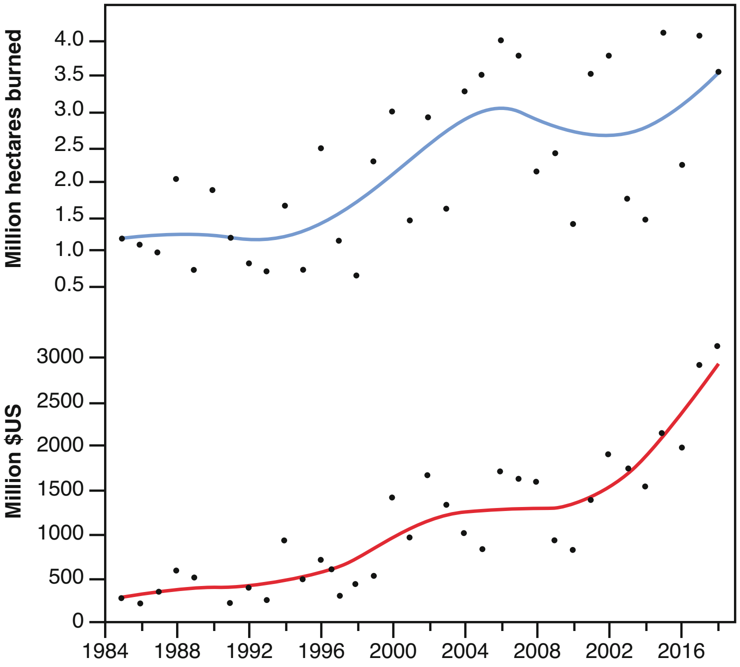


Fig. 10.3 Observed (*dots*) and smoothed (*lines*) area burned in the USA and costs of fire suppression (1985–2018, adjusted for inflation) based on data from the National Interagency Fire Center. (From Fernandes et al. 2020)

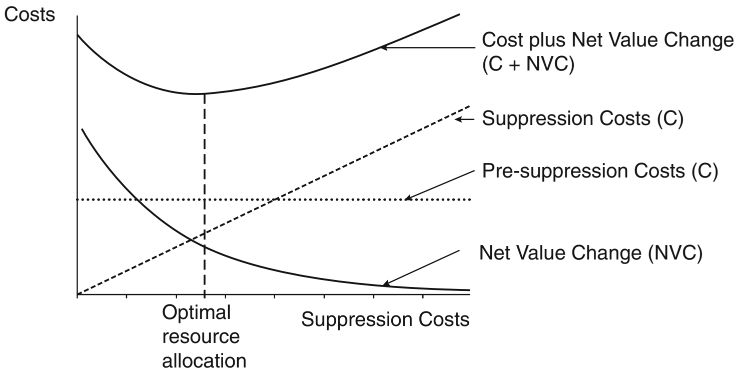


Fig. 10.4 The Cost plus Net Value Change (C + NVC) model for fire management with the indication of the optimal resource allocation for the Suppression Costs, considering Pre-suppression Costs separate from Suppression Costs. The total Cost plus Net Value Change is obtained by adding Pre-suppression and Suppression Costs to the Net Value Change resulting from the wildfires. (Redrawn from Donovan and Rideout 2003)

minimum of the Cost Plus Net Value Change (C + NVC) function (González-Cabán et al. 1986; Mavsar et al. 2010).

The C + NVC model has been widely applied in strategic budgeting in fire management and has integrated benefits from fire and ecological restoration (Rideout et al. 2014, 2017). However, this is challenging as fire management includes multiple objectives. The costs associated with suppression are often easier to estimate than the other costs that may be 2–30 times than the fire suppression (AFE and IAWF 2015). The costs associated with fire management include a diverse array of activities from prevention (including personnel, education, training, detection, enforcement, and equipment), to mitigation (including personnel, fuels management, insurance or disaster assistance), and suppression (including personnel, equipment, training), and post-fire management, as well as legal issues and regulations. This complexity increases when considering the direct and indirect costs of fire management and fire effects in the wildland-urban interface (WUI) fires (Thomas et al. 2017). In WUI fires, because of the people and property values at risk, the tactics and the costs of fire suppression are very different from those in fighting remote fires; WUI fires account for as much as 95% of suppression costs (Schoennagel et al. 2017) and risk to fire personnel.

Fires have sometimes burned electrical power lines and other infrastructure. Sparks from electrical power lines have ignited fires during windy, dry conditions, and the companies distributing electricity have been sued for related fire damages. As a result, Pacific Gas and Electric stopped providing power during high fire danger in California during the summer of 2019 (Abatzoglou et al. 2020). Avista Utilities (2020), a major utility company in the northwestern US, has a comprehensive fire management plan designed to reduce risks to the public, workers, and infrastructure while also limiting the impact of electric system outages due to fires. In addition to hardening the powerline grid by replacing infrastructure such as wooden poles with metal poles in fire-prone areas, the plan calls for managing vegetation to reduce the potential for trees to fall into power lines, improving situational awareness to aid managers, installing automated systems to alter powerline systems in response to fire, and improving operations and emergency personnel. The company works closely with local communities and fire management personnel.

Adverse health impacts of smoke from fires represent a cost to society, but the multiple costs can be difficult to quantify (Kochi et al. 2010; Moeltner et al. 2013). Visits to hospital emergency rooms for respiratory or cardiac complaints due to smoke increased over 3 years in Nevada, USA (Moeltner et al. 2013). More people were exposed to more smoke when fires consumed more fuel close to urban areas in Indonesia, Florida, and elsewhere. Better data on the area burned, the amount of fuels burned each day, and daily medical cost records are needed to inform alternative fire management strategies (Moeltner et al. 2013). Smoke impacts on urban areas are often part of fire suppression decisions. See Sect. 10.4 for information on smoke effects on human health.

Because it can be challenging to value the ecosystem impacts and benefits fiscally, Net Value Change (NVC) is even more difficult to estimate than costs. Quantifying NVC requires information about the direct and indirect effects of fire on the spatial and temporal provision of goods and services, and information about how fire-induced marginal changes in the quality and quantity of goods and services will affect social welfare (Venn and Calkin 2007; Mavsar et al. 2010).

Alternative systems for valuing intangible resources are needed. Rideout et al. (2012) elicited relative values of various natural and cultural resources, from wildlife habitats to archaeological sites. They worked with managers to estimate the relative degree to which the resources would be enhanced or harmed by wildfire in four national parks in the USA.

10.2.3 The Environmental Perspective: Focusing on Ecosystem Services

Ecosystem Services are “the benefits people obtain from ecosystems” (Millennium Ecosystem Assessment 2005). People value many ecosystem services for contributing to health and well-being. Some of these services are provided at the landscape scale. The concept of Landscape Services has also been proposed as a unifying common ground where scientists from various disciplines are encouraged to cooperate in producing a common knowledge base that can be integrated into multifunctional, actor-led landscape development (Termorshuizen and Opdam 2009). In Chap. 9, we discussed both the positive and negative effects of fire on ecosystems. Fire management at the landscape scale will be discussed and exemplified in Chaps. 11–13. Here, the term Ecosystem Services will be used in a broad sense encompassing various scales.

Ecosystem services include (a) provisioning, as ecosystems provide both nutritional and non-nutritional materials, water, and energy; (b) regulation and maintenance in ways that affect human health, safety, and comfort; and (c) cultural values, including how people feel about and see places (Haines-Young and Potschin-Young 2018). People have taken advantage of burned areas and used fire to make openings for grazing, agriculture, and hunting, consume fuels and stimulate the production of desirable biomass, including forage, seeds or fruits, and provide edible, medicinal, or other culturally important plants (Huffman 2013). Fires can consume fuels that would otherwise accumulate to fuel future fires, though fires may also stimulate grass and other surface fuel to grow (See Chap. 11). Fire can be used to regulate carbon (see Case Study 13.1), to create and maintain habitat for plants and animals or to enhance biodiversity, vegetation composition, and to influence pest populations (Pausas and Keeley 2019). Certainly, subsistence hunting and agriculture, and some recreational hunting can be enhanced in burned areas (Huffman 2013; Pausas and Keeley 2019).

Having enough water of sufficient quality is a growing global problem exacerbated by fires (Doerr and Santín 2016). Water quality and quantity are essential ecosystem services as most people depend on streams and other surface water for drinking for people and animals and often for agriculture. Martin (2016) declared fires to be a severe threat to water supply globally, as fire-prone ecosystems, including forests, shrublands, grasslands, and peatlands, provide about 60% of the water for the 100 largest cities in the world. Vegetation fires burn about 4% of the burnable land globally each year. Years of widespread fires are dry years. In droughts, the competing demands for water use for agriculture, industry, drinking water, habitat for fish and other aquatic organisms, and other services often exceed available water. Surface water supplies can be vulnerable to fires if the amount of sediment, debris flows, and wood increases after the lands adjacent to streams, lakes, and reservoirs burn, especially when high-intensity rain falls before vegetation recovers from fires. Areas that burned severely may develop hydrophobic layers in the soil that limit infiltration (See Sect. 9.5). How fires affect vegetation and soils and how quickly vegetation recovers can influence whether surface runoff increases post-fire. Nunes et al. (2018) provide a useful framework for assessing and managing the potential for fires to influence water (Fig. 10.5).

Because of this strong connection between fire and ecosystem services, Pausas and Keeley (2019) consider fire an ecosystem service, summarizing both the evolutionary and socioecological benefits generated by fires. However, while many ecosystem services increase in the short or long-term after fires, many others decrease because of fires. It is, therefore, more appropriate to see fires as a part of a complex network of ecosystem processes whose interactions may translate into services or disservices for society (Sil et al. 2019).

10.2.4 An Integrated Fire Risk Framework

A more comprehensive fire risk framework is needed, one that integrates the definitions from other hazards and the aspects specific to fires. Miller and Ager (2013) proposed a generalized framework for fire risk based upon their review of advances in risk analysis for wildland fire management (Fig. 10.6). They defined risk as the expected loss or gain, similarly to the Net Value Change concept. Risk results from the combination of the likelihood, or probability, of the fires occurring, as well as the intensity of the fire, and the resulting fire effects, that are valued positively or negatively according to the value system (ecological, social, economic) used. This framework acknowledges that both the likelihood of the fire and its intensity are related to fire behavior, ignition, fuels, and weather (Fig. 10.6).

One of the most complex issues in fire economics results from the fact that fires are different in their behavior and, therefore, in their effects. This issue is solved, from a quantitative point of view, by Finney (2005) in his formula to integrate likelihood, intensity, and effects in the calculation of risk as the expected Net Value Change to resource j:

$$E(NVC_i) = \sum_i^n \rho_i \, x \, RF_{ij} \tag{10.1}$$

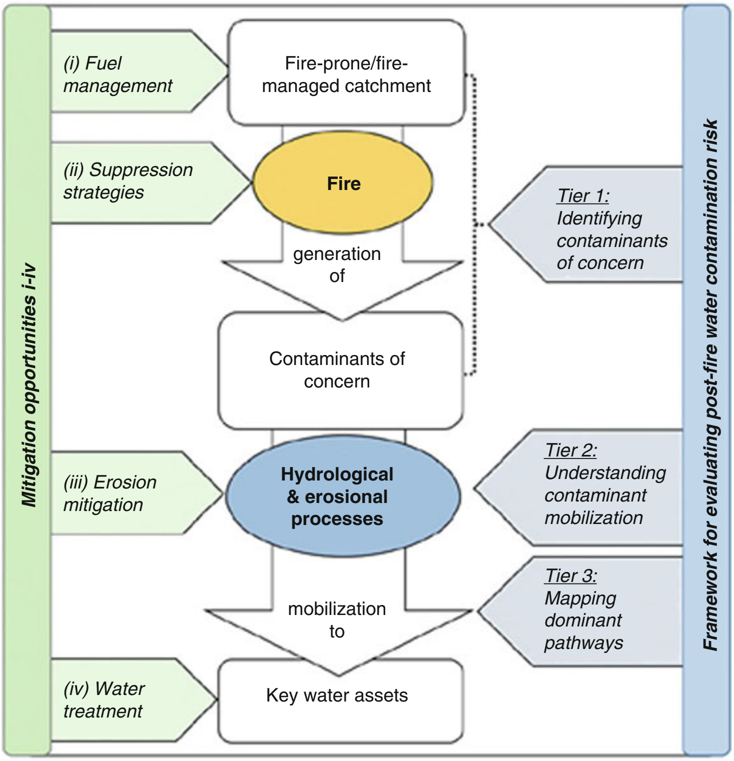


Fig. 10.5 Mitigating the risk of high severity fire is a high priority in key watersheds, such as those that supply drinking water. In some, contamination by sediment and chemicals may also be mobilized during and after fires. This framework is valuable, but it does not reflect the effects of burn severity, size of burned patches and proximity to streams, nor time since fire and degree of vegetation recovery, all of which affect fire effects on water and watersheds. (From Nunes et al. 2018)

where p_i is the probability of fires of intensity i and RF_{ij} is the response function of resource j as a function of a fire at intensity i.

The difficulties in calculating NVC values are the same as before, and the temporal dynamics of risk are not fully integrated. However, in this formulation, fires of different intensity, or severity, will have effects associated with resource values in resource functions. It also allows the integration of different resources in the same analysis.

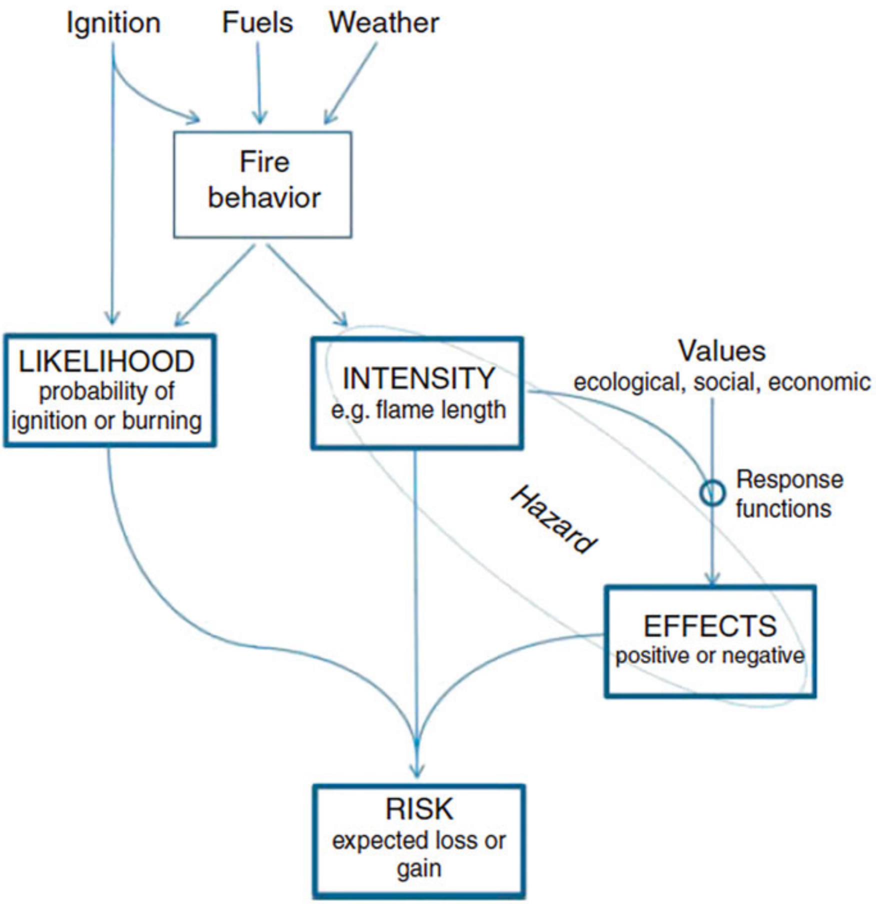


Fig. 10.6 Fire risk can be evaluated as expected loss or gain based upon how likely fires are to occur, their intensity, and both positive and negative effects of fire. (From Miller and Ager 2013)

10.3 Protecting People from Fires

The exposure to heat, embers, and smoke generated during a fire can cause various impacts on human health, property, and infrastructure. People's vulnerability from wildfires depends on several factors, including fire behavior and effects, and people's mobility and health. The safety of people traveling in the area often depends on timely (think early!) advice on escape routes. For residents, shelter in a safe building is usually preferable to trying a last-minute escape. Threats to houses and other infrastructures are often associated with exposure to heat and embers. Here we focus on concepts associated with estimating heat effects on people and buildings. See the discussion about embers and extreme fire behavior in Chap. 8.

The heat from fires can injure or kill people. Fire's effect on people depends upon the level of exposure. Exposure can include both the amount of heat and the duration over which heating occurs. Heat damage to human health, including pain and skin blisters, can be limited by the personal protective clothing (PPE) worn by wildland fire personnel. Similarly, fire fighters develop safety zones to reduce the heat exposure of fire personnel so that they can survive the passing of a fire front without the use of a fire shelter. Drawing upon the concepts in earlier chapters, we first discuss the direct effects of heat from fires on individual people. Then we address strategies for protecting people and their property from fires.

We acknowledge but don't address the mental and physical toll that increasingly long fire seasons in recent decades are having for fire fighters, residents, and politicians.

10.3.1 Fire and Skin

Human skin provides natural protection against radiation, in particular, that from the Sun. The Sun has a temperature of around 5780 K, an emissivity of 1, and it radiates with an average energy flux of 632.8×10^2 kW m^{-2}. Taking into account the radius of the Sun (6.96×10^8 m) and the distance between Sun and Earth (1.49×10^{11} m), the maximum potential radiant heat flux received at Earth's surface (q_{rad} in W m^{-2}) is:

$$\begin{aligned} q_{rad} &= \left(632.8 \times 10^2\ \text{kW m}^{-2}\right)\left(6.96 \times 10^8\ \text{m}\right)^2 \div \left(1.49 \times 10^{11}\ \text{m}\right)^2 \\ &= 1.38\ \text{kW m}^{-2} \end{aligned} \tag{10.2}$$

With an average value of the albedo at around 0.7, the radiant heat flux from the Sun at the Earth's surface is about 1.0 kW m^{-2}. It should be no surprise that 1.0 kW m^{-2} is also the radiant heat threshold to cause pain to a human's bare skin after prolonged exposure (Quintiere 2016).

The effects of radiant heat flux on the human skin have been a subject of many studies (e.g., Wieczorek and Dembsey 2016) that conclude that the human body cannot tolerate elevated temperatures for long periods of time without causing pain, blistering, or other injuries. Humans feel pain when the skin temperature reaches about 43 °C, and exposure to a heat flux of 4 kW m^{-2} for 20 s will cause blisters on bare skin. The relationship between radiant heat flux (q_{rad}) and the exposure time required for a human to feel pain or cause blisters (Fig. 10.7) and can be estimated using Eqs. (10.3) and (10.4) (Stoll and Green 1958, 1959; Quintiere 2016):

$$\textit{Pain threshold} \quad q_{rad} = 30\, t^{-0.75} \tag{10.3}$$

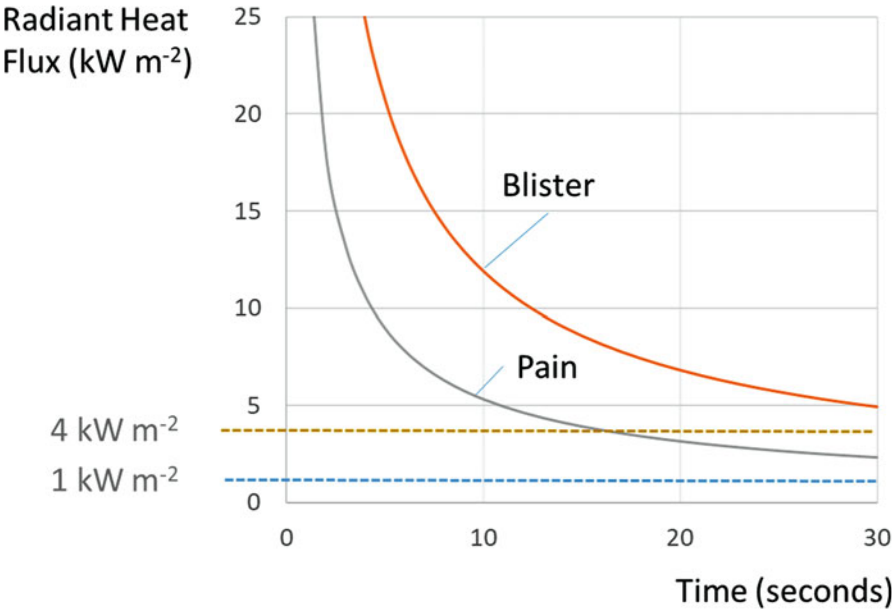


Fig. 10.7 Approximate relations showing the combinations of radiant heat flux (q_{rad}) and exposure time for the thresholds of pain and blister of bare human skin

$$\text{Blister threshold} \quad q_{rad} = 75\, t^{-0.80} \tag{10.4}$$

where q_{rad} is the radiant heat flux threshold (kW m^{-2}), and t is the time of skin exposure (seconds). The thresholds of exposure to radiant heat for bare skin pain, blisters, or for protected fire fighters have been used to calculate safety distances and safety zones, as discussed next.

10.3.2 Safe Distances from Fires for Fire Personnel and Others

The safety of fire personnel is of concern in all fire operations, whether in fighting wildfires or in prescribed burning. Whether people experience pain or injury from heat exposure from a fire depends on radiant heating (Table 10.1) and the degree to which their skin is protected from heat. There are two strategies for limiting the heat exposure of fire personnel: wearing personal protective equipment and creating safe separation distances between people and flames (Fig. 10.8). This section draws upon the concepts we presented in Chaps. 3 and 5 on heat production and heat transfer from fires.

Table 10.1 Thresholds of pain and injury from radiant heat to unprotected skin, quantified as radiant heat flux (kW m^{-2}). (Adapted from Drysdale 1990; Quintiere 2016; Zárate et al. 2008)

Radiant heat flux (kW m^{-2})	Effect
1.0	Threshold for indefinite skin exposure
2.1	Threshold for pain after 60 s
4.0	Threshold for pain after 20 s, first skin blisters
4.7	Threshold for pain after 15 s, skin blisters after 30 s
6.4	Threshold for pain after 8 s
7.0	Threshold for fire fighters with protective clothes
10.4	Thresholds for pain after 3 s
12.5	Volatiles from wood may be ignited by pilot after prolonged exposure
16.0	Skin blisters after 5 s
29.0	Wood ignites spontaneously after prolonged exposure
52.0	Fibreboard ignites spontaneously in 5 s

Fire fighters use personal protective equipment, including Nomex clothing, to provide protection from the heat and flames and ultimately reduce the risk of injury. Tests of the effectiveness of protective clothing have used different radiant heat flux levels (typically from 1.5 to 10 kW m^{-2}) applied to thermal manikins covered with the test clothing. The time to attain the pain threshold (43 °C) is recorded to evaluate the adequacy of the clothing for the different fire operation activities (e.g., Heus and Denhartog 2017). With a single layer of 210 g m^{-2} Nomex clothing, second-degree burns will occur after 90 s when a fire fighter is subjected to radiant heat fluxes greater than 7.0 kW m^{-2} (Butler and Cohen 1998).

Fire fighters experience heat through a combination of radiation and convection. Historically, wildfire fire safety studies assumed that radiation was the dominant heat transfer mechanism affecting fire personnel. Radiation modeling can be used to estimate the separation distances required between flames and some target, such as a fire fighter or a home, to prevent ignition or injury. Recent work has built upon lessons learned from radiation modeling while incorporating convective heat transfer into the estimation of safety distances.

The radiative power (P_g) from the flame can be calculated as:

$$P_g = \epsilon \sigma_{SB} T^4 \tag{10.5}$$

where ε is flame emissivity, σ_{SB} is the Stefan-Boltzmann constant (5.67×10^{-11} kW m^{-2} K^{-4}), and T is the absolute temperature (K) of the flame (See Chap. 5 for more about radiation). In many studies, authors assume a surface flame temperature of 1200 K and an emissivity of 1 (e.g., Zárate et al. 2008). For high-intensity fires, where there are typically more fire safety concerns, the corresponding radiative powers range from $P_g = 82$ kW m^{-2} to $P_b = 118$ kW m^{-2}.

Fig. 10.8 (**a**) A fire fighter is close enough to feel the heat from a high-intensity experimental fire in Portugal. (**b**) A prescribed burn with much smaller flames in northern Portugal

The transfer of heat between the radiating surface and the object can be estimated using approaches that span a range of detail, accuracy, and applicability. A method that is commonly used in wildland fire safety distance studies is called the solid flame model. In this method, the flame can be represented using a variety of simple geometric shapes, including cylinders and rectangles. The thermal radiation is assumed to be emitted from the surface of the object (Fig. 10.9).

The radiative heat transfer from the flame to an object using the solid flame model can be estimated by multiplying the radiative power by the view factor ($\mathrm{F_{ab}}$) :

$$q_{rad} = F_{ab} P_g = F_{ab} \epsilon \sigma_{\mathrm{SB}} T^4 \tag{10.6}$$

The view factor considers the geometry of the flame and the object receiving the radiation, the distance and the angle between the emitter and target, and whether or not the emitter and receiver can "see" each other. The view factor can take on values from 0 to 1. Equations to estimate the view factor for several simplified 2- and

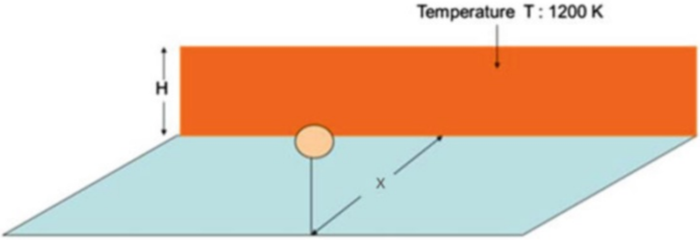


Fig. 10.9 Representation of an object, receiving a radiant heat flux (q_{rad}) from a fireline, represented as a wall of flames of height H, at a temperature of 1200 K (typical of flames), and at a distance x

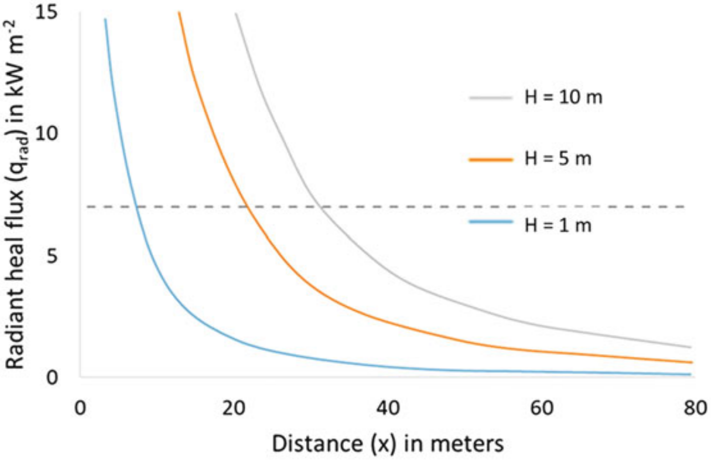


Fig. 10.10 Radiant heat flux (q_{rad}) received as a function of the distance (x) for diverse flame heights (H) from flames with surface temperature T = 1200 K, with an emissivity (ε) of 1.0, $P_g = 118$ kW m^{-2}, and a flame front of 20 m. (From Zárate et al. 2008)

3-dimensional scenarios can be found in heat transfer textbooks such as Incropera et al. (2007). Using the view factor from Zárate et al. (2008) for the scenario shown in Fig. 10.9, the radiative heat flux increases as a function of the flame height and decreases as a function of the distance between the flame and the target (Fig. 10.10). These calculations can be combined with the threshold radiative heat flux from Table 10.1 to identify the safe separation distance.

Safe Separation Distance is defined as "the minimum distance a fire fighter in standard Nomex wildland protective clothing must be separated from flames to prevent radiant heat injury". Using a solid flame model approach, Butler and Cohen (1998) suggested that an appropriate rule of thumb for the safe separation distance is at least four times the maximum flame height. This is the rule of thumb used in the BehavePlus system to calculate fire safety distance (Andrews 2014). There, the flame length is used in place of flame height, as a worst-case estimate. The

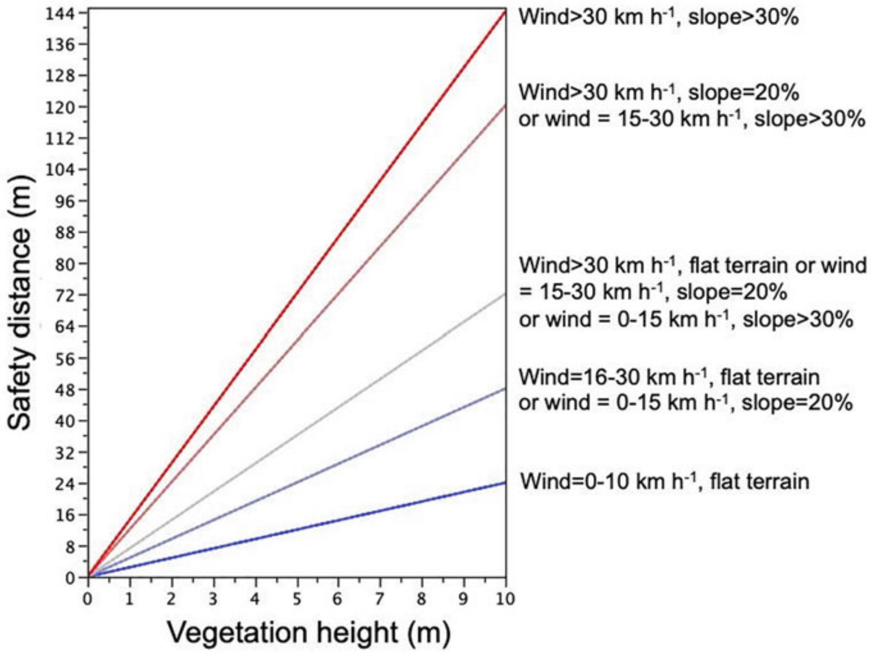


Fig. 10.11 The safe distance and the size of safety zones for fire fighters varies with the height of the surrounding vegetation, wind, and slope. Graph by the authors based upon the rule of thumb in https://wildfiretoday.com/2014/07/11/revised-guidance-for-safety-zones-is-released/, accessed 11 September 2020

idea is for fire personnel to identify both safety zones and escape routes to those safety zones at all times when they are working near fires. Safety zones are sufficiently large that people in their center will be at low risk of injury even if the vegetation surrounding the safety zone burns intensely. A more recent rule of thumb replaces flame height with twice the height of the surrounding vegetation, which eliminates the need to predict flame height. The distance of transport of convective energy ahead of the fire front is at least equal to two or more flame lengths under steep terrain or windy conditions (Butler 2014). To account for convective heat, the previous quantity (8 times vegetation height) is then multiplied by a slope-wind factor that varies from 1 to 6 and increases with wind speed and terrain slope (Fig. 10.11).

10.3.3 *Protecting Peoples' Homes*

Fires can endanger people due to heat and smoke, and disrupt lives when homes and property burn. Though "no one should ever die to save a house" (Kolden 2013), many fire fighters may risk injury or death to protect people and property. Further, most of the money spent during fire suppression is used to protect homes (Steelman 2016). For more about fire management costs, see Sect. 10.2.

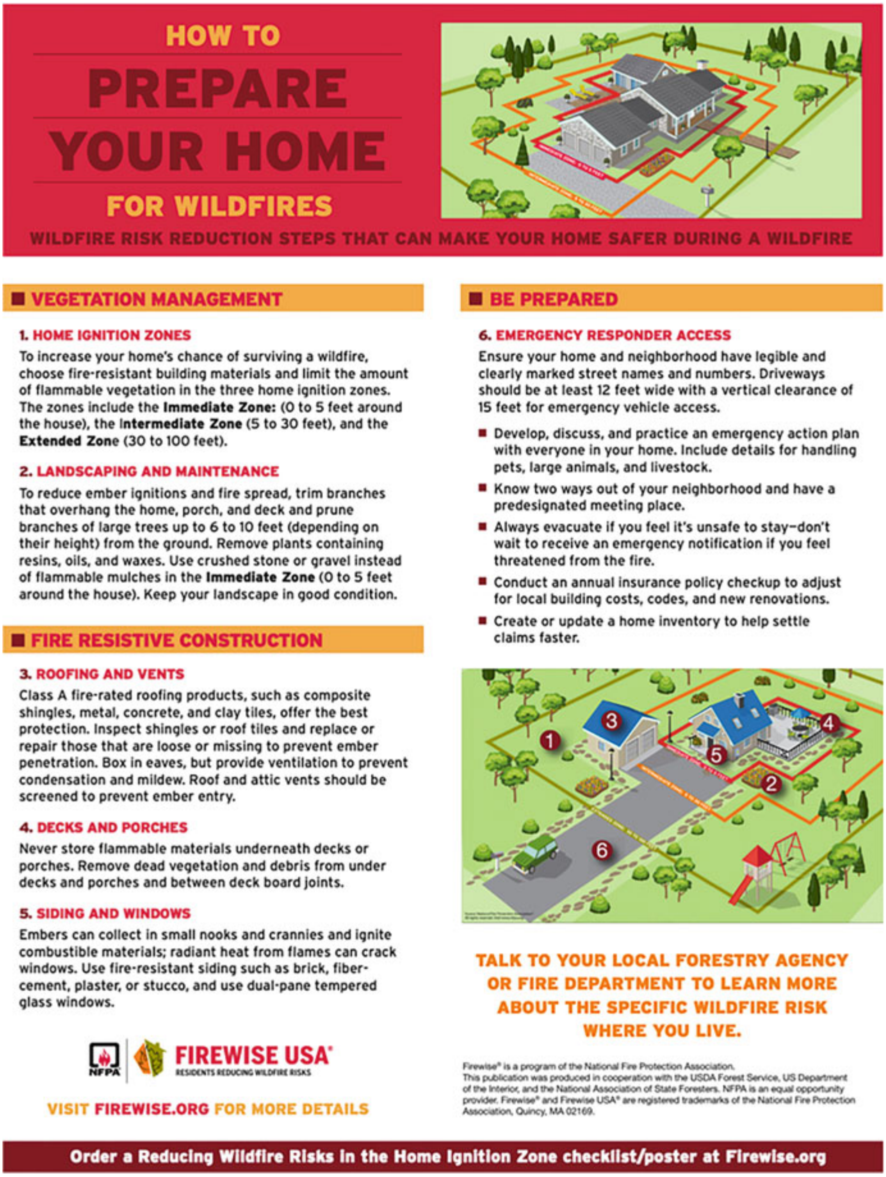
Fires have threatened and burned homes worldwide, including China, Mexico, and southern Europe, not just in Australia and the US, where most of the research has been done on protecting people and property from fires (Mutch et al. 2011). Most of the homes that have been threatened or burned are located in the Wildland-Urban Interface (WUI). Many of the strategies for protecting people and property within the WUI are focused on preparing for fire by managing fuels around homes, reducing the ignitability of the homes themselves, and readying people for early evacuation if needed.

The WUI is commonly defined as an area where buildings meet or intermix with vegetation that can support fires. Sometimes the WUI is divided into two unique areas, the interface, and the intermix, depending upon the density of homes and the amount of vegetation cover. This division effectively distinguishes areas where homes are adjacent to wildland vegetation from areas where homes are interspersed with wildland vegetation. Definitions of WUI can vary from location to location, so it is essential to know what definitions are being used in mapping WUI.

Incorporating fire-resistant building materials and removing fuels from the immediate vicinity around homes can greatly reduce the potential that homes will ignite during a fire. The FIREWISE program addresses the home plus the surrounding Home Ignition Zone up to 30 m from the home (Fig. 10.12). Cohen (2008) developed the Home Ignition Zone concept based upon empirical observations of homes that did or didn’t burn in large wildland fires, empirical modeling, and experiments. Recommended treatments are designed to limit the probability that embers will ignite a home or that flammable material on the home will ignite by flame contact. As in Australia (Handmer and Tibbets 2005), many of the homes burned in wildfires are ignited by embers. Cohen (2008), Calkin et al. (2014), and others emphasize that it is the house, the roof, and the fuels within 30 m of the home that are most important. When houses don’t ignite from the shower of embers, houses are more likely to survive fires burning surrounding vegetation. If houses have few flammable parts and the flames don’t come into contact with them, homes are more likely to survive when even intense fires pass.

The International Wildland-Urban Interface Code (IAWF 2013; International Code Council 2015) is used by local to national governments to guide building and community design to reduce fire risk to homes and the people in them. These codes mainly address home construction based on the science of fire behavior both in and outside of homes. They are designed to limit contact of embers and flames with the house or fuels adjacent to the house—hence the focus on screening, cleaning, and limited fuels in contact with buildings.

Preparation of home is key to avoiding urban disasters. Even the best fire fighters and fire suppression equipment can be overwhelmed when fires threaten many homes at once (Calkin et al. 2014, Fig. 10.13). This is more than creating defensible space, for fire fighters may not be there to defend homes when fires burn near them. Calkin et al. (2014) aptly point out that if homes did not ignite, then they would not burn, and so WUI fires are a home ignition problem rather than a fire control problem. Preparation in advance of fires is key, as is early evacuation.



HOW TO

PREPARE YOUR HOME

FOR WILDFIRES

WILDFIRE RISK REDUCTION STEPS THAT CAN MAKE YOUR HOME SAFER DURING A WILDFIRE

■ VEGETATION MANAGEMENT

1. HOME IGNITION ZONES

To increase your home's chance of surviving a wildfire, choose fire-resistant building materials and limit the amount of flammable vegetation in the three home ignition zones. The zones include the **Immediate Zone:** (0 to 5 feet around the house), the **Intermediate Zone** (5 to 30 feet), and the **Extended Zone** (30 to 100 feet).

2. LANDSCAPING AND MAINTENANCE

To reduce ember ignitions and fire spread, trim branches that overhang the home, porch, and deck and prune branches of large trees up to 6 to 10 feet (depending on their height) from the ground. Remove plants containing resins, oils, and waxes. Use crushed stone or gravel instead of flammable mulches in the **Immediate Zone** (0 to 5 feet around the house). Keep your landscape in good condition.

■ FIRE RESISTIVE CONSTRUCTION

3. ROOFING AND VENTS

Class A fire-rated roofing products, such as composite shingles, metal, concrete, and clay tiles, offer the best protection. Inspect shingles or roof tiles and replace or repair those that are loose or missing to prevent ember penetration. Box in eaves, but provide ventilation to prevent condensation and mildew. Roof and attic vents should be screened to prevent ember entry.

4. DECKS AND PORCHES

Never store flammable materials underneath decks or porches. Remove dead vegetation and debris from under decks and porches and between deck board joints.

5. SIDING AND WINDOWS

Embers can collect in small nooks and crannies and ignite combustible materials; radiant heat from flames can crack windows. Use fire-resistant siding such as brick, fiber-cement, plaster, or stucco, and use dual-pane tempered glass windows.

NFPA FIREWISE USA®
RESIDENTS REDUCING WILDFIRE RISKS

VISIT FIREWISE.ORG FOR MORE DETAILS

■ BE PREPARED

6. EMERGENCY RESPONDER ACCESS

Ensure your home and neighborhood have legible and clearly marked street names and numbers. Driveways should be at least 12 feet wide with a vertical clearance of 15 feet for emergency vehicle access.

- Develop, discuss, and practice an emergency action plan with everyone in your home. Include details for handling pets, large animals, and livestock.
- Know two ways out of your neighborhood and have a predesignated meeting place.
- Always evacuate if you feel it's unsafe to stay–don't wait to receive an emergency notification if you feel threatened from the fire.
- Conduct an annual insurance policy checkup to adjust for local building costs, codes, and new renovations.
- Create or update a home inventory to help settle claims faster.

TALK TO YOUR LOCAL FORESTRY AGENCY OR FIRE DEPARTMENT TO LEARN MORE ABOUT THE SPECIFIC WILDFIRE RISK WHERE YOU LIVE.

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Order a Reducing Wildfire Risks in the Home Ignition Zone checklist/poster at Firewise.org

Fig. 10.12 Reducing risk of home ignition during a wildfire involves proactively managing the vegetation around the house, ensuring your home is constructed of fire-resistant materials, and being prepared for evacuating if needed as fires approach. (From NFPA n.d.)

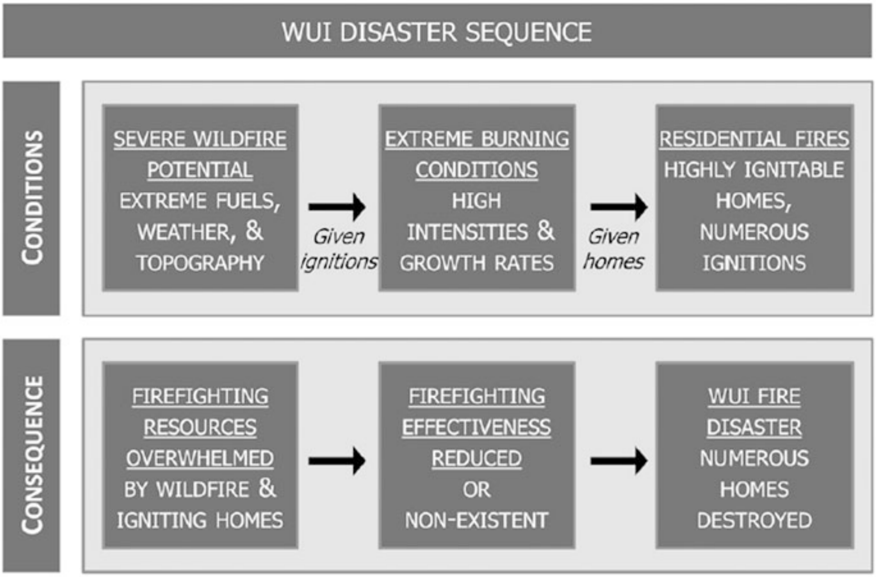


Fig. 10.13 Disastrous losses of homes in the Wildland Urban Interface can be avoided if homes are prepared so they are unlikely to ignite, thus increasing the success of structure protection. (From Calkin et al. 2014)

Fuels management near homes can alter fire behavior, aid fire fighters or homeowners in structure protection, and increase the potential that houses will survive when surrounding vegetation burns (See Chap. 11). Fuels management at a distance from homes well beyond the Home Ignition Zone could alter how fires and their embers approach homes. The effect of fuels treatments far from homes is enhanced when used as part of integrated fire management. Three points are important. *First,* fuel treatments alone, especially if they are limited to public lands, will not fully address the vulnerability of WUI communities to fire, for communities are vulnerable if individual homes are vulnerable. Fuel treatments need to be part of broader fire management strategies that also include prevention to limit ignitions by people and other strategies that help communities become adapted to fire and smoke (see Sect. 10.4.2). *Second*, fuel treatments are less effective as the vegetation regrows. *Third,* only 10% of the total number of fuel treatments completed by the US Forest Service 2004–2013 later burned (2005–2014) (Schoennagel et al. 2017, Fig. 10.14). However, fuels management can help people feel safer and can be part of community-based forest management and landscape management that can contribute to jobs and engage communities in helping themselves thrive. The 2010 WUI in the western United States (Martinuzzi et al. 2015) will grow to cover 40% of the landscape area in some locations (Theobald and Romme 2007). With extensive areas burned in recent decades and projected to increase in many areas, much attention and fire fighting resources are focused on the WUI (Schoennagel et al. 2017). See Chap. 11 for more about fuels

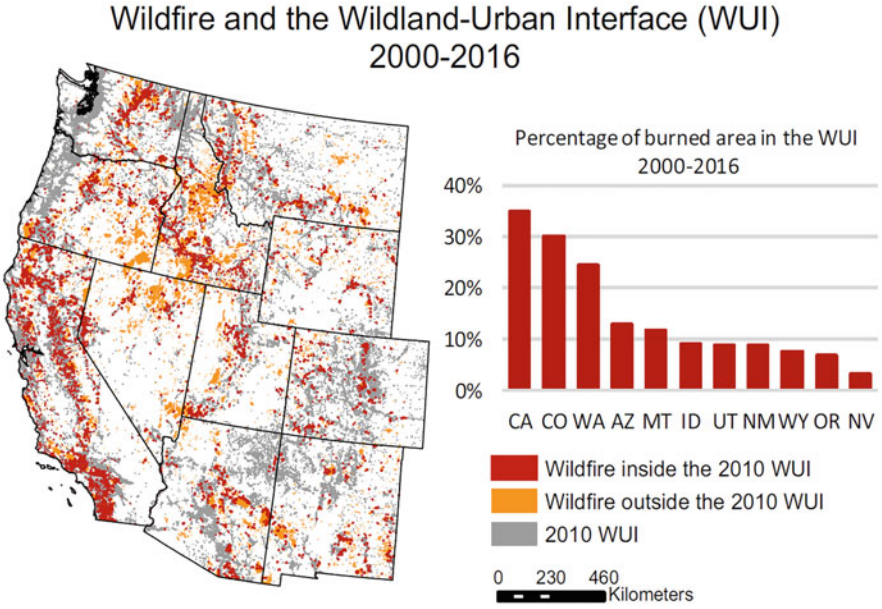


Fig. 10.14 Homes in the Wildland Urban Interface (WUI) are likely to be threatened by fires and smoke when surrounding landscapes burn (Schoennagel et al. 2017)

treatments, including their purpose, effectiveness, and strategic placement in landscapes.

Early evacuation of residents is widely encouraged when fires threaten homes. Most civilian deaths during fires are from heat exposure when fires trapped the people evacuating. Ready, Set, Go! and similar programs are widely used to encourage people to prepare for evacuation in advance in the event of a fire, and then evacuate early. Since the 2009 Black Saturday fire in Australia, in which 173 people died, early evacuation has mostly replaced the shelter in place strategies promoted during the early 2000s (see discussions by Paveglio et al. 2014; McCaffrey et al. 2015). However, some residents (11% in studies cited by McCaffrey et al. 2015) prefer to manage fuels around their homes actively and then stay to protect them in the event of fire despite the challenges and risks of doing so (Paveglio et al. 2014). McCaffrey et al. (2015) found that many emergency responders felt that in the interest of public safety, they needed to provide information to people about how to prepare for fires in case people chose not to evacuate or could not evacuate safely. Also, emergency responders in communities affected by wildfires thought that early evacuation would reduce uncertainty for both residents and emergency responders. Where limited access makes evacuation difficult, early evacuation is especially important. Indeed, if people do evacuate, it is better to do so early rather than at the last minute to avoid the potential for being trapped because of poor roads, smoke limiting visibility, or where trees or power lines and poles have fallen on the road. Traffic snarls when people flee while fire fighters are trying to access key areas for their fire suppression efforts. However, evacuation is emotional, stressful, and costly, particularly when residents don't know whether the homes they left are safe or not (McCaffrey et al. 2015). Planning and practice help people prepare mentally and physically, and both need to fit the people and place. The fire behavior conditions should be considered, including extreme fire weather and the potential for embers and long-term smoke exposure (Mutch et al. 2011).

10.4 Smoke Can Compromise Human Health

Although the heat from fires can pose significant threats to people, inhaling particulates and other components of smoke from burning vegetation is a much more common threat to peoples' health and well-being. Smoke can also affect visibility that can interfere with traffic and therefore contribute to traffic accidents or interfere with views enabled by the exceptionally good air characteristic of many national parks. Smoke is often regulated as air pollution, especially particulate matter. The small airborne particulate matter of various sizes (Fig. 10.15) in smoke can affect visibility and also cause short-term and chronic harm to people. Young children, elderly adults, pregnant women, and people with asthma or other respiratory

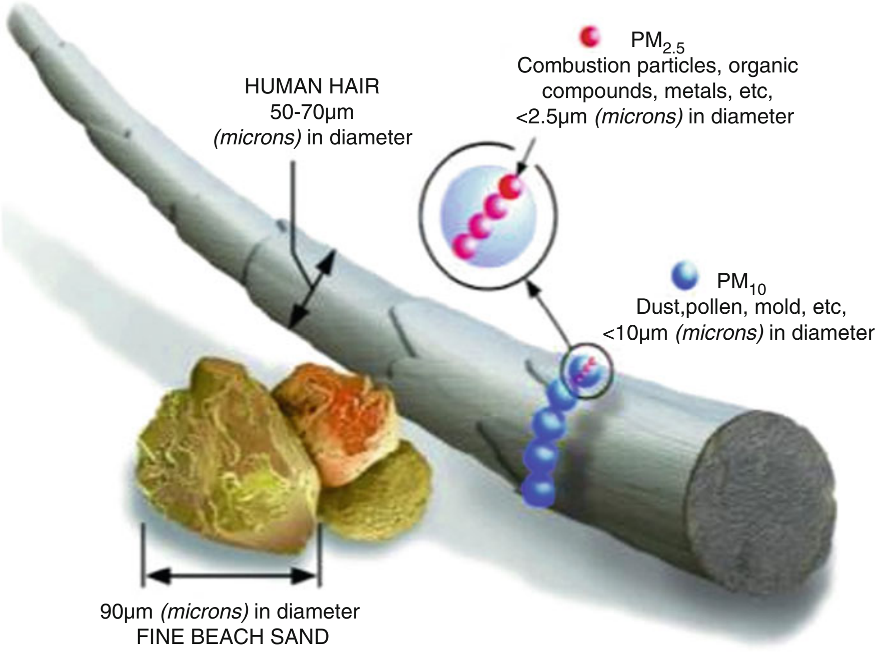


Fig. 10.15 Much of the particulate matter in smoke from vegetation fires is much smaller than a human hair and thus small enough that they can be drawn deep into our lungs. Air quality regulations often limit the concentration of particulates (especially those smaller than 2.5 μm in diameter, PM2.5). (From Peterson et al. 2018)

Table 10.2 National ambient air quality standards for the USA. The air quality index is used in the USA to communicate the health hazards of ambient smoke to the public to encourage people to take care of themselves during smoke exposure from wildland fires. (From the US Environmental Protection Agency (2014) in Peterson et al. (2018)

Air quality	24-h average particulate matter PM < 2.5 μm (μg m^{-3})
Good	<12
Moderate	12–35
Unhealthy for sensitive groups	35–55
Unhealthy	55–150
Very unhealthy	150–250
Hazardous	>250

ailments are especially sensitive to smoke. Exposure to the smallest particulates, those less than 2.5 μm in diameter, commonly called PM2.5, poses the greatest risk because these fine particulates can be drawn deep into our lungs and can reach our bloodstream. The particulates and the tars and resins that have condensed on them irritate lung tissues. Due to the importance of the particulate matter, the air quality index used in many countries to communicate with the public is focused on particulate matter (Table 2.4 in Chapter 2). In the USA, federal and state regulators set limits based on the Clean Air Act for air pollutants, including particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide. Many air pollution regulations are focused on the concentration and duration of PM2.5 (Table 10.2). Smoke also includes other air pollutants such as carbon monoxide, sulfur dioxide, nitrogen dioxide, volatile organic compounds (VOCs), aldehydes, benzene, as well as metals, soil, pollen, bacteria, and mold spores (Kobziar et al. 2018; Peterson et al. 2018).

Healthy children and adults usually quickly recover from short-term exposure to smoke. However, many people are more sensitive. Chronic exposure is also problematic and may lead to long-term health consequences. Fire fighters exposed to smoke suffer both acute and chronic health hazards. Eye and nose irritation, nausea, and headaches are usually relieved with a brief respite in clean air (Peterson et al. 2018). However, more serious, chronic health effects may result from repeated and long-term exposure to smoke, including that experienced by fire fighters on firelines and in fire camps. These pose occupational safety risks and are being studied (Peterson et al. 2018).

Smoke from wildland fires poses health hazards for people and may cause lung irritation, hospital visits, and in some cases premature death, particularly where biomass burning is widespread (Johnston et al. 2010), such as in the tropics (Fig. 10.16). Historically, at least seven times more area burned in the western USA than currently, and emissions were accordingly high (Leenhouts 1998; Stephens et al. 2007). Fire and smoke are part of most forests, woodlands, shrublands, and grasslands. Although the area burned has increased in recent decades in some regions, the global burned area is decreasing. Expanding intensive farming has resulted in the fragmentation of some tropical savannas and grasslands

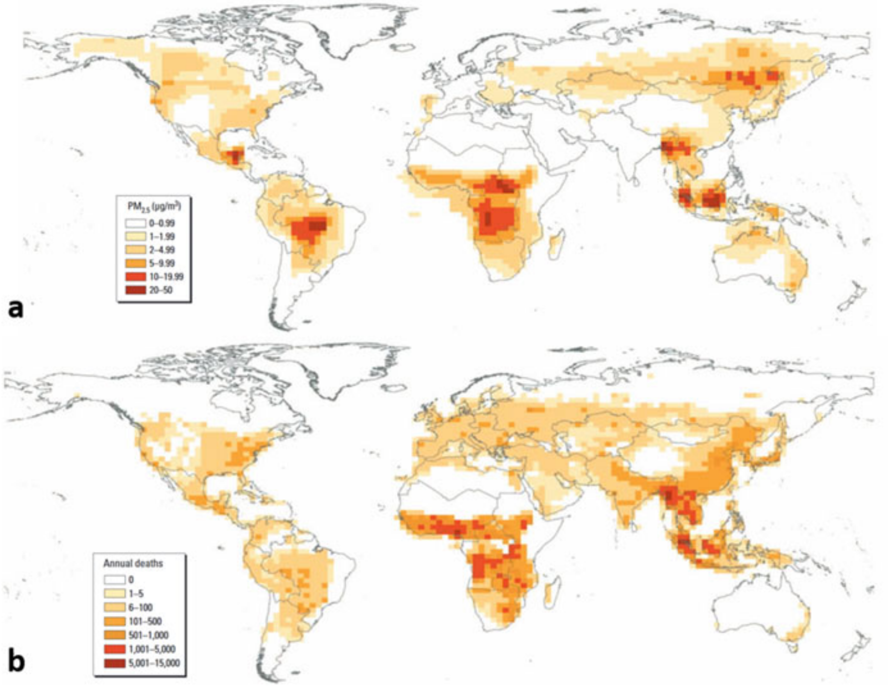


Fig. 10.16 (**a**) Estimated annual average (1997–2006) of fine particulate matter concentrations (PM < 2.5 μm in diameter) from wildland fires in the air people breathe. Estimates are based on a chemical transport model and satellite-based observations. (**b**) Estimated human mortality from smoke from wildland fires. (Both from Johnston et al. 2010)

and so they burn less (Andela et al. 2017). Global change could result in more smoke exposure to more people in many areas (Fig. 10.16, Johnston et al. 2010).

10.4.1 Smoke from Prescribed Fires and Wildfires

In general, prescribed fires produce less smoke than wildfires (Fig. 10.17), though this depends on the fuel type and amount of fuel consumption. There are many reasons for this (Navarro et al. 2018). *First,* prescribed fires are often initially set under conditions that will lead to low-intensity fires that consume less fuel. For example, prescribed fires can be implemented such that there is limited consumption of the duff and large woody fuels to decrease soil heating, potential loss of soil fertility, or carbon emissions. *Second,* prescribed fires often occur over a relatively short time, limiting people's overall exposure to smoke. *Third*, the smoke from prescribed fires is usually more localized than wildfires (Navarro et al. 2018). See Chap. 11 for more discussion about prescribed fires and alternative fuels treatments.

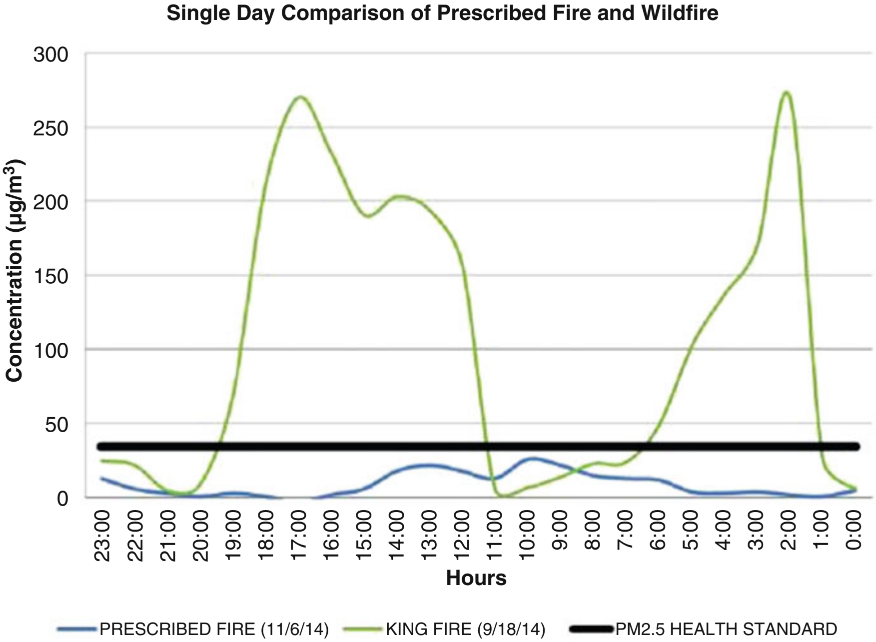


Fig. 10.17 Daily concentration of fine particulates from a distant wildfire (green) and a prescribed fire near Washoe County, Nevada. Currently, in the US, 3.2–3.6 million ha are prescribed burned annually compared to an average of 4 million ha burned in wildfires in 2017. However, in the USA, most of the prescribed burning is in the southeastern USA. (From Peterson et al. 2018)

Generally, air quality regulations are applied to smoke from prescribed fires but not from wildfires. In some countries, air quality regulations are applied to smoke from prescribed fires but not from wildfires because wildfires are considered exceptional events out of our control. Nonetheless, wildfires may contribute significantly to long-term exposure to smoke in some locations (Peterson et al. 2018). Further, future wildfires may burn more intensely and produce more smoke if fuels have accumulated in the absence of prescribed fires or other treatments.

10.4.2 Smoke Management

Smoke management programs are often designed to limit smoke exposure for people, communities, and areas, especially those designated as sensitive (Peterson et al. 2018). Managers utilize weather, smoke, and emissions forecasts (Fig. 10.18) to estimate the potential impacts of smoke and guide management and communication strategies.

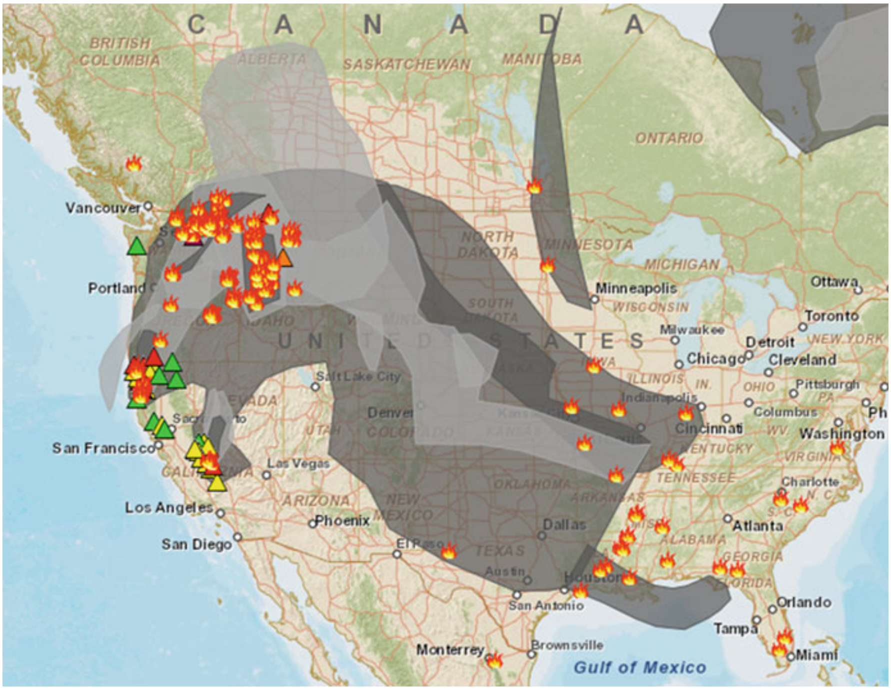


Fig. 10.18 Smoke forecasting tools are used by fire managers and those concerned about smoke impacts on people. On August 24, 2015, many large wildfires burned in the US and Canada. The red symbols indicate actively burning large fires, and the triangles indicate urban areas being subjected to low (green), moderate (yellow), or high (red) health hazards from smoke from fires. Shaded areas indicate smoke in the air, with darker shading indicating more smoke in the air. Clearly, smoke can affect people far from fires. (From EPA 2014)

Smoke forecasting is especially important for prescribed burning operations. Managers can choose to ignite prescribed fires when smoke will carry away rather than into areas with many people. Managers can limit the amount of fuel consumed by burning when the fuel is relatively moist, limiting the area burned, or burning before rains or in the spring before the largest fuels are dry. They may also burn to favor flaming combustion over smoldering combustion (Peterson et al. 2018) when the higher intensity and resulting convection can help carry the particulates up to mix with ambient air. Managers may voluntarily coordinate their burning with others to share the airshed and thus limit total smoke in the air. Despite these efforts, smoke and smoke impacts will happen, particularly during nighttime inversions and for areas close to fires and downwind or downslope from fires. Increasing the area burned for ecological restoration (see Chap. 12) could increase the number of smoky days even if the total particulates are low if relatively little fuels burn in repeated fires. Smoke must be considered in planning prescribed fires and managing ongoing wildfires with less than the most aggressive suppression. In all cases, monitoring smoke and communicating with the public and with air quality regulators are key to success. Providing air filters to schools and childcare centers, or to especially vulnerable people as recommended by their doctors, has helped reduce the negative impacts of smoke. Managing smoke for large burns (whether planned or not) over multiple days is a growing challenge, especially when those fires are managed with limited suppression to reduce costs or to provide natural resource benefits (Schultz et al. 2018, 2019).

10.4.3 Future Opportunities and Challenges

Smoke affects human health and well being. Globally, fires and their smoke have affected 5.8 million people, caused more than 1900 deaths of people, and cost more than US$52 million from 1984 to 2013 (Doerr and Santín 2016). The indirect costs are orders of magnitude more than the direct costs of suppression (Doerr and Santín 2016; AFE 2015). These trends will likely increase as the global human population increases, especially where people move into areas where they could experience fires and smoke. Fire fighters, fire managers, and fire lighters often work in the smoke, but the effects of repeated and extended exposure to smoke are not well understood. Likewise, there has been little study of the long-term implications of the extended exposure of the public to smoke when smoke spreads into towns from fires burning far from the towns. Indeed, many people object to smoke in the air.

Proactively addressing concerns about smoke impacts on air quality will require engagement among fire managers, policymakers, people potentially affected by smoke, and regulators (Peterson et al. 2018). One thing that seems inevitable is that smoke will continue to be part of our landscapes. Many scientists and managers have called for increased prescribing burning (e.g., Schoennagel et al. 2017; Moritz et al. 2018), and for managing for more “good” fires. However, in most regions of the world, the area burned in wildfires far exceeds the area burned in prescribed fires or treated with other methods. Considerations of the smoke effects on human health are central to fire management decisions today and moving forward. Key considerations are: how much smoke is expected, how many people will potentially be exposed to the smoke and for how long, and what alternative strategies can be used to manage smoke exposure.

The reality is, however, that we cannot avoid smoke or fire entirely, and we likely do not wish to avoid fire because of the many ecosystem services that come from burned areas. Prescribed burning provides two benefits as it reduces the fuels available to burn in a future wildfire. It also allows a level of control of how much smoke is produced and where it goes that is not possible with wildfire management (See Chap. 11). Smoke is regulated as a component of air pollution in many places. Even in the absence of regulations, public concerns about smoke can significantly affect public perceptions, enough to limit the use of prescribed fires in some locations. Paradoxically, smoke from prescribed fires is often less acceptable to people if it is perceived as optional while smoke from large vegetation fires can be very unpopular but may be perceived as inevitable. If we can accept that fires will occur and that we cannot fully suppress all wildland fires, then we can have the needed conversations about how we will adapt to more fire and more smoke in the future in some places.

Smoke is just one of multiple barriers for implementing prescribed burning on federal lands in the western USA (Schultz et al. 2018, 2019). Near large populations of people and where air quality is already low, limiting smoke is especially crucial for prescribed fire programs. The greatest challenges to implementing a successful smoke management program are limited funding and availability of trained people and equipment, lack of incentives and internal agency support for prescribed burning, and having enough people with needed expertise available when weather is conducive to prescribed burning (Schultz et al. 2018, 2019). Sharing resources for planning and conducting burns helps, as do programs where people come together with skills and equipment to conduct burns while also documenting the training and experience gained. Prescribed Fire Councils (Coalition of Prescribed Fire Councils n.d.) have also fostered policy, media outreach, partnering, and other ways that local people help each other with their challenges to enable successful prescribed fire programs. For more on these and other approaches, see Chap. 13 for case studies of Integrated Fire Management.

Managing smoke is an essential skill to master if we want to use prescribed fire to foster resilient, fire-adapted communities and landscapes and to have safe, effective, and efficient fire management. These are the goals of the National Cohesive Wildland Fire Strategy that involves all levels of government agencies from federal to state and county as well as non-governmental organizations and the public in the USA (USDA and USDI n.d.). Similar goals guide fire management in other countries, e.g., Canada (Canadian Council of Forest Ministers 2016).

10.5 Communities Becoming Fire-Adapted

Fire Adapted Communities have citizens who work together to coexist and thrive in ecosystems. They work closely with local, state, and federal land management agency personnel and organizations to lessen the need for protection when surrounding ecosystems burn (https://fireadapted.org/, accessed 22 June 2019). Through actions, learning, and communication, communities become more resilient. Fire Adapted Communities can become more so as they gain skills, knowledge, and experience.

Communities differ in their adaptive capacity (Fig. 10.19) for recovery from fires, their experience and acceptance of fire and smoke, and their past exposure to fire (Paveglio et al. 2015, 2018). Adaptive capacity depends on the combination of four different aspects. *First,* interactions and relationships amongst people determine how communities take collective action and the degree to which locals volunteer to reduce risk. *Second,* access to and ability to adapt scientific and technical knowledge affects the degree to which local people and community organizations understand fire suppression responsibilities and accept land use and building standards. *Third,*

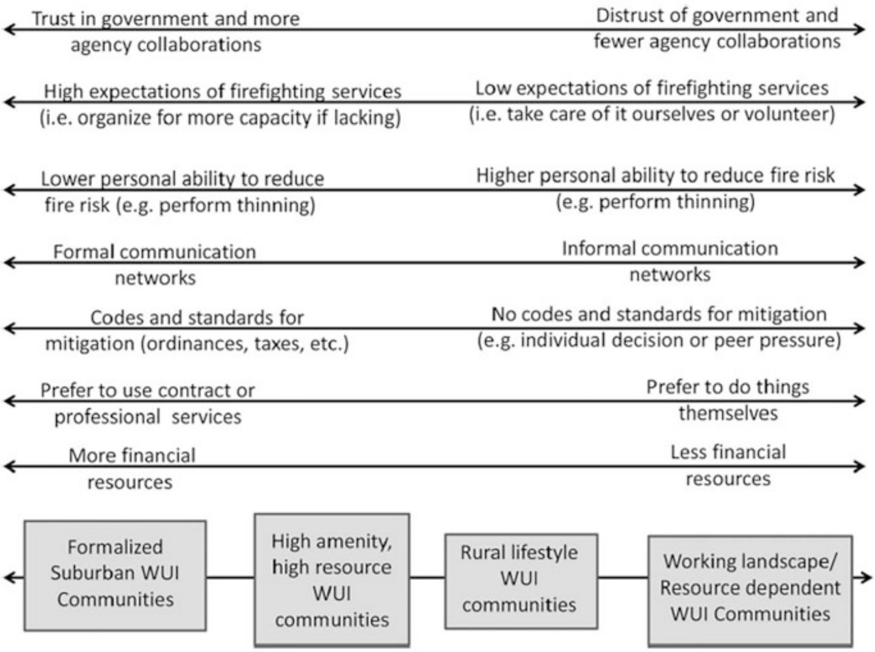


Fig. 10.19 These four archetypes of communities of people who live in Wildland-Urban Interface areas differ in ways that affect what messages and strategies for coping with fire will be useful, and the strategies people are most likely to adopt. The communities are groups of people with similar characteristics, experiences, and ways of functioning. Many towns have a mix of communities of people in them, and some communities may occupy a large geographic area. (From Paveglio et al. 2015)

place-based learning grows with local peoples' experience with wildfire and awareness of wildfire risk. *Fourth,* demographics and structural characteristics include whether there are local wood products operations, patterns of development, and willingness to pay for fire mitigation. Paveglio et al. (2015, Fig. 10.19) described four different archetypes of communities. Each archetype represents groups of people with similar human behavior that will affect what levels of trust exist, what communication strategies will be the most effective, and the strategies communities are most likely to adopt as they adapt to fire. These can inform the pathways for effective action, learning, messaging, and incentives (Carroll and Paveglio 2016; Paveglio et al. 2018). The archetypal communities are not necessarily towns. They are groups of people who identify with each other around common values and perspectives that often reflect their experiences with fire and resource management issues. They are in a place, but communities change as people come and go and as they learn. Understanding who the actors are and the social dynamics are critical for effective community engagement and building adaptive capacity (Paveglio and Edgeley 2017; Paveglio et al. 2018).

Programs such as Fire Adapted Communities Network (https://fireadaptednetwork.org/, accessed 18 June 2019) help people work together to plan for and take actions that will help them prepare for and be resilient to wildfires burning in surrounding landscapes. Some get grants, some share knowledge, and other people work to clear brush, retrofit homes with wildfire-resistant building materials, and develop emergency plans that include evacuation routes, communities can be made safer from fire. Homeowners can design or retrofit their buildings with a fire-resistant roof, screening vents, soffits, and areas under decks to exclude embers. Additionally, they can manage the vegetation and landscaping around their properties. Developers, community planners, and local regulators can insist upon subdivision design and management that decreases rather than increases potential threats from fires to people and their homes (Rasker 2015). The Fire Adapted Communities Learning Network (https://fireadaptednetwork.org/, accessed 21 June 2019) helps share lessons learned elsewhere.

Land-use planning can be an important, proactive part of living with fire. Various strategies can be used during land-use planning to reduce fire risk, incorporate multiple escape routes, to require ignition resistant landscaping, and to incorporate fuel breaks into planned open spaces (Rasker 2015). Zoning, limiting the growth of communities, conservation easements, educational programs, and community assistance are also used in fire-adapted communities to reduce the risk of WUI disasters (Mutch et al. 2011; Rasker 2015; Smith et al. 2016).

10.5.1 Learning Together Through Collaboration

Lack of trust impedes integrated fire management. Sometimes trust can be built with monitoring and stakeholder engagement in land management decision making. Trust of people in leaders and leaders trusting in local people are always important but more so during fires. Gaining and holding trust depends on integrity, transparency, accountability, compassion, and a willingness to listen and try new ideas and approaches.

Fires have brought many communities together (Prior and Eriksen 2013). Many people who might otherwise disagree with one another have collaborated out of both a fear of fire and a sense that people can make their communities safer. Some people have found economic opportunity in community-based forestry around thinning and fuels management. Local approaches to fires change through time (Paveglio and Edgeley 2017).

Increasingly, fire and natural resource managers must work across boundaries between lands managed by different organizations and boundaries within organizations to address barriers to and create opportunities for prescribed burning (Schultz et al. 2018). Resistance to prescribed burning and other fuels management and to smoke is internal to public land management agencies and the public.

Cross-boundary collaboration is not easy (Schultz et al. 2019) but necessary to work at the scales needed to address large fires. Conversations among the many stakeholders and decision-makers involved can be helpful, as can articulating the implications of management alternatives, including no action. Transparency and shared ownership of outcomes are useful. Working with the media is essential, as the media about fires shape people's attitudes about fire and smoke (Paveglio et al. 2011; Paveglio and Edgeley 2017).

10.5.2 Learning from Traditional Practices and Scientific Knowledge

Traditional knowledge (TK) can complement scientific knowledge. These different ways of knowing, learning, and teaching (Mason et al. 2012; Lake et al. 2017, Table 10.3) can enrich our understanding of fire from either perspective alone. Both are grounded in observation, learning from trying, and reflecting upon new practices. TK, including Traditional Ecological Knowledge and Indigenous knowledge, is developed by those with long experience in a place and often shared between different generations of people. Many cultural practices developed through millennia through teaching, learning, and adapting from culture to culture and through time. Traditional knowledge about fire draws on this long-term, often anecdotal but immensely deep appreciation for the power of fires to affect plants, consume fuels, and alter landscapes (Lake et al. 2017). Place-based knowledge, including the local expertise from Indigenous peoples or from others (local ranchers and farmers) who have lived and learned in a place for many years, can be immensely valuable as all fires are local. Whatever the source of knowledge, thinking must be broad, flexible, and forward-looking to address the complex challenges fire poses to people in a rapidly changing world. Not all knowledge is wise, and not all ideas are adaptive (Berkes et al. 2000), so users need to be flexible and always willing to question and learn.

Table 10.3 Traditional knowledge and scientific knowledge are complementary. The best managers use both to inform actions with science and learn from observation and local adaptive management and share by example. (Adapted from Berkes et al. 2000, Mason et al. 2012, Huffman 2013)

Traditional knowledge	Scientific knowledge
Qualitative	Quantitative
Intuitive, anecdotal	Intellectual
Place oriented	Short time series and broad generalities
Holistic	Reductionist
Insights shared among practitioners	Researchers share data by publication

People in Indigenous cultures worldwide often used fire skillfully and carefully. Indigenous people ignited fires for clearing land, to fell trees, to provide nutrients to crops, to maintain and improve pasture (against invasion by trees, for instance), to hunt or attract game, to promote medicine and food plants, and in warfare, as well as in many ceremonies (Mason et al. 2012; Huffman 2013). For many Indigenous people, fires were one of the few tools they had for managing vegetation. Fires were essential to life. Those who could ignite, carry, and use fire were often influential and respected within their communities. Indigenous people currently manage or have tenure rights to over 25% of the world's land. Their territories include much of the global biodiversity and forest carbon, so their fire and vegetation management matters to us all.

Management practices around the world often blend scientific with traditional knowledge and local experience. Local wisdom must include humility, recognition of uncertainty, and the need for learning using both traditional ways of seeing and science observations going forward.

10.6 Implications and Management Considerations

"We need a dedicated prescribed fire workforce. Imagine if, for every fire fighter poised and ready to extinguish any start, we also had a fire lighter." Jeremy Bailey, The Nature Conservancy

Imagine a world where fire-wise homes, fire-adapted communities, and fire-resilient landscapes are commonplace rather than exceptional. A world such as this will require people from various backgrounds to work together and take ownership of their collective risk. Fire adapted communities need to expect fires to happen and tolerate smoke. To this end, communities must learn together, whether by biomimicry (Smith et al. 2018) or otherwise thinking "outside the box" or applying practical lessons learned from past fires and other communities. Especially, let's use what social scientists are learning about what shapes understanding and actions by people.

Fire in the WUI is not a public lands issue; it is a private lands issue (Calkin et al. 2014). If homes were less likely to ignite from fires, fires would be less damaging (Calkin et al. 2014). By preparing for fires and managing the fuels within the Home Ignition Zone, homeowners would be less reliant upon fire fighters to protect their homes.

Although we emphasize homes here, both whole communities and the landscapes around them are part of what people consider home. In some cultures, fields of crops or the forest and wildlands are more important than homes. Fires burning far from homes can affect communities through smoke or by changing water supply, altering places special to people, and affecting ecosystem services and long-term sustainability. There is no uniform way to assess the degree to which fires affect both people and the places they love (Smith et al. 2016). Limiting fires and keeping landscapes from burning also has positive and negative effects. Many areas are beautiful

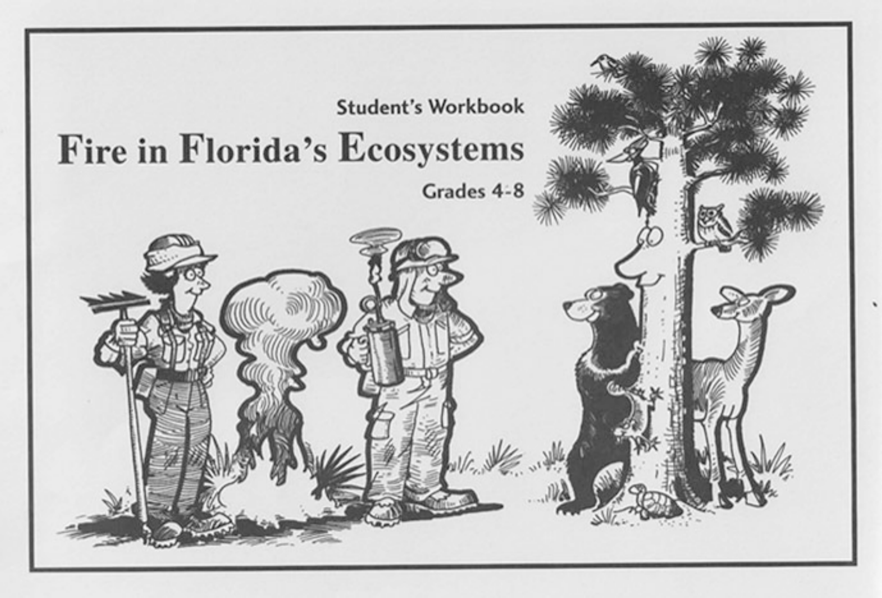


Fig. 10.20 Fire superheroes work effectively with communities in ways that benefit both people and ecosystems in understanding and using fire. (Rick Henion illustration in Brenner et al. 1999)

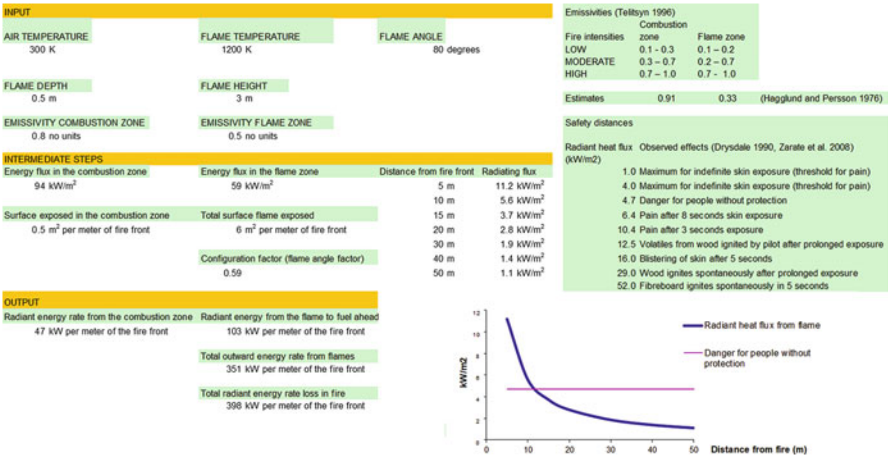
because they burned in the past, and many burned areas will become lovely given time. The ecosystem services humans depend upon, such as clean water, depend on healthy ecosystems that, in turn, depend upon fires. Yet, people are more likely to vilify fire than celebrate it. Fire fighters are often viewed as heroes. We still need those heroes, but we also need superheroes using prescribed burning and fuels treatments toward future resilience (Fig. 10.20).

Steelman (2016) and Fischer et al. (2016) argued that the current fire management paradigm, which emphasizes fire control and suppression, is financially costly without making significant progress in reducing structure loss and fatalities. The current challenges associated with wildland fires are likely to increase in scale and complexity as climate change continues, the human population grows, and social values about risk and ecosystem services change. Fear of destructive fire and adverse effects on ecosystem goods and services perpetuates increased investment in fire suppression. Incorporating social-ecological perspectives can assist societies in moving from fighting fires to living well with fires (Moritz et al. 2014). Finding solutions to what can seem a "wicked problem" will require embracing the diversity of human attitudes about fire with the biophysical realities of fire as a process (Smith et al. 2016). Working effectively with all of the different people involved depends on us listening. Cultural differences, experience with fire, the trust of government, and appreciation for science and other ways of knowing all influence how we view fire, hear messages, and the sorts of practices we will engage in and support (McCaffrey

2015). In the US, the National Cohesive Strategy (Forest and Rangelands n.d.) is a collaborative effort to create all-lands solutions across the nation that address three goals: to restore and maintain fire resilient landscapes, create fire-adapted communities, and safe, effective fire response. People are central to all of these, and people will be essential to successful integrated fire management.

10.7 Interactive Spreadsheet: RADIATION_Fireline_Safety

We provide an interactive spreadsheet, RADIATION_Fireline_Safety_v2.0, that readers can use to explore the implications of different inputs for the calculation of safe distances and exposure to radiative heating from flames. An example of the output is presented in Fig. 10.21. Note that Chap. 2 also includes an interactive spreadsheet, COMBUSTION_v2.0, that includes the prediction of smoke emissions.



INPUT

AIR TEMPERATURE
300 K

FLAME TEMPERATURE
1200 K

FLAME ANGLE
80 degrees

FLAME DEPTH
0.5 m

FLAME HEIGHT
3 m

EMISSIVITY COMBUSTION ZONE
0.8 no units

EMISSIVITY FLAME ZONE
0.5 no units

INTERMEDIATE STEPS

Energy flux in the combustion zone
94 kW/m^2

Energy flux in the flame zone
59 kW/m^2

Surface exposed in the combustion zone
0.5 m^2 per meter of fire front

Total surface flame exposed
6 m^2 per meter of fire front

Configuration factor (flame angle factor)
0.59

Distance from fire front	Radiating flux
5 m	11.2 kW/m^2
10 m	5.6 kW/m^2
15 m	3.7 kW/m^2
20 m	2.8 kW/m^2
30 m	1.9 kW/m^2
40 m	1.4 kW/m^2
50 m	1.1 kW/m^2

OUTPUT

Radiant energy rate from the combustion zone
47 kW per meter of the fire front

Radiant energy from the flame to fuel ahead
103 kW per meter of the fire front

Total outward energy rate from flames
351 kW per meter of the fire front

Total radiant energy rate loss in fire
398 kW per meter of the fire front

Emissivities (Telitsyn 1996)

Fire intensities	Combustion zone	Flame zone	
LOW	0.1 - 0.3	0.1 – 0.2	
MODERATE	0.3 – 0.7	0.2 – 0.7	
HIGH	0.7 – 1.0	0.7 - 1.0	
Estimates	0.91	0.33	(Hagglund and Persson 1976)

Safety distances

Radiant heat flux (kW/m2)	Observed effects (Drysdale 1990, Zarate et al. 2008)
1.0	Maximum for indefinite skin exposure (threshold for pain)
4.0	Maximum for indefinite skin exposure (threshold for pain)
4.7	Danger for people without protection
6.4	Pain after 8 seconds skin exposure
10.4	Pain after 3 seconds exposure
12.5	Volatiles from wood ignited by pilot after prolonged exposure
16.0	Blistering of skin after 5 seconds
29.0	Wood ignites spontaneously after prolonged exposure
52.0	Fibreboard ignites spontaneously in 5 seconds

Fig. 10.21 Example of inputs and predictions from the interactive spreadsheet, RADIATION_Fireline_Safety_v2.0, used to evaluate safety distances from fires of different characteristics

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