# Wildland Fires

# 87

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## Introduction

Wildland fires have a big impact on the environment, human life, and property and have posed significant economic losses as demonstrated by devastating wildfires that occurred over the last few years. In August 2012, the total of 1470 $km^2$ (3.64 million acres) burned by wildfires in the United States ranked as the highest for any August since 2000. Moreover, nearly half the entire acreage burned since January 2012 occurred within the single month of August and brought the total acreage burned in a year to the highest on record, exceeding 3100 $km^2$ (7.72 million acres) [1]. The ignition and corresponding spread of these fires were predominantly influenced by extreme drought and high winds. At the global scale, the impact of wildfires is expected to increase dramatically in the future because of the combined effects of the spreading of the Wildland Urban Interface (WUI) and climate changes [2, 3].

The WUI problem is particularly relevant to fire protection engineering because it impacts people's safety and activities, as well as property and structures. In the future, this problem will shape the way of life of a large part of the population as the WUI is growing faster than any other populated areas [4]. The main differences between building fires and WUI fires are the scale of the phenomenon—with a large number of structures being impacted at the same time (an example is the Waldo Canyon fire in Colorado in June 2012 [5])—and the fact that the structures have to be protected from a fire coming from the outside.

Several issues linked to WUI fires can benefit from further developing fire protection engineering solutions, such as improving structure design to make them more fire resistant, creating new protection systems for houses and other structures, improving evacuation schemes, or supporting communities to develop their wildfire protection plans [6]. The scientific community has developed many tools through research in wildland fire spread, prevention, and suppression that are helpful to mitigate wildland and WUI fire problems. However, fire behavior is still a young and immature topic, particularly compared to other fields of science relevant to wildland fires, such as forestry, ecology and geoscience. It would benefit greatly from the application of approaches developed in fire science as some of the already developed tools could be adapted and applied to wildland and WUI fires.

This chapter presents some basic knowledge about fire behavior and the basic tools that are available in literature to help dealing with wildland and WUI fire problems. The next section presents the wildland fire context both in terms of the general problem and the related scientific

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M. Hurley (ed.), *SFPE Handbook of Fire Protection Engineering*,
DOI 10.1007/978-1-4939-2565-0_87, 

issues. Then, the fundamental mechanisms that drive fire behavior are detailed in the following section and different kinds of extreme fire behavior are reviewed as they become more common every day. Two additional sections present the different kinds of models that allow predicting fire spread and the fire danger estimation systems that are available and currently used around the world. Finally, the last section presents some ways to estimate fire impact on people and structures.

## The Wildland Fire Context

Beyond the fact that they already represent a global problem, wildland fires are emerging as an increasing threat on humans and ecosystems. The dire consequences of these fires include loss of life and injuries, health impact through smoke exposure, property and infrastructure loss, business interruption, ecosystem degradation, and soil erosion, all of this despite huge firefighting costs. In addition to the 2012 fires cited in the previous section, the fires in Southern California in October 2007 and the Black Saturday fires in Australia in February 2009 are perfect examples of the increasing impact that wildland fires have on people, property and the environment. These fires had a large impact on the WUI. The state of emergency was declared in California in 2007 and over 1600 houses were burnt for losses estimated over $1.8 billion [7].

Wildland fires are likely to occur more frequently and to be more intense because of global warming. For instance, the number of uncontrolled fires is expected by USDA to increase by around 50 % in the region of San Francisco and by more than 100 % in Northern California [8]. Their impact will also increase because the Wildland Urban Interface (WUI) is spreading quickly. As an example, during the 1990s, WUI area in the three States of the U.S. West Coast increased by 11 % to nearly 53,000 km$^2$ and the number of housing units at the WUI was around 6.9 million units in 2000, increasing by more than 15 % every 10 years [2]. This combination of factors is not specific to the US and is relevant to many other regions of the world [9, 10].

The occurrence of massive fires at a growing WUI overwhelms fire fighting and induces huge losses. This growing problem is fully described in the final report of the 2009 Victorian Bushfires Royal Commission [11], which documents Australia’s highest loss of life ever induced by bushfires. Among the 173 fatalities, 113 people died inside their houses. The cost of the disaster is estimated to be more than $4 billion. Similar events could potentially happen in other locations, such as California or the South of Europe [11]. The report is very extensive and includes a lot of recommendations about safety policy, emergency management, fire fighting, fuel management and research among others, which are based on the statement that these kind of fires are likely to occur more frequently.

In this context, it is of primary importance to develop the auto-resistance of structures at the WUI and to make them more defendable. It would reduce the economic loss and provide shelter to the population. All protagonists are concerned with this global threat, from private owners, who have to clean vegetation around their houses to central governments, which create regulations and national policies. Some of the players lack the technical skills required to understand fire behavior and evaluate its impact and they would benefit greatly from the development of fire protection engineering solutions.

The fires in developed countries are given extensive media coverage because their impact on human lives, human activities and infrastructures is huge. However, greater surfaces are burned in Asia and South-America for agricultural reasons. Every year, Amazonian and South-Asian forests burn because of the development of cropping, grazing and plantations [12] or because of extreme weather events, of which the intense fires caused by El Niño in 1997 in Kalimantan and Borneo, Indonesia are examples [13]. These fires have dramatic effects on the ecosystem and produce emissions that have a global impact. In addition to these regions, Africa is named the ‘Fire Continent’ and experiences large savannah fires on a yearly basis. It is also subjected to changing fire regimes in damp forests and excessive logging.

Wildland fire can be mitigated through fire fighting and prevention. In many countries, fire fighting absorbs the great majority of the financial and human resources devoted to wildfires [14]. In the US, the total (federal, state and local) government firefighting cost grew from $1.3 billon/year in the 1990s to $3.3 billion/year in the 2000s [15]. Despite the huge resources used in firefighting, there is always a threshold when firefighting is overwhelmed by the size and intensity of the fire. Then, the fighting means can only be devoted to protect infrastructure and people at the WUI or to prepare future actions to fight the fire under more favorable conditions. In the US, 97 % of all fires are contained to 40,000 $m^2$ (10 acres) or less, and the remaining 3 % of large fires have a strong impact on the WUI [15]. It is estimated that the majority of the suppression costs are devoted to protect private homes [16].

On the other hand, prevention is necessary to decrease fire intensity over the long term and make fire fighting more efficient. This objective becomes of primary importance in the frame of global climate and socioeconomic changes (such as urban sprawling), leading to the emergence of new and more intense fire regimes. The most developed prevention approach is fuel treatment (or fuel reduction) in forests or at the WUI to increase the auto-resistance of vegetation.

In the US, congress devoted $500 M/year in the 2000s to support this activity [17]. Fuel treatment is done by cleaning the understory and/or thinning trees in order to avoid crowning and fires that consume the whole vegetation layer. Mechanical or chemical fuel reduction techniques can be used, but prescribed burning remains the main tool because it allows covering large areas with low resources and it can be applied in difficult topographies. Prescribed burning consists in conducting low to medium intensity fires out of the peak fire season to "clean" vegetation, mainly the fuel laying on the ground and the shrub layer but also sometimes the tree branches. The aim is to remove the dry and live fuel that may sustain fire.

The technique used in the specific location will depend on the local context and none is better than the others. At the WUI, cleaning around infrastructures can be drastic in order to break the fire dynamics and decrease infrastructure exposure. Several best practice programs exist to support fuel treatment around infrastructures, such as FireWise (USA), FireSmart (Canada) and FireSafe (California). Fire resistant structures can also be developed, and several standards exist as displayed in Table 87.1, which includes the standards applicable to the WUI.

These programs, codes and standards provide some guidance to develop fire protection solutions at the WUI (NFPA), to provide guidance for building construction at the WUI (ICC) or to develop test methods for materials exposed to fires at the WUI (ASTM). While they represent very valuable tools to help protecting the WUI, a lot remains to be done. For instance, the exposure techniques used in the different codes and standards need to be better linked to the actual exposure conditions happening during WUI fires. Recent field studies show the tendency of firebrands to ignite many houses during WUI fires, even the ones protected by fuel treatment, and the ability of a burning house to create a large amount of firebrands that may propagate a fire in a community, even when the wildland fire no longer impacts it [18]. These topics are the object of research [19].

Over the last 60 years, the scientific community has become more involved in the modeling of forest fires, and a number of physical approaches have emerged. The understanding of the physical mechanisms that control wildfire ignition and spreading constitutes the keystone of the development of fire protection engineering tools useful to management and fire fighting. Wildfire is a complex phenomenon in which the levels of description cover a huge range, from the details of the kinetics of gaseous combustion and thermal degradation of fuels, up to the chemical and physical characterization of the flame and the vegetation cover as a fuel. Figure 87.1 represents an overview of the different space and time scales involved in wildfires and the related difficulties for modeling.

**Table 87.1** Existing code and standards related to the WUI

| | |
|---|---|
| **National Fire Protection Association (NFPA)** | |
| 1141 | Standard for Fire Protection Infrastructure for Land Development in Suburban and Rural Areas |
| 1142 | Standard for Water Supplies for Suburban and Rural Fire Fighting |
| 1143 | Standard for Wildland Fire Management |
| 1144 | Standard for Reducing Structure Ignition Hazards from Wildland Fires |
| 1145 | Guide for Use of Class A Foams in Manual Structural Fire Fighting |
| **International Code Council (ICC)** | |
| 2012 (year) | International Wildland-Urban Interface Code |
| **ASTM International (E05.14 Subcommittee on External Fire Exposure)** | |
| E108—11 | Standard Test Methods for Fire Tests of Roof Coverings |
| E2632/E2632M—13e1 | Standard Test Method for Evaluating the Under-Deck Fire Test Response of Deck Materials |
| E2707—09 | Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure |
| E2726/E2726M—12a | Standard Test Method for Evaluating the Fire-Test-Response of Deck Structures to Burning Brands |

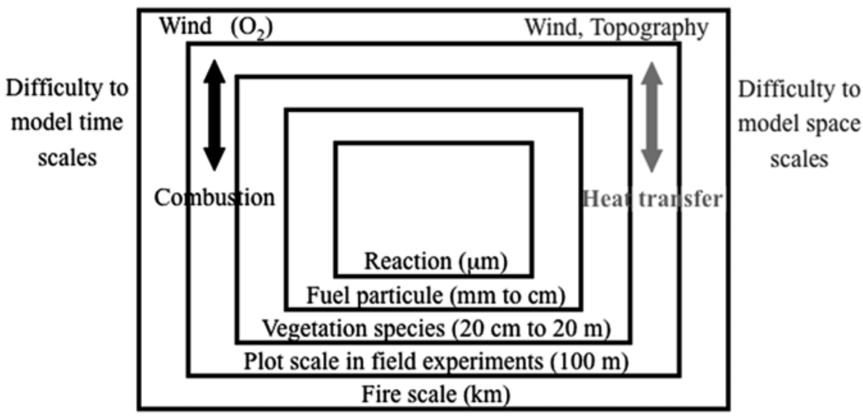


**Fig. 87.1** Different space and time scales involved in wildfires

Even if the physical laws are known and GIS and weather models can provide the environmental data, modeling fire spread is really challenging. The difficulties rely in the high variability of the environmental parameters, in the large range of scales, and also in the huge number of phenomena involved in the process, such as drying and degradation of vegetation, flaming and smoldering combustion, flow inside and above the fuel bed, turbulence, and radiative transfer. These phenomena are all coupled and their respective importance in driving fire spread is difficult to assess and varies with the fuel and external condition. The next section describes the basics of wildfire spread in general terms, as well as different kinds of extreme fire behavior.

## Fire Behavior

### Mechanisms of Fire Spread

#### Basic Mechanisms

An unburned piece of vegetation (Fig. 87.2a) can be approximated as being a fuel particle. This particle is submitted to a heat insult when the fire front is getting closer.

The heat transfer influence on fire spread is essentially through two modes: radiation and

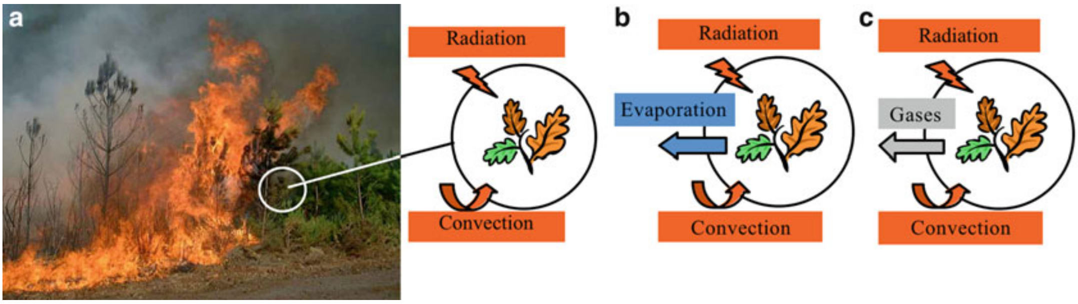


**Fig. 87.2** Fire spread mechanisms—(**a**) fuel particle and thermal transfer, (**b**) drying, (**c**) pyrolysis

convection. Radiative heat transfer acts at a larger range than convective heat transfer ahead of the fire front. Radiant sources are the flame front and the smoldering vegetation. Heating by convective heat transfer needs some flow to come from the burning area and to be in contact with unburned vegetation (otherwise, vegetation is only cooling by convection).

When a vegetation particle is submitted to thermal transfer from the fire front, it heats. When its temperature is high enough (usually around 100 °C), it starts to dehydrate (see Fig. 87.2b). The water content in vegetation, called fuel moisture content (FMC), plays an important role in fire spread because it acts as a heat sink, which can delay or even prevent fuel ignition.

Once the vegetation particle has dried, it starts to pyrolyze. The proximity of flames makes the flammable mixture ignite and the fire spread. First, combustion occurs in the gas phase. Then, embers appear when the particle has finished emitting gases and is fully converted into char. The combustion appears at the surface of the char and the particle glows. The embers emit a large amount of radiation and burn slowly. When the embers are fully consumed, the particle turns into ash.

A fire spreads in the presence of three simultaneous factors: flammable gases, oxygen (in air) and a heat source strong enough to ignite the flammable mixture.

## Parameters

The most obvious parameters driving fire behavior are the properties of vegetation, wind and topography. They are diverse kinds of vegetation properties: particle and bulk properties, fuel moisture content (FMC), and the spatial distribution of vegetation [20]:

- The particle properties represent vegetation as a fuel. They include the physical and chemical properties. The physical properties are the thermal properties—such as the heat capacity, heat conductivity, absorptivity and emissivity of radiation—the density, and the surface-to-volume ratio. The surface-to-volume ratio is an important parameter regarding heat transfer that will condition radiative and convective transfer between vegetation and the flame. The chemical properties are the chemical composition of vegetation (cellulose, hemicellulose, lignin, extractives, and minerals) that conditions the nature and quantity of the degradation gases, the latent heats of drying and pyrolysis, the heats of combustion of the pyrolysis gases and of the char. Some vegetal species are more flammable than others, such as sapwood compared to hardwood.
- The bulk properties represent vegetation as a fuel layer. They include bulk density, permeability (or drag forces) and attenuation of radiation [21]. All of these bulk quantities are a mix of particle properties and porosity. For instance, permeability depends on many fuel properties, including the surface-to-volume ratio, the roughness of the particle's surface and the fuel bed porosity. Wildland fuels are different from the usual fuels encountered in the built environment. Among all fuels present in a vegetation layer, it is commonly

accepted that only the thinner particles (diameter lower than 6 mm) are involved in fire spread [20], i.e. the leaves or needles, burn faster than branches or trunks and are the main contributors to fire spread. However, larger particles can burn later and participate in a structure's or soil's life exposure to heat. They can also create hot spots that have the potential of igniting new fires after the initial fire has gone. Vegetation is porous, with porosities ranging from 0.05 for pine needle litters to 0.002 for tree canopies [22, 23]. The bulk density represents the quantity of fuel mass (usually only considering thin particles) per unit volume. The permeability represent the interaction between vegetation and flow, either meteorological wind or wind induced by the fire itself. The attenuation of radiation represents how radiation coming from the fire front is absorbed by unburned vegetation. Many other properties can be represented as bulk properties. For instance, convective and conductive transfer will be conditioned by porosity and empirical laws including porosity can be derived [24]. Combustion in the fuel layer will depend on the availability of oxygen and hence be a function of porosity and drag forces.

- FMC is one of the most critical parameters. It is the main energy sink that can slow down ignition and decrease the fire heat release rate. Its value will condition the ability of a fire to spread and its rate of spread. The factors influencing FMC are as diverse as the air humidity, the air temperature, the sunlight exposure, the soil moisture, and plant physiological factors [25]. FMC varies in time and space, depending on local conditions and can create heterogeneous burn patterns [26]. The dynamics of FMC variations is very different for dead and dry fuels. Dry fuels are very sensitive to short term variations of weather conditions whereas moist fuels are more sensitive to long term variations. Dry fuels are mainly located on—or close to—the ground (litter/grass) and live fuel can be located at the surface (grass, shrubs) or at the top of higher vegetation (chaparral and tree canopies). The dry fuel is classified as 1 h, 10 h, 100 h, and 1000 h fuel, depending on the time it takes to adjust to changes in the external conditions. The time-lag classification is directly related to the size of the particles, 1 h fuels being particles no greater than 6 mm in diameter and 1000 h fuels being larger than 7.5 cm in diameter [20]. Fine dead FMC determines the rate of fire spread in surface fires. Live fuels are less sensitive to weather conditions in the short term but exhibit seasonal FMC variations due to plant physiology. This pattern is important to estimate the risk of crown fires. The worst-case scenario is the combination of drought and low seasonal FMC that can lower canopy FMC and even add dead fuel from otherwise live plants. In some ecosystems, this combination happens in winter or spring.
- The spatial distribution of the fuel can influence fire spread. There are two types of spatial distributions: vertical and horizontal. Vertical distribution is related to fuel layers. Fuel layers are usually defined as ground layer (duff or peat), surface layer (litter, herbaceous vegetation, and low shrubs), and crown layer (large shrubs and tree canopy). If these layers get very close to each other or overlap, a 'fuel ladder' exists that may create intense fires involving all vegetation at once. Horizontal distribution represents the fuel layer density, as for instance open or close canopies, as well as larger heterogeneities such as non-flammable areas (for instance rocks, rivers, and roads). The horizontal heterogeneities have a strong influence on fire spread. They also condition the occurrence of crown fires and can create heterogeneous fire patterns [26].

Wind has the effect of tilting flames. It also brings fresh air and thus fresh oxygen to enhance combustion and make flames longer. The flames being longer and tilted, the thermal transfer towards the unburned fuel will be increased greatly (see Fig. 87.3a and compare to Fig. 87.2a): the radiative source is larger and

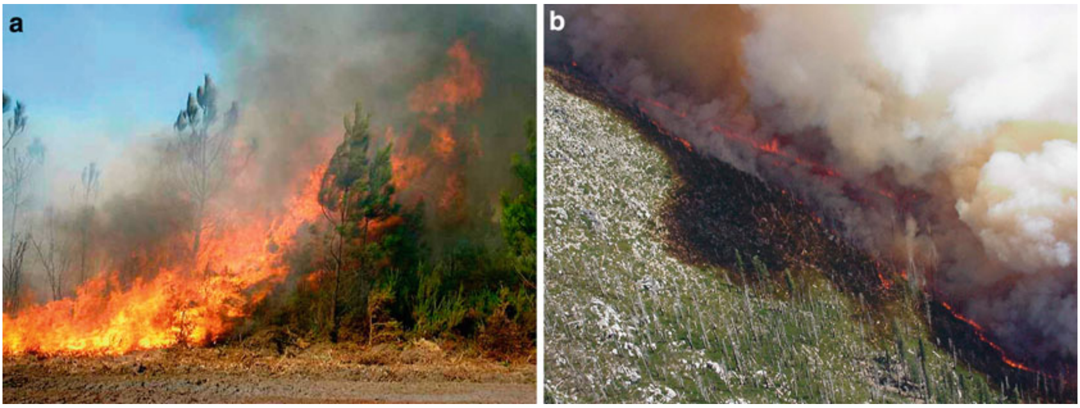


**Fig. 87.3** External parameters for fire spread—(**a**) wind effects, (**b**) slope effects

closer and sometimes flames will engulf unburned vegetation and increase convective transfer. This change in behavior can induce steep accelerations of the fire front. Another wind effect is to make the fire front deeper by increasing the fire rate of spread. More vegetation is ignited ahead of the fire while vegetation is still burning at the back of the fire. Such fires are usually intense and difficult to fight. However, the impact on the ecosystem can sometimes be less dramatic because wind also cools the fuel after the fire, and the heat insult on vegetation and on the soil can be shorter.

The last effect is the effect of topography and more specifically of slope. The flame front is closer to vegetation in the slope direction, so a particle located ahead of the fire in the direction of slope will be heated more by radiation than another particle located on the flanks of the fire (because of the radiative view factor between the fire font and the particles). The fire head will then spread faster than the flanks and it will accelerate. This effect creates the specific pointed heads that are encountered for upslope fire spread as seen in Fig. 87.3b. For fires spreading under windy conditions, the flames are tilted in the wind direction and this effect of pointed head does not appear.

Except for the pointed head, the effects of wind and slope are similar for low winds and low slopes. For instance, when a fire spreads upslope, the vegetation facing the slope will be closer to the flames and the radiative transfer will be enhanced. Air is entrained more into the fire front from downslope than upslope. In confined conditions, such as canyons, this effect can increase the fire rate of spread as described in the next section for eruptive fires.

Obviously, this representation of the basics of fire spread is simplified, and all the phenomena are coupled, making predictions difficult. The coupling between the fire and the atmosphere will be mentioned later.

## Extreme Fire Behavior

The previous section described the basics of fire behavior, but under specific conditions, fire can shift to extreme behavior that, when unexpected, can have catastrophic consequences. Several types of extreme fire behavior exist. Fire eruptions or blowups, crown fires, spot fires, fire whirls, and peat fires will be presented in this section.

### Eruptive Fires

Eruptive fires imply a sharp acceleration of the fire in confined topography. Under specific slope, wind, and vegetation conditions, a fire that spreads in a usual way can ‘erupt’ and multiply its rate of spread by 5–10 [27]. This induces the creation of a large area simultaneously on fire.

An example of such a fire can be seen in Fig. 87.4a for a fire that happened in Corsica, France in 2000 [29]. The picture is extracted from a movie taken by a tourist and is the only

**Fig. 87.4** (**a**) Video capture of a fire eruption [28]. (**b**) Eruption laboratory experiment at ADAI laboratory, Portugal

known video recording of such an event. The area simultaneously on fire was estimated to be around 6 ha and the fire rate of spread during the eruption was estimated to be around 20 km/h. When firefighters are caught in such a phenomenon, they usually die or are severely injured, even when sheltering in their vehicles. Europe has a long record of death by such events, numbering more than 200 fatalities over a 30 years period [29].

The factors leading to eruptions are only partially understood. Several physical and chemical phenomena could cause them: wind, topography, vegetation distillation, and smoke accumulation are found as potential explanations in literature. Experimental studies conducted in Portugal [28] allowed reproducing eruptions at the laboratory scale and demonstrate a strong coupling effect between a canyon—in the case of the experiments, a bi-panel tilted bench (see Fig. 87.4b)—and the fire that increases heat transfer at the fire head. This explanation is similar to the trench effect demonstrated for the King's Cross station fire in London [30]. However, laboratory studies and feedback studies from past accidents do not allow separating all the potential causes of fire eruptions, and a general theory is still to be developed. More research is necessary to understand the phenomena involved in fire eruptions and the mechanisms that trigger them. This research will have the potential to improve fire fighter safety, particularly in canyon configurations.

This behavior in canyons is called 'blowup' in the US, and the difficulty of conducting feedback studies for such complex and extremely rapid phenomena led to the definition of an alignment of factors. The difficulty lays in identifying which of these factors really triggers blowups. However, the specific meteorological phenomenon of 'Cold front' seems to be one of them and was apparently involved in several accidents [31].

## Crown Fires

Crown fires can produce intense wildfires and are overwhelming for anyone who observes them. Van Wagner [32] defined three classes of crown fires:

- Passive crown fire: When the crown cannot sustain fire spread and needs the energy from the surface fire to get a flame in the crown layer. In this case, the rate of spread of the surface fire controls the crown fire.
- Active crown fire: When the crown cannot sustain fire spread but can develop a substantial flame that creates a heat feedback to the surface fire. Then, the crown fire and the surface fire spread together at a rate that is greater than the rate of spread of the surface fire, would it be alone.
- Independent crown fire: When the crown can sustain fire spread and does not need to receive additional heat from the surface fire. Then, the crown fire will spread on its own, faster than the surface fire.

The latter class is the most dangerous with the highest rates of spread and heat release rates and is most likely to occur under strong winds. However, the optimal conditions to get independent spread are so difficult to reach that long-lasting independent crown fires are rare events.

Another way to classify crown fires is between wind-driven and plume-dominated fires [33]. For wind-driven fires, the plume is tilted in the direction of wind, and for plume-dominated fires the plume is vertical. Under wind conditions, the power of wind and the power of the buoyancy-induced fire plume compete to create one or the other kind of plume, depending on the size and intensity of the fire. The wind-driven fires are more likely to lead to independent crown fires and to send a large quantity of firebrands in front of the fire. However, the turbulence created by the plume-dominated fires can create a recirculation of hot gases in front of the fire and induce sudden and unexpected accelerations of the fire front [20].

## Spot Fires

Spot fires are created by firebrands that land on unburned vegetation. Firebrand generation is the process through which fuels such as shrubs and trees are heated and broken into smaller burning pieces during a fire [34]. Subsequently, they may be transported far away from the fire through the plume [35]. If firebrands are still burning when landing and if the recipient vegetation on the ground is dry and dense enough, they may create spot fires.

Firebrand effects can be split in long-range and short-range effects. Long-range firebrands are lifted by the fire plume at high altitude and are transported horizontally by wind over a long distance. If these firebrands start a new fire, it will be independent from the source fire, at least during its growth. The very short-range firebrands don't really influence fire spread because the fires they may start are absorbed by the main fire front before having time to develop. However, they can sometimes allow a fire to cross small natural or man-made obstacles. Short-range firebrands that land at a longer distance from the fire front can accelerate the fire spread by creating a spot fire that had enough time to develop and that is drawn into to the main front when getting closer to it, hence accelerating the fire spread. This phenomenon is dangerous for firefighters if they get caught in the middle, before they realized that a fire has ignited behind them [20].

The analysis of spot fires is complex because they are made of several distinct stages that are still poorly described [35]:

- Firebrand production that depends on the fuel type, the fire plume intensity, and the local burning dynamics of vegetation.
- Travel distance that is a function of the size and shape of firebrands, the plume intensity, and the wind velocity.
- Landing conditions that depend on the burning state of the firebrand (smoldering or flaming), the fuel type at the landing spot, the FMC and even the type of contact to transfer enough heat to ignite the ground fuel.

For more than 40 years, studies have focused on understanding how far firebrands can fly [36, 37], whereas more recent studies evaluated the production and ignition processes [19, 38].

## Fire Whirls

Fire whirls are due to the combination of the strong buoyancy created by the fire front and any phenomenon that creates air rotation. They can pose an issue for prescribed burning or for fire fighting safety [20]. In wildland fires, this rotation usually happens on flat ground, at the leeside of obstructions, or at mountain ridges [20]. The combustion rate is multiplied inside the fire whirl, increasing the heat release rate and the fuel consumption [20]. Some fire whirls can propagate the fire front by moving towards unburned vegetation or by producing a large amount of firebrands that land close to the fire. The resulting firebrands can be larger than usual because of the strength of the vertical winds inside the fire whirl that can lift large burning particles. The created spot fires can suddenly enlarge the fire front and make it much more intense than the supporting fire [20].

Fire tornadoes can be created when large pyro-cumulonmibi develop over massive fires.

Fire tornadoes occurred during the 2003 Camberra fires that were estimated to be at least of F2 intensity on the Fujita scale [39].

Fire whirl mechanisms are not different from those encountered in other fires in the open like urban conflagrations and they can be described in the same way [40].

### Peat Fires

Peat fires are not labeled as extreme because of their rate of spread or their intensity but because of their magnitude and the fact that they happen during extreme weather conditions, such as the fires that circled Moscow in June 2010.

Peat fires are smoldering flameless fires that spread slowly in the soil layer [41]. They occur relatively frequently in Northern boreal ecosystems and can also happen in humid tropical forests like during the Indonesia fires of 1997 [13]. Usually, peat fires are ignited by surface wildfires that migrate into the peat layer, which thickness ranges from 0.5 to 12 m. The fires can be totally underground because of the low intensity of smoldering combustion that does not require much oxygen. Once ignited, they are particularly difficult to extinguish despite extensive rains or fire-fighting attempts and can linger for long periods of time (weeks and up to years) [13] and spread over very extensive areas of forest and deep into the soil. The oxygen is supplied through cracks in the ground, and the heat loss is low in the insulating soil layer, which can sustain fire for months. Very often, they allow flaming combustion to re-establish during wildfires at unexpected locations (e.g. across a fire break) and at unexpected times (e.g. long after burnout of the flame front). This feature is also shared with duff fires, and to a lesser extent, with hummus fires. The usual way to fight these fires is to create trenches by digging to the mineral soil and creating a fuel break or trying to soak them with water. These techniques are challenging to use when the underground fire is not accurately located and the area to cover is large [41].

Peat fires can cover wide areas and consume large quantities of carbon. It has been reported that smoldering of surface fuels can consume around 50 % or more of the total burned biomass in temperate and boreal fires, as well as in Amazonian tropical-woodland fires [42]. Smoldering of forest fuels is also responsible for a significant fraction of the total pollutants emitted into the atmosphere during a wildfire [13]. Peat fires play a major role in the global emission to the atmosphere, the destruction of carbon storage in the soil and the damage to the natural environment. In addition, large peat fires can create health issues for the exposed population and economic losses, such as those induced by airport closure or the loss of activity for industries sensitive to smoke pollution.

Small-scale laboratory experiments have studied the ignition and spread of peat fires [43]. The governing factors are heat transfer, oxygen availability and FMC [44].

## Models and Simulators

Several reviews have been published about fire-spread modeling [45–49]. Based on the classification proposed by Weber [45], three types of models can be identified. The first type includes statistical models that do not consider any physical information at all. The second type of models incorporates semi-empirical models. They are based on the principle of energy conservation without distinction between the different mechanisms of heat transfer. Finally, physical models describe the various mechanisms of heat transfer and production. Among those, the detailed approach takes the finest physical and chemical mechanisms into account and is the most detailed modeling that has been developed so far [24]. Contrarily, simplified physical models only consider the main mechanisms involved in fire spread [47].

### Empirical Models

Empirical models are based on simple equations that do not include any physical information but that relate the fire head rate of spread to a set of statistically significant parameters. The data is collected in experimental fires or in well documented prescribed or wildland fires. Some of these models are part of simulators that are efficient for places with homogeneous vegetation and external parameters, such as Australian grasslands or Canadian boreal forest.

The Australian fire behavior meters provide the rate of spread of the fire head as a function of environmental parameters, FMC, and fuel availability for fire spread in grasslands [50] or Eucalyptus forests [51]. Fire predictions are given by fire danger meters, which are disks for which the alignment of the parameter values will give the fire head rate of spread. These meters are used on a day-to-day basis by foresters and firefighters in the field. Noble et al. [52] have expressed the meters as equations. For instance, the MK4 meter for grasslands predictions provides the rate of spread as [53]:

$$F = 2\exp\left(-23.6 + 5.01\,C_d + 0.0281\,T_a - 0.226\,H_r^{1/2} + 0.663\,U_{10}^{1/2}\right) \tag{87.1}$$

where $C_d$ is the degree of curing, $T_a$ is the ambient temperature in Celsius, $H_r$ is the air humidity in percentage and $U_{10}$ is he wind velocity at 10 m in m/s. $F$ is the fire index and the rate of spread is given by:

$$V = 0.036\,F \tag{87.2}$$

The Canadian Fire Behavior Prediction System is not directly used as a prediction system for the fire rate of spread by itself, but it is integrated in the fire weather index (FWI) that provides a daily estimation of the fire risk in Canada [54]. The following equation provides the fire rate of spread:

$$RSI = a\,[1 - \exp(-b\,ISI)]^c \tag{87.3}$$

where $ISI$ is the Initial Spread Index and $a$, $b$, and $c$ are fuel-dependent factors that are divided in eight classes representative of Canadian ecosystems [54]. $ISI$ is expressed as:

$$ISI = 0.208\exp(0.0504\,U_{10})\,91.9\exp(-0.138\,FMC)\left(1 + \frac{FMC^{5.31}}{4.93}10^7\right) \tag{87.4}$$

These models are statistically derived to provide the rates of spread for a given range of fuel and weather conditions, and they must be used with care when the conditions differ from the ones used to derive the model. The Canadian FWI has been extended and adapted with success to other regions of the world for the local ecosystems [55].

## Semi-empirical Models

Semi-empirical models are based on the principle of energy conservation but do not discriminate the different types of heat transfer and the different combustion processes. The energy conservation principle means that the energy produced by the fire is either transferred to the unburned fuel to maintain the fire, or lost to the ambient. The formulation of the energy balance takes the following general form:

$$Q = \rho\,h_i\,R \tag{87.5}$$

where $Q$ is the net energy going through the ignition surface per unit of surface area, $\rho$ is the fuel density, $h_i$ is the enthalpy per unit mass that is required to ignite the fuel and $R$ is the rate of fire spread. These models are steady-state—in the sense that one set of conditions gives one rate of spread—and one-dimensional.

$Q$ is expressed by using heat transfer laws but its different components are estimated empirically by conducting a large number of laboratory fire spread experiments under varied experimental conditions.

The most famous of these models that is still extensively used is Rothermel's model [56], which is based on Frandsen's model of fire spread [57]. The equation for the rate of spread of the fire head is expressed as:

$$R = \frac{(I_p)_0 (1 + \varphi_W + \varphi_S)}{\rho_b \varepsilon Q_{ig}} \quad (87.6)$$

where $R$ is the rate of spread (m/s), $(I_p)_0$ is the heat flux from the fire front that reaches the unburned fuel ahead of it for a fire spreading on a flat surface and without wind (kW/m$^2$), $\rho_b$ is the fuel bulk density (kg/m$^3$), $\varepsilon$ is an effective number that defines the amount of fuel which is available to sustain fire spread (-), $Q_{ig}$ is the heat which is necessary to bring the fuel to ignition (kJ/kg), and $\varphi_w$ and $\varphi_s$ are correction factors for wind and slope, respectively (-).

The different parameters are either obtained from the physic-chemical properties of the fuel or empirically derived. The huge number of experiments conducted along time in the most diverse configurations allows the model to provide a good estimation of the fire rate of spread for a large range of conditions. As for the Canadian system [54], several fuel classes have been developed that are characteristic of American ecosystems [58, 59]. The model—and in general terms, the semi-empirical approach—is more general than the empirical approach and provides acceptable results in diverse configurations. However, the parameters still remain in a relatively narrow range, and the model is challenged when applied to areas with a large variability of parameters, like the Mediterranean basin.

The main simulation tools currently used by foresters and firefighters in the field are based on Rothermel's model [56]. For instance, Behave Plus [60] provides a quick estimation of the fire head rate of spread through nomograms and Farsite [61] is a whole GIS-based simulation suite that extends Rothermel's model to two-dimensions along the ground by applying Huggens' ellipse principle. Farsite also includes other models as detailed later. Even if they are widely used, these tools are more of strategic value, as they give an indication of the long term tendencies of a fire, than of tactical value to base any immediate decision on their short term predictions. These predictions can be biased because of the simplified nature of the models.

## Physical Models

### Simplified Physical Models

These models are conceptually more general than empirical and semi-empirical models. They can provide the fire shape and rate of spread, as well as an estimation of heat transfer and energy release with simulation times that can be close or even under real time, if some optimization techniques are used for computation. However, they have not been used extensively until now due to the fact that it is difficult to ensure that the chosen simplifications are relevant to diverse sets of conditions. Contrarily, empirical and semi-empirical models have the benefit of being statistically relevant to given conditions.

Simplified models do not calculate the flow as it is too computationally expensive but usually provide the fire rate of spread and the fire shape on the ground. The general formulation is around a single thermal balance with the addition of sub-models to take into account phenomena such as combustion or wind [62, 63]. The fuel is assumed as being a medium equivalent to the gas and the solid phases that coexist inside the fuel layer, and thermal equilibrium is assumed between phases. The flame has to be modeled as it cannot be computed in the absence of flow. It is often described as a radiant panel with a given height and emissivity.

As an example, the following thermal balance can be written, taking into account heat transfer mechanisms (radiation and convection) and heat production [64]:

$$\frac{\partial T}{\partial t} + k\vec{V}_g \cdot \vec{\nabla} T = -h(T - T_a) + K\Delta T + R - q\frac{\partial \sigma}{\partial t} \quad (87.7)$$

where $k$ is the advection coefficient, $K$ is the diffusion coefficient, $h$ represents the loss to the ambient, $q$ is the heat of combustion of the fuel and $\sigma$ is the fuel load (mass per unit area). The model is closed by using sub-models: a simplified flow model to obtain the horizontal flow velocity in the fuel layer $\vec{V}_g$, a radiant panel approximation to describe the radiative transfer from the flame $R$, and a simplified mass loss law to describe the variation of $\sigma$ due to the combustion reaction.

Several other variations exist that complicate more or less the formulation to describe better some aspects of the fire [65, 66].

A recent simplified model has been tested with a large set of available experimental data at laboratory scale for fire spread under diverse conditions [67]. The model has demonstrated good predictive capabilities that demonstrate the potential of simplified physical models to provide a general frame for improved predictions compared to the existing tool based on semi-empirical models. The predictive ability of the model at field scale has been improved by coupling it with an atmospheric model [68].

## Detailed Physical Models

The multiphase approach is described as an example of detailed physical models as it is the most detailed available formulation. The full details of the model presented below can be found in [69]. This approach represents the fire spread medium as being multiphase, reactive and radiative [24]. The medium is defined by the fluid phase and $N$ solid phases. Each solid phase consists of a set of particles that possess the same geometry and thermochemical properties (see Fig. 87.5). An elementary multiphase volume is defined that allows describing the fire phenomena at the relevant scale. A volume averaging procedure is applied to the volume to obtain averaged properties for both the gaseous and solid phases.

The system of averaged equations includes balances of mass, species, momentum and energy for each species, as well as a radiative transfer equation. The strong coupling between the solid and gas phases is represented by interface relationships. For clarity, no volume averaging symbol is added and only the mass equations are presented:

$$\text{Gas phase}: \frac{\partial}{\partial t}\left(\alpha_g \rho_g\right) + \vec{\nabla}\left(\alpha_g \rho_g \vec{V}_g\right) = \sum_{k=1}^{N}\left[\dot{M}\right]_{gk} \tag{87.8}$$

$$\text{Solid phase } (N \text{ equations}): \frac{\partial}{\partial t}(\alpha_k \rho_k) = -\left[\dot{M}\right]_k^{surf} - \left[\dot{M}\right]_k^{pyr} \tag{87.9}$$

$$\text{Interface equations} (N \text{ equations}): \left[\dot{M}\right]_{gk} = \left[\dot{M}\right]_k^{surf} + \left[\dot{M}\right]_k^{pyr} \tag{87.10}$$

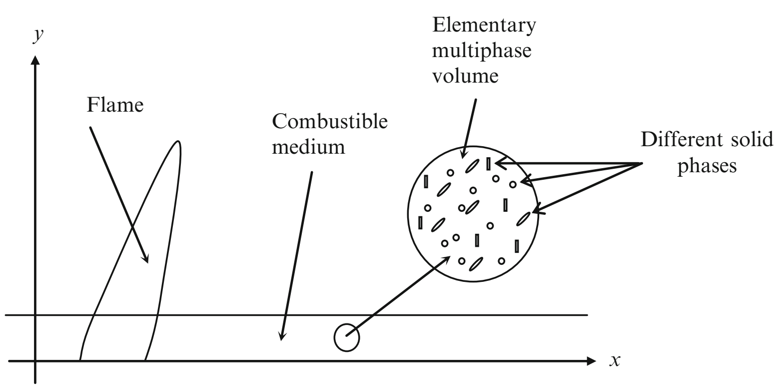


**Fig. 87.5** Schematic representation of the problem for the multiphase approach

where $\alpha$ is the volume fraction of the considered phase (percentage of the volume occupied by the phase), $\rho$ is the density and $[\dot{M}]$ is the mass flux. The subscripts $g$, $k$ and $gk$ denote the gas phase, the $k^{th}$ solid phase and the flux from the $k^{th}$ solid phase into the gas phase, respectively. The superscript *surf* denotes the surface reaction of oxidation (smoldering) and *pyr* denotes the gasification of the solid phase (pyrolysis gases fuelling the flames).

From this method, different terms appear on the right side of the balance equations that need to be determined via sub-models. For the mass equations, they consist mainly in Arrhenius type laws for drying, pyrolysis and charring of vegetation. One of the key issues of applying the model is to design proper experiments to evaluate the sub-models under actual fire conditions, which can be very difficult, if not impossible to achieve for some of the sub-models.

The model—as other CFD models—provides fields for all variables, such as temperature and velocity, but also species mass fractions and turbulent kinetic energy. However, it is difficult to design experiments to validate its results. Usually, the rate of spread and the flame geometry are compared to experiments [70], but it does not represent a proper validation as these experimental parameters are not directly related to the variables of the model.

## Simulators

Table 87.2 presents the main simulators that are available to describe fire spread and provide at least the fire rate of spread and the fire shape. Other tools exist that provide nomograms, statistical fire behavior or spatial analysis, such as Behave plus [60], Nexus [70], and FlamMap [73].

Farsite [61] provides the fire shape and rate of spread as a function of vegetation and external parameters. Several other outputs are available, such as the fire-line intensity [74] (defined as the mean heat release rate per meter of fire front), crown fire initiation [32] and spread [33], as well as the basic effects of fire-fighting on fire spread. The predictions for crown fire spread underestimate actual fire spread because the crown fire models have been developed based on a very limited set of experiments and have not been fully validated [75]. Additionally, the surface and crown fire models are of different nature, making their coupling very difficult to achieve [75]. This statement extends to the other simulation tools based on empirical and semi-empirical surface fire models that are not described in this section. Simple wind modeling that represents the variability of wind with topography can be coupled to Farsite and allows substantially improving its predictions [76].

NCAR [25] is dedicated to the understanding and description of the direct atmosphere/fire interaction, as well as fire emissions. As it uses Rothermel's model [56], the description of the fire is submitted to the same limitations described for the semi-empirical approach. However, the atmospheric aspect allows describing the large scale effects that happen due to the fire/atmosphere coupling and that can influence fire spread, particularly for massive fires.

WFDS [71] is a full simulation suite that is based on the multiphase approach detailed above. It is dedicated to describe Wildand urban interface fires. It resolves flow, heat transfer and combustion at the scale of vegetation.

**Table 87.2** Simulation tools available in literature

| Simulator | Type of fire model | Fire/atmosphere interaction |
|---|---|---|
| Farsite [61] | Semi-empirical | Constant or topographical wind effect on fire |
| NCAR [25] | Semi-empirical | Atmospheric coupling (MM5) |
| WFDS [71] | Detailed physical | Detailed physic-based (no atmospheric coupling) |
| Firetec [72] | Detailed physical | Atmospheric coupling (HighGrad) |
| Forefire [68] | Simplified physical | Atmospheric coupling (Meso-Nh) |

The simplifications in the model based on the Fire Dynamics Simulator [77] allow the model to describe the fire at the fire front scale with the use of heavy parallel computational power.

Firetec [72] couples fire spread modeling in a simpler way than the multiphase approach to atmospheric modeling. It is very efficient to describe fire spread in relation with the local flow around the fire. However, the computational needs imply the use of supercomputing capacities to be able to simulate the scale of a small wildland fire.

Forefire [68] couples simplified physical fire-spread modeling to atmospheric modeling to study fire spread and emissions. The fire plume and the fire/atmosphere interaction are described at a scale much larger than the fire.

WFDS [71] and Firetec [72] are still research tools but they represent the future of fire-spread simulation that will allow going beyond the current limitations of available simulators. They will not be used as operational simulation tools for a long time, and their applicability is not even assured because of their complexity and the large number of parameters and inputs they require. However, they will allow developing simpler models that will include the relevant phenomena that actually drive fire behavior. This is something that the semi-empirical models are not able to achieve. Forefire [68] is already a step in this direction.

Another approach, which could improve the predictive capability of fire spread models, is data assimilation. This approach was initially developed in meteorology. It consists in informing the fire spread model with real-time measurements from the fire it aims to predict. The data is used to correct the model's predictions through a reevaluation of its parameters [78], hence avoiding the increasing gap between model predictions and actual fire behavior that systematically happen along time. This divergence is due to many factors, such as the variation of conditions, the inaccuracy of parameters, or the approximate nature of the fire spread model. The application to Rothermel's model showed that this approach has the potential to improve predictions [79].

## Fire Danger

Operational fire danger rating systems have mainly been developed in Australia [80] Canada [54] and the US [58]. The Canadian system has particularly been adopted by several countries and adapted to local conditions [55]. The main variables taken into account in the systems are live and dead fuel FMC, as well as meteorological variables, such as wind, air temperature and air humidity [81].

The most empirical approach is used in Australia because of the fairly constant external conditions that exist in many parts of the country and the large amount of empirical data that was collected allow obtaining good results with the empirical models for fire spread in grassland [50] and eucalyptus forests [51]. The meteorological parameters are wind velocity and ambient air conditions, as well as rain history. For grasslands, the percentage of dead material (curing) is an important parameter because it drives fire behavior for such very fine fuels constituting a single vegetation layer.

The Canadian Forest Fire Danger Rating System [59] is more detailed than the Australian one and aggregates different types of fuel ecosystems from grassland to forest through its fuel models. It combines the effect of weather conditions and FMC on fire behavior. The moisture of the soil fuel layer is finely described as it represents the potential of a fire to ignite. The danger is expressed as the expected fire-line intensity [74], which is a combination of the initial rate of spread (given in the previous section) and the fuel load:

$$I = HWR \qquad (87.11)$$

where $H$ is the heat of combustion of the fuel (kJ/kg), $W$ is the fuel mass consumed per unit area (kg/m$^2$), and $R$ is the rate of fire spread (m/s).

The National Fire Danger Rating System is used in the US [82] and is similar in nature to the Canadian system. The main difference is that it includes semi-empirical modeling that is more detailed than the modeling used in the Canadian

System. For instance, the fire rate of spread is determined with Rothermel's model [56] and the soil moisture is determined by a semi-empirical approach that balances precipitation and evapotranspiration [82].

All these models have proven to be efficient and are used routinely for the daily assessment of fire danger all around the world. However, they have shown their limitation in the context of the occurrence of extreme conditions when the values of the parameters are well out of range and the empirical and semi-empirical models cannot provide good predictions anymore. Despite this, there is no physical approach available yet and the models are extrapolated to try to anticipate higher levels of risk that become more and more common due to socio-economic and climate changes.

## Fire Impact

Fire impact under the fire safety viewpoint refers mainly to the impact on people and structures. The main mechanism that supports the impact on people is heat transfer, i.e. radiative and convective transfer from the fire front. The main factor that influence structural ignition at the WUI is also heat transfer from approaching flames but firebrands deposit has to be added. Firebrands can ignite a structure by two ways: they can accumulate on the outer surface of a structure and ignite it, or they can find a way through the structure to reach easy-to-ignite fuels.

Other forms of impact, such as ecological impact or health impact are not developed here.

### Heat Transfer

Heat transfer can impact people or structures. The impact on structures is mainly related to the WUI problem. It is difficult to ignite wood panels or vinyl siding only by radiation, and flame contact is often necessary [83]. Fuel treatment programs, such are FireWise are based on this observation and recommend fuel removal up to a certain distance around houses.

The people who are close enough to be impacted by fire and can sustain exposure to relatively high heat fluxes are fire-fighters wearing personal protective equipment. Thus, the main concern for people exposure is fire-fighters safety, and a better evaluation of safety distances would improve it greatly. The safety distance is related to three aspects: the intensity of the fire, the mode of heat transfer, and the resistance of the target to the heat insult. The exposure time is also an important parameter. In this context, the knowledge of fire behavior and the good representation of the heat transfer are of primary importance.

The current models used to evaluate safety distances are only based on radiative transfer. They use the solid flame assumption (flame equivalent to a radiant panel) with constant values of flame height and flame temperature [84, 85] and express the fire radiative impact as a function of the flame height. A latter model [86] takes into account finite fire front width, which is more realistic, and express the safety distance as a function of the fire front width/flame height ratio. The problem of these models is that they assume that the flames have constant properties, whereas flame radiation is defined by the turbulent nature of flames with changing geometry and distribution temperature. Furthermore, radiation has a relatively short range effect [87] and at a short distance, convective transfer is likely to have a strong role [88]. The models will need to take this transfer into account to provide better estimations of the safety distance. The solid flame models do not describe the flow, and adding convection could be difficult. CFD models could potentially yield much better results, but they are not mature enough to be used in this context. They are also very sensitive to radiation as a slight variation in flame properties (emissivity, temperature distribution, and volume) can have a large effect on radiative transfer.

## Firebrands

If the research has focused for quite a long time on radiative and convective impact on structures, recent field studies have highlighted that structural ignition from embers is a main cause of structure loss at the WUI [18, 89].

The structure ignition can come from a single ember that found its way to the weak points in a structure, like going through vents or depositing under the roof. However, the main impact happens during exposure to the short-range firebrand shower that induces exposure to a large quantity of burning (smoldering and flaming) firebrands, creating accumulations in wedges, corners, and cracks [18, 90]. In this case, several parts of a structure are likely to ignite, such as roofs, decks, siding, and even surrounding elements, such as fences and any pile of combustible materials (as wood stored for winter) that would spread a fire to the structure when ignited.

NIST has a research program to characterize ember production, as well as vegetation and structure ignition when submitted to an ember shower [19]. In the case of a firebrand landing on vegetation, it is more likely that vegetation will ignite when the firebrand is still flaming [91]. In the case of an accumulation of firebrands, the structures are very weak and ignite quickly by the roof, sides and decks [90].

For fires spreading at the WUI, it is common to experience structural loss even at locations inside communities that were not touched by the fire front, highlighting the issue of structural ignition by firebrands [89]. When a structure is ignited, the fire can spread from structure to structure by two mechanisms: heat transfer from the burning structure to the next one if the structures are close enough. This is similar to the issue of building-to-building spread in urban settings [92]. The second mechanism is again by firebrands generated by the burning structure that have the potential to ignite neighboring structures, at distances greater than the zone of influence of the flames. It has been found that firebrands generated from structures are larger and broader than those generated by burning vegetation [93].

## Summary

Societies face great challenges due to wildland and WUI fires, and they will benefit greatly from a more systematic approach of fire safety engineering.

Wildland fires represent an intricate problem that adds the complexity of vegetation, large scale effects and open boundaries to usual fire problems, rendering any quantitative estimation of fire spread and fire impact difficult.

If it is already difficult to predict fire behavior under usual conditions, extreme fires pose additional challenges and more research is needed to understand them and predict their occurrence.

Wildland fire science is still a young science that was able to deliver some operational tools at the empirical and semi-empirical levels. The physical approach is promising and may produce the tools of the future, but it will necessitate a long investment in the fundamentals and in validation.

**Acknowledgements** The author is grateful to A. Maranghides and D. Morvan for their discussions and the information they provided. It helped developing some critical aspects of this chapter.

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