Chapter 7
Wildland Fire

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7.1 Introduction

Wildfires can have profound impacts on humans and the environment [1]. They are important to the functioning of many ecosystems globally, influencing the distribution, abundance and structural form of many plant species and vegetation communities [2]. Yet, they also threaten human life, property and the environment, with people killed, homes destroyed [3, 4], and ecosystems services like water supply severely disrupted [5].

The most devastating impacts are often associated with extreme fires that result from dynamic fire behaviours [6–8].These extreme fires carry particularly high human costs when they occur in the Wildland-Urban Interface where urban sprawl into more natural areas puts people and their dwellings in proximity of flammable vegetation [9, 10]. Ecological values in many areas are under threat from altered fire regimes, whether it be an increase in the frequency, severity, and extent of wildfire or the absence of fire in a system that is well-adapted to fire [11–13].

Climate change has the potential to amplify the social, environmental and economic impacts of wildfires [14]. In many parts of the world, we are already seeing longer fire seasons as the number of dry and hot days increases [15, 16] and more extreme fires occur [17]. This was especially apparent during the 2019/2020 fire season in south-eastern Australia, where record temperatures and drought conditions contributed to the most extensive forest fires in this region in recorded history [18].

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In this chapter we examine the impact of wildfires on a range of values:

- communities – human life and property,
- biodiversity – particularly plants and animals,
- soil and water, and
- air quality.

We then highlight the role of dynamic fire behaviours and their disproportionate contribution to wildfire impacts. The chapter closes within a reflection on Australia's 2019/2020 wildfire season (Black Summer fires hereafter). We describe these fires and their impact on people and the environment.

7.2 Impacts on Communities

Wildfires result in widespread destruction and damage to a range of economic and social assets and functions. Their impacts include losses of human life and property, livestock and crops, loss of tax revenues, property value and unemployment [19]. Wildfires also impact upon social systems causing psychological distress [20], social disruption [21] and preventing the use of recreational land [22].

Wildfire impacts on private property and public lands have increased dramatically during the past few decades [10]. They threaten many lives and cost billions of dollars in damage (Table 7.1). Many of the most destructive fires have occurred in south-eastern Australia, California USA, the Mediterranean region of Europe, south-western Canada, and Siberia and Far East of Russia.

A number of recent wildfires have impacted communities in locations where historically fires are rare or extraordinary events. For example, wildfires occurred in the tropical and temperate rainforests of Chile in 2014 and 2017 with 12 people killed and hundreds of homes destroyed [40, 41]. In Bolivia in 2017 wildfires resulted in 3 deaths, 1479 people injured, and 3000 homes lost [42]. There were wildfires close to the Arctic circle in Sweden, Norway, Greenland and Scotland [43–45]. In 2014 wildfires in Sweden killed one person, damaged or destroyed 71 buildings, and over 1000 people were evacuated [46]. In 2019 hundreds of people were forced to evacuate due to an extraordinarily high number of extreme wildfires in Norway and Sweden [44].

Wildfires cause the greatest loss of human life and damage to property in the Wildland-Urban Interface (WUI) compared with the broader vegetated landscape. The WUI is "the line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetation fuels" [47]. Greater losses occur due the density of people and houses within this zone. In some parts of the world a large proportion of the population lives within the WUI. For example, it is estimated that in Australia about 20.3% of addresses are within 700 m and 4.1% within 50 m of forested areas in major capital cities and surrounding areas [48].

Analysis of wildfire related life loss in WUI area of Australia over the past 110 years (1901–2011) showed that over 78% of all fatalities occurred within 30 m

Table 7.1 Examples of wildfires with large social, economic and environmental impacts from 2010–2020

Name	Region	Impact
2019 black summer fires	Australia	33 people killed and over 3000 houses destroyed [23]
2018 camp fire	USA	85 fatalities and nearly 19,000 structures destroyed [24]
2018 Attica fires	Greece	102 fatalities and approximately 3000 houses burned [25]
2017 Thomas fire	USA	1300 structures lost and 2.2 billion USD in damages [26]
2017 British Columbia fires	Canada	1.2 million hectares burned and 65,000 people evacuated [27, 28]
2017 wildfires	Portugal	112 human lives lost with 424,000 hectares burned [29]
2016 Fort McMurray wildfire	Canada	2400 houses lost and 6 billion CND in damages [27, 28]
2016 wildfires	Portugal	4 people killed and more than 1000 evacuated [30]
2015 wildfires	Russia	33 people killed and 1300 houses burned [31]
2015 South Australia fires	Australia	2 lives lost and 88 houses burned [32]
2013 red October fire	Australia	224 structures destroyed and 1 person died [33, 34]
2012 Chios fire	Greece	9 villages evacuated and 7000 hectares burned [35]
2011 slave Lake fire	Canada	374 properties destroyed and 700 million CND in damages [36]
2011 Bastrop County complex fire	USA	2 deaths and 1645 homes lost [37]
2010 wildfires	Russia	53 fatalities and 2500 houses lost [38, 39]

of the forest [3]. For wildfires occurring under extreme weather conditions, fatalities within structures represented over 60% of all fatalities. It was shown [49] that there is a correlation between life loss and house loss. These findings highlight the importance of fire performance of structures in reducing life loss. The impact of wildfires on communities is expected to increase dramatically with the rapid expansion of population in the WUI [50] and because changing climate will likely increase the occurrence and intensity of wildfires [51].

The ignition of structures in communities is caused by exposure to heat fluxes (convective and radiative) from flames or firebrands generated by the wildland fire itself or from adjacent houses already burning [52]. The majority of houses are burnt at peak levels of fire danger [53]. Firebrand generation is the process through which wildland fuels, such as shrubs and trees are heated and broken into smaller burning pieces during combustion. In wildland fires a huge amount of smouldering and flaming firebrands are produced and transported by the convection column and the wind over long distances [54–56], leading to the formation of new spot fires and the ignition of structures. Firebrands deposit and accumulate on the outer surface of a building or find a way through the structure to reach easy-to-ignite fuel or structural elements within [57]. The intense exposure to firebrands in the vicinity of a fire front is called a firebrand shower (Fig. 7.1). This is the main condition of exposure from firebrands in the WUI [58]. Studies show that most house loss during a wildfire occurs via ignition from firebrands [10].

7.3 Impacts on Biodiversity

Fire is an important global force, shaping the distribution of biomes and driving biodiversity [2, 59]. Biodiversity is defined as the variety of all life including species, ecosystems and genes. Fire influences biodiversity in various ways such as killing individual organisms, disrupting competition and providing conditions for certain species to thrive [2, 60]. Fire is crucial for maintaining the structure and function of fire-prone ecosystems and many species across the globe require fire for their ongoing persistence.

A single wildfire can have wide-ranging effects on biodiversity. The effects of a single fire will depend on properties of the fire *event* such as fire behaviour, intensity and extent. However, knowledge of the history of preceding fires is often required to fully comprehend the effects of individual fire events. Together the properties of fire frequency (interfire interval), intensity, season and spatial extent define the *fire regime* of an area and are crucial to understanding the effects of fire on biodiversity [61–63]. Chemicals used for fire suppression also affect biodiversity (see Chap. 8).

Here we describe major effects of wildfires and associated fire regimes on biodiversity with a focus on plants and animals as two important and widely studied groups of organisms in the context of fire.

7.3.1 Plants

Wildfires consume an enormous amount of plant biomass across the globe with between 300 to 500 million hectares of vegetation burnt each year [64]. Plants and plant derived material typically provide fuel for fire, but as sessile organisms they also are vulnerable to its lethal effects. Fire affects two fundamental parts of plant

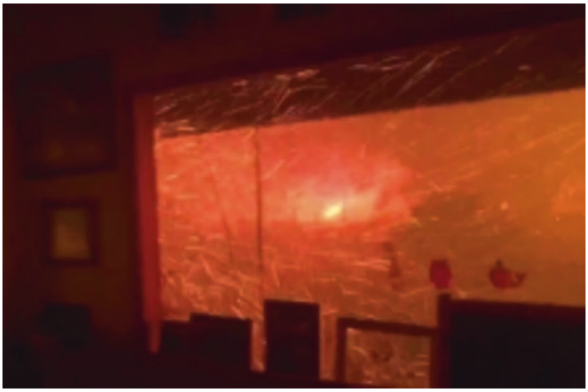

Fig. 7.1 Firebrand shower from a passing wildland fire, Western Australia. (Credit: Department of Fire and Emergency Services)

life cycles; causing mortality of existing plants and promoting recruitment of new plants. This leads to four conceptual, contrasting responses of plants to individual fire events: high recruitment-low mortality, high recruitment-high mortality, low recruitment-low mortality and low recruitment-high mortality [65]. The first three can be considered either fire dependent or fire tolerant whereas fire would result in local extinction of plants in the latter category.

Survival mechanisms include insulating sensitive tissues from the heat of fire in thick bark or soil and resprouting from underground or aboveground tissues [66]. Recruitment involves either germinating from stored seed buried in soil or held on the plant [65]. Plants that do not possess recruitment or survival strategies are vulnerable to local extinction in the event of fire and as such are reliant on dispersal to recolonise areas after fire [61].

The effects of wildfires on plants is dependent upon interactions between the fire regime and species response traits. Where species responses are adapted to a particular fire regime, local extinction may occur where it experiences a regime that is outside its tolerance for survival or reproduction [67]. This is clearly epitomised by serotinous species (plants that store seeds in the canopy) that are sensitive to multiple fires occurring at short intervals. Serotiny is a fire adapted trait that is common across the different biomes of the world including many coniferous forests in the northern hemisphere, and shrublands in the Mediterranean climate regions of Southern Australia and South Africa [68]. Plants showing this trait typically require crown fire to trigger the opening of woody cones or fruits before they subsequently germinate in ash beds [69]. Where fires occur at short intervals there may not be sufficient time for juvenile plants to produce enough seed before they are killed in the second fire, risking local extinction. For example, the dominant overstorey *Eucalyptus* species in mountain wet forests of south-eastern Australia are killed by high intensity fires and only reach sexual maturity after approximately 20 years [70]. Large areas of alpine ash (*Eucalyptus delegatensis*) forest burnt in three successive wildfires from 2003 to 2014 resulted in regeneration failure across multiple stands [71]. Similarly, lodgepole pine (*pinus contorta*) forests in North America have reduced regeneration and ultimately marked changes in structure and function after short-interval wildfires [72]. Ecosystems with a high incidence of serotinous species are also vulnerable to the long-term absence of fire [62]. However, increasing fire frequency and intensity with climate change poses greater risk of abrupt state-change due to loss of key species through short intervals between wildfires [73].

Climate change has the potential to compound the ecological effects of fire regimes with increasing temperatures and rainfall variability. Climatic conditions can both make plants more vulnerable to severe fires and affect plant establishment and ongoing survival after fire [74]. Rainfall in the years following wildfire is a major determinant of the trajectory of plant and ecosystem succession [75]. Post-fire drought in widespread areas of Conifer forests across North America placed increased stress on juvenile or fire damaged plants and affected subsequent recovery, increasing the risk of forest conversion to shrublands or grasslands [76]. Furthermore, drought conditions preceding fire can make certain plants more vulnerable to mortality and damage [77, 74].

Recently, there has been increased occurrence of wildfires in ecosystems that have rarely encountered fire associated with shifts towards a warmer climate [42, 78, 79]. While the long-term impacts of this are yet to be fully understood, increased fire frequency may pose a risk to biodiversity where systems include plant species that are fire sensitive and do not readily survive or reproduce after fire. For example, pencil pines *Athrotaxis cupressoides* are a rare, slow-growing paleo-endemic relict that occupy high elevation and high rainfall regions of Tasmania. This species occupies forests that are usually too wet to burn and lacks adaptations for surviving fire and reproducing in the aftermath. Climate change induced drying and increase in fire weather contributed to recent wildfire-driven loss of entire stands of this species [80], threatening its ongoing survival.

Another risk that wildfires pose to plant biodiversity is through the promotion of invasive plants. In the aftermath of a wildfire, conditions are ideal for many invasive species, such as ample light, a nutrient rich ash bed and reduced competition from established species [62]. The management of invasive, fire-promoted plants is a serious management challenge across the globe. Where invasive species dominate, they can alter fire regimes at the expense of other species [81]. For example, gamba grass *Andropogon gayanus* increases fuel load and fire severity in northern Australian savannahs, resulting in increased mortality of overstorey trees and thus more favourable conditions for its persistence and spread [82]. Invasive species can even promote fire where it otherwise rarely occurs, resulting in large shifts in structure and function of these ecosystems [83].

7.3.2 Animals

Animals, unlike plants, do not have structural or physiological mechanisms that allow them to survive the heat of fire. Individual animals rely on mobility or behavioural strategies to avoid death or injury in a fire event [84]. The immediate effects of a single fire on individual animals are influenced by the traits of the animals such as their size, mobility and life stage [85]. Larger mammals and birds that are highly mobile may be able to escape the immediate effects of fire [86]. Many fossorial animals survive fire by burrowing into soil however their ability to do so will depend on fire intensity and associated depth of heat penetration into the soil [87]. Animals with reduced mobility such as small reptiles, amphibians and invertebrates that live in substrates that regularly burn such as leaf litter may be especially vulnerable to immediate fire effects [88, 87].

The direct effects of wildfire on animal populations is likely to be dependent upon fire intensity, season and extent. Extensive high intensity wildfires reduce the ability of many individual animals to survive fire and may pose an extinction risk for species with restricted distributions [87]. The negative effects of wildfire on animal populations may be attenuated by refugia within fire boundaries [89]. Refugia can include patches of unburnt vegetation associated with less flammable vegetation such as those in riparian zones or vegetation types with less flammable plants or even areas burned at low severity within a wildfire boundary [90]. The extent to which moisture and fuel properties influence fire severity and the creation of refugia is dependent upon fire weather and under extreme conditions the abundance of unburnt patches or lower severity patches is diminished [91].

In many cases the aftermath of fire is of greater risk to many animals than fire itself [84]. For example, a large proportion of an elk (*Cervus canadensis*) population survived a large wildfire in Yellowstone National Park but mortality was high in the year after fire [92]. Fire results in resource depletion and many predators increase activity [93] posing risks of death by predation and starvation to many species. The risk from predators to animal populations after fire may be particularly acute where species are vulnerable to invasive predators [94].

The ability for animals to recover as conditions become suitable after wildfire is critical for sustaining populations. Recovery can take place in-situ, from refugia or from outside the fire boundary [85, 89]. After fire, movement is critical for recolonization and for maintaining genetic diversity of populations but may be impaired where fire occurs among fragmented landscapes where an inhospitable matrix inhibits movement [86, 95].

Arguably the most important effect of fire regimes on the long-term persistence of animal populations is the effect on habitat features that provide critical resources such as food, shelter and protection from predation [96]. Fire can affect specific resources that species require. For example, woodland caribou (*Rangifer tarandus*) forage on lichen in boreal forests to help survive winter months [97]. This food resource is reduced until approximately 50 years after fire and as such this species prefers older stands for foraging. Wildfire can also affect habitat features that are important for suites of organisms such as leaf litter and woody debris that take many years to recover, yet high intensity fire is important for creating suitable habitat conditions for many species [98]. Many important habitat features and resources are influenced by properties of fire regimes. In many ecosystems, animal species rely on habitat elements that are at risk of short or long fire intervals such as leaf litter, hollow logs or tree hollows [99]. Short intervals between wildfires can remove tree canopies and habitat features such as hollows in some systems, risking local extinctions of arboreal fauna [10v0].

Animals and plants are likely to be affected by climate change and its interactions with fire regimes. More frequent, intense wildfires may threaten certain vulnerable species such as those with restricted distributions or that occupy habitat types that are sensitive to such regimes. Furthermore, post-fire growing conditions affects subsequent recovery of plants which affect the resources used by many animals. Drought alone has negative consequences for many animal species [101, 102] and wildfires can potentially compound the effects of this and other threatening processes, resulting in population declines.

7.4 Impacts on Soil and Water

Globally, a significant number of people depend on water supplied from forests, grasslands or peatlands [103]. Many of these catchment areas are prone to wildfires. Wildfires can alter the movement of water and sediment on burnt hillslopes [104]. In some circumstances, this can have very serious implications for downstream water quality and yield, posing a threat to water security for the people and aquatic wildlife downstream [105]. In other circumstances, wildfires have seemingly little impact on soil and water. The degree of impact is determined by a complex interaction of factors and thresholds [106]. Understanding these factors and their interactions is critically important for predicting and managing the potential threat of wildfire to water security.

Streamflow in vegetated catchments is mostly provided by subsurface flow, with the soil acting as a filter for contaminants [107]. Surface runoff and erosion rates are low due to the combined effects of vegetative cover, high soil organic matter, and high soil porosity. Vegetation intercepts precipitation, reducing the amount of water available to infiltrate into the soil or become surface runoff [108]. Transpiration from living plants regulates the amount of moisture in the soil, while leaf litter on the soil surface reduces soil evaporation. Vegetation (particularly leaf litter) also protects surface soil from erosion caused from the impact of raindrops and overland flow [109]. Soil organic matter acts as a binding agent for soil particles, providing the soil structure that is crucial for water movement and water storage in the soil [110]. Macropore spaces created by cracks, old root channels and earthworm holes, provide preferential flow channels for more rapid infiltration of water into the soil, reducing the amount of water available to become runoff [107].

Increased runoff and erosion following wildfires is caused by several interacting factors. Rainfall interception by vegetation is reduced, which means there is more water available to potentially become runoff [104]. This is compounded by a reduction in the infiltration capacity of the soil caused by a combination of reduced soil organic matter, soil sealing, and soil water repellency. The combustion of soil organic matter reduces soil aggregate stability, pore size and total porosity [110, 111]. Soil aggregates are further destroyed by the impact of raindrops on the bare soil surface, which can lead to soil sealing [110, 112, 113]. Soil water repellency is another important contributor to enhanced runoff on burnt hillslopes [114, 115]. It can be created, strengthened, relocated or destroyed as a result of soil heating during wildfires. Low infiltration rates post-fire are often attributed to strong soil water repellency, though it can be difficult to quantify its influence on runoff rates relative to other factors, especially at larger spatial scales [113, 116, 117]. Without the protection of a layer of leaf litter, erosion caused by rain drop impact and runoff is enhanced [112]. In some circumstances, ash protects the soil surface from rain drop impact and acts as a water store, reducing runoff [118]. Conversely, it can contribute to soil sealing by clogging macropores and therefore contribute to increased runoff.

Wildfire impacts on runoff and erosion vary widely depending on a range of factors including fire severity, soil type, rainfall intensity and hillslope gradient. The largest impacts are observed where a high severity wildfire intersects [119] with an intense rainfall event in steep terrain [120]. These conditions can produce debris flows, a particularly destructive form of post-fire erosion [121, 5]. In areas of high fire severity, a large proportion of the vegetation cover can be consumed by the fire, maximising exposure of the soil surface [122, 123]. Furthermore, soils can be exposed to high temperatures for long durations, leading to the loss of soil organic matter [111, 112] and intensification of soil water repellency [124]. In contrast, lower severity fires, generally have lower runoff and erosion rates [125, 126]. These lower severity fires require a higher threshold of rainfall and steeper slopes for substantial amounts of runoff and erosion to occur post-fire [127, 128].

Vegetation type and its rate of recovery also determines the magnitude of post-fire runoff and erosion. Forests are susceptible to the largest increases in runoff and erosion while grasslands and shrublands generally exhibit the smallest changes [129]. This reflects lower fire severities and faster rates of vegetation recovery in grasslands and shrublands. The magnitude of post-fire runoff and erosion also declines with time since fire. This is sometimes referred to as the 'window of opportunity' before the vegetation recovers following a fire, with the greatest amounts of runoff and erosion most likely when intense rainfall occurs within 1–2 years of the fire [130, 131].

Higher rates of runoff and erosion within burnt catchments can have detrimental consequences for water quality in streams and water reservoirs [105]. Concentrations of a range of water quality constituents may be elevated, such as suspended sediments, ash, nutrients (N, P) and metals. Increased suspended sediment is the most commonly reported. Trace elements, bacteria and nutrients have a high affinity to fine sediment, so their levels are often correlated with levels of suspended sediment. Although most studies report an increase in suspended sediment, the magnitude increase is highly variable (e.g. from 11 to 500,000 mg L^{-1}) [105]. This reflects the complexity of factors influencing both post-fire erosion (as discussed above) and sediment movement through the catchment, most notably post-fire rainfall. In some forest systems, debris flows are considered the dominant risk to downstream water quality [132].

Elevated constituent concentrations in streams may pose problems for aquatic ecology [133, 134], water supply for domestic and agricultural purposes [105], recreation and aesthetics [105]. For example, domestic water supply was disrupted following the 2003 and 2006/2007 wildfires in south-eastern Australia resulting in boil water notices, water restrictions, water carting and the costly installation of new water treatment facilities for some towns [135]. Following an intense fire in Yellowstone National Park in 1988, aquatic macroinvertebrate richness, total density and composition fluctuated for the duration of a 10 year study rather than reaching a constant equilibrium [136].

Loss of vegetative cover may also impact streamflow and catchment water yields. Initially, reductions in rainfall interception and evapotranspiration, coupled with lower rates of soil infiltration, can equate to higher streamflow [137, 138]. Peak flows, including flash floods, can occur more frequently during this initial phase, with small, steep, severely burnt catchments being the most vulnerable [139].

Long-term trajectories for evapotranspiration and streamflow following fire are highly variable and depend on a range of factors including fire severity, vegetation type, regeneration mechanisms, and post-fire climatic conditions [140–142]. For example, forests with eucalypt trees that resprout via epicormic buds can recover rapidly following fire, with evapotranspiration and streamflow returning to pre-fire levels within 8–12 years, after a period of higher evapotranspiration [143]. In contrast, reduced streamflow can persist for 100–150 years, peaking 20–30 years post-fire, in Mountain ash (*Eucalyptus regnans*) forests that regenerate from seed following high severity fire [144]. In areas where the wildfire causes a substantial shift in vegetation type from forest to shrubland or grassland, reduced evapotranspiration and increased streamflow can persist for at least 10 years [145].

7.5 Impact on Air Quality

Wildfires release large amounts of smoke, which can pose a hazard to human health by impacting air quality. Global average wildfire emissions were estimated to be 2.2 billion tons per year from 1997 to 2016 [146]. In addition, chemicals in plastics and other materials are released into the air when structures and furnishings burn. Air pollution from wildfires affects visibility, human health and contributes to climate change [147]. Globally, average annual mortality from fire smoke is estimated to be 339,000 deaths, with the worst impacted areas being sub-Saharan Africa and South east Asia [148].

Smoke from wildfires is made up of small particles, gases and water vapor. Carbon dioxide and water vapor are the main constituents, generally contributing over 90% of total emissions [149]. The remainder includes carbon monoxide, nitrogen oxide, irritant volatile organic compounds, air toxics and very small particles (particulate matter or PM). The particulate matter in wildfire smoke is the sum of all solid and liquid particles suspended in air and includes both organic and inorganic particles. The particulate matter tends to be divided into two principal groups: coarse particles (PM_{10}) and fine particles ($PM_{2.5}$). The barrier between these two fractions of particles is fixed by convention at 2.5 μm in diameter. $PM_{2.5}$ is the most abundant constituent in terms of the number of particles, but only contributes a few percent of the total mass of smoke due to its small size [150]. It has been attributed to adverse health outcomes and mortality [148].

Smoke composition and quantity varies depending on the fire intensity (the amount of heat released) and rate of spread of the fire [151]. Wildfires with rapid rates of spread and high intensity but relatively short duration, burn at high temperatures and produce only small amounts of smoke. In contrast, wildfires with longer burning durations consume a larger portion of biomass through smouldering, which results in high levels of smoke production relative to the fuel consumed. Smouldering produces a large amount of carbon monoxide, hydrocarbons, nitrogen oxides, and sulfur oxides, all of which increase the toxicity of smoke [149].

Wildland fires (especially peat fires) can smoulder for months and accumulate high concentrations of smoke near the ground. For instance, the Capital of Central Kalimantan (Indonesia) in 2015 experienced 2 months of smoke. Daily average PM_{10} levels during these fires exceeded 3800 μg/m^3, shockingly higher than the World Health Organization air quality guideline (50 μg/m^3 24-h) [152]. During active wildfire periods, levels of carbon monoxide can increase 30–40% and polycyclic aromatic hydrocarbons can be 15 times higher compared with periods with no fires [153]. As a result, wildfires can cause severe levels of human exposure to toxic compounds.

Many wildfire emissions can have acute or long term health implications on the exposed populations [147, 151]. $PM_{2.5}$ is the principal air pollutant in wildfire smoke of concern for public health and it has various effects on human health [148, 151]. Fine particles may reach the alveoli in the lungs, and if not sufficiently cleared, may enter the bloodstream or remain in the lungs, resulting in chronic lung disease such as emphysema. Other wildfire emissions like volatile organic compounds may cause skin and eye irritation, drowsiness, coughing and wheezing, while others like benzene may be carcinogenic [150].

Among wildfire emissions, PM_{10} and $PM_{2.5}$ are the most studied in terms of their effects on human health. Daily and hourly $PM_{2.5}$ and PM_{10} concentrations can be increased dramatically by wildfires burning hundreds of kilometers away because of the ability of the aerosol to be transported long distances [154]. In terms of health, several studies have found a significant association between PM and respiratory symptoms, increased respiratory hospital admissions and increased emergency department visits [150]. Fine particles have been observed to cause changes in lung function, leading to increases in respiratory and cardiovascular mortality and morbidity including asthma. Studies have also found an association between daily mortality from wildfires for all-causes of death, including cardiovascular disease [155].

Not everyone who is exposed to thick smoke will have health problems. The level and duration of exposure, age, individual susceptibility, including the presence or absence of pre-existing lung or heart disease, and other factors play significant roles in determining whether someone will experience smoke-related health problems [151]. The elderly, people with pre-existing cardiopulmonary conditions, smokers and people with smaller airways may experience more severe short-term and chronic symptoms [150]. Additionally, fire fighters are at higher risk due to their level of exposure [156].

Population exposure and respiratory health impacts of wildfire smoke is likely to grow in the future as global wildfire activity and human population growth both increase. It is estimated that $PM_{2.5}$ exposures due to wildfire smoke in the western US for 2046–2051 under moderate climate change will be 160% higher than currently observed [157]. Liu et al. [158] found that both climatic change and projected increases in population will increase the number of respiratory hospitalizations due to wildfire smoke exposure. They estimated that premature deaths attributable to wildfire-generated $PM_{2.5}$ will double by late twenty-first century compared to early twenty-first century under climate change.

7.6 Disproportionate Impact of Extreme Wildfires

Extreme wildfires pose a disproportionate risk to environmental and human assets and result in enormous impacts [23]. Their occurrence and behaviour are driven by complex processes. Fire propagation can be significantly affected by dynamic feedback processes that result in unpredictable behaviour, and the continual escalation of fire spread rates and intensities even when environmental conditions are consistent. The erratic behaviour and difficulty of control of extreme wildfires means they can result in the worst impacts, burn larger areas and cause loss of human life. The trend for the occurrence of extreme wildfires appears to be increasing each year [16, 159–161].

Dynamic feedback processes or dynamic fire behaviours (otherwise known as "extreme fire behaviours", EFB) can occur within any wildfire [17, 162–164]. According to Filkov et al. [8, p.3] dynamic fire behaviour (DFB) is a *"physical phenomenon of fire behaviour that involves rapid changes of fire behaviour and occurs under specific conditions which has the potential to be identified, described and modelled."* DFBs can influence the intensity, rate of growth and impact of wildfires [6, 7, 165, 166]. Fires in which DFBs occur contribute disproportionately to damage statistics. For example, in the 2003 Canberra fires in southeastern Australia, two separate fires (the McIntyre's Hut and Bendora fires) merged and created a series of violent pyro-convective events and a fire tornado [7]. The merging fire apex spread rapidly, becoming extremely destructive and resulting in four deaths, many injuries and property losses valued at $AUD600 million to $AUD1 billion [167]. The 2016 Fort McMurray wildfire in Canada is another example. It cost $6 billion CND and caused the largest Canadian wildfire evacuation on record, 88,000 residents [27]. Approximately 2400 buildings were destroyed. Record-breaking temperatures (>30 °C) and strong wind (about 72 km/h) created ideal conditions for DFBs [168]. The high amounts of energy released by this fire resulted in a pyro-convective event and the transport of firebrands up to 40 km ahead of the flame front. Multiple spot fires and fingers of fire front merged together and produced fast rates of spread and high fire intensity.

There are nine recognised DFBs, see Table 7.2 [8].

DFBs are relatively frequent in medium to large fires. Analysis of historical fires greater than 1000 ha in Australia that occurred between 2006 and 2016 [8] revealed that more than half of the fires had at least one DFB (overall 60%). Spotting and crown fires were the most frequent DFBs, making up a total of 50% of all DFB observations (Fig. 7.2). Pyro-convective events (PyroEvs), eruptive fires and conflagrations were observed to have similar frequencies of occurrence, accounting for 39% of the remaining observations. Junction fires, fire tornado/whirls, fire channelling and downbursts combined accounted for 11% of DFBs in total. The low frequency of the last four DFBs was assumed [8] to reflect limited understanding of them in the fire community and therefore challenges with identification.

Table 7.2 Dynamic fire behaviours [8]

Type	Definition
Spotting	Spotting is a behaviour of a fire producing firebrands or embers that are carried by the wind and which start new fires beyond the zone of direct ignition by the main fire [47].
Fire whirls	A fire whirl is a spinning vortex column of ascending hot air and gases rising from a fire and carrying aloft smoke, debris, and flame. Fire whirls range in size from less than 0.3 m to over 150 m in diameter. Large fire whirls have the intensity of a small tornado" [47].
Fire channelling	Fire channelling/lateral vortices is a rapid lateral fire spread across a steep leeward slope in a direction approximately transverse to the prevailing winds [170].
Junction fires	Junction fires/junction zones (jump fires previously) are associated with merging of two fire fronts intersecting at an oblique angle, producing very high rates of spread and with the potential to generate fire whirls and spotting [163].
Eruptive fires	Eruptive fires are fires that occur usually in canyons or steep slopes and are characterised by a rapid acceleration of the head fire rate of spread [163].
Crown fires	Van Wagner [171] recognized three types of crown fires according to their degree of dependence on the surface fire phase: passive, active, and independent. Active and independent crown fires are recognised as dynamic fire behaviours [8]. Active crown fire is "a fire in which a solid flame develops in the crowns of trees, but the surface and crown phases advance as a linked unit dependent on each other" [47]. Independent crown fires "advance in the tree crowns alone, not requiring any energy from the surface fire to sustain combustion or movement" [47].
Conflagrations	Conflagrations are raging, destructive fires [47] that occur when several fires grow up and unite. Their interaction will increase the burning rates, heat release rates, and flame height until the distance between them reaches a critical level [172].
Pyro-convective events	A pyro-convective event is an extreme manifestation of pyroconvection, the buoyant movement of fire-heated air. A flammagenitus cloud, generated by the heat of a bushfire, often rises to the upper troposphere or lower stratosphere [173], and transforms into cumulus (CuFg) or cumulonimbus (CbFg) cloud (also known as PyroCu or PyroCb).
Downbursts	Downbursts are violent and damaging downdrafts associated with cumulonimbus flammagenitus clouds [173], that induce an outburst of strong winds on or near the ground [174]. These winds spread from the location of the downbursts and may result in a fire spread contrary to the prevailing wind direction.

Fires with DFBs tend to exhibit two or more different types of DFB [8]. This association between DFBs could reflect a causal relationship between some types of DFB, e.g., crown fires and PyroEvs could facilitate long distance spotting and fire tornados/whirls. DFB can happen at any scale, even smaller fires can have multiple DFBs [8].

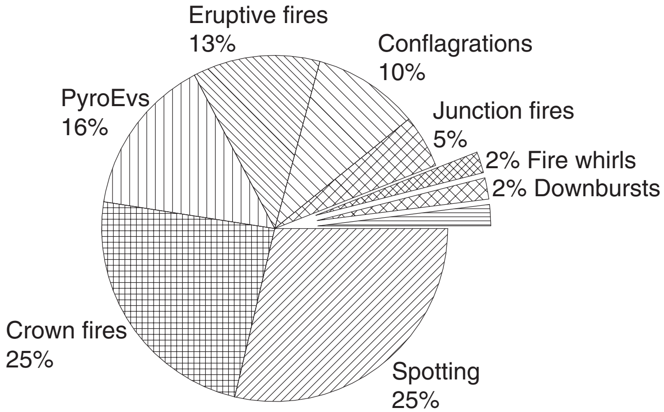

Fig. 7.2 Relative frequency of each dynamic fire behaviour phenomenon. The sum of all DFBs is 100% [8]. (Open Access paper. Under the terms and conditions of CC BY license)

7.7 Case Study - Black Summer Fires of 2019/2020 in South-Eastern Australia

Arguably, the 2019/2020 fire season in southern Australia is the worst on record. In September 2019, wildfires started in New South Wales and Southern Queensland, one month earlier than the typical start to the fire season. These fires, and others which ignited later in other states, continued to burn for months, culminating in approximately 10 million hectares burnt in south-eastern Australia, 33 people killed and over 3000 homes destroyed.

7.7.1 Preconditions

The Black Summer fires occurred during a period of unprecedented weather conditions. Record breaking temperatures were recorded across the continent, with 2019 declared Australia's warmest year on record (Fig. 7.3) [175].

Rainfall was extraordinarily low, comparable only to the driest periods in Australia's recorded history (Fig. 7.4). Across much of Australia, 2019 was the driest year on record and this followed an extremely low rainfall period starting from 2017 for much of New South Wales and southern Queensland [175].

The impact of low rainfall over the period was exacerbated by the record high temperatures, which caused higher rates of evaporation. Low rainfall also led to very low soil moisture across large areas of Australia during 2019 (Fig. 7.5). The combined effects of high temperatures, rainfall deficit and prolonged drought resulted in increased fuel availability and very high fire danger indices [176, 18].

The Forest Fire Danger Index (FFDI) is used to estimate the difficulty of fire suppression in Australian forests [179, 180]. It combines wind speed, temperature and humidity with a long term drought factor based on rainfall and evaporation. By Spring 2019, more than 95% of Australian territory had accumulated FFDI values that were very much above average, including almost 60% of the country that was highest on record [181]. The accumulated FFDI for Australia in spring 2019 was significantly higher than any other season on record (Fig. 7.6).

7.7.2 Impact

The Black Summer fires were unprecedented for south-eastern Australia in terms of the amount of forested land burnt. The fires burnt about 10 million hectares, destroyed over 3000 houses, killed 33 people and more than 1 billion animals [23] (Table 7.3). With fires burning across several states and territories, fire-fighting resources were stretched and smoke impacts widespread.

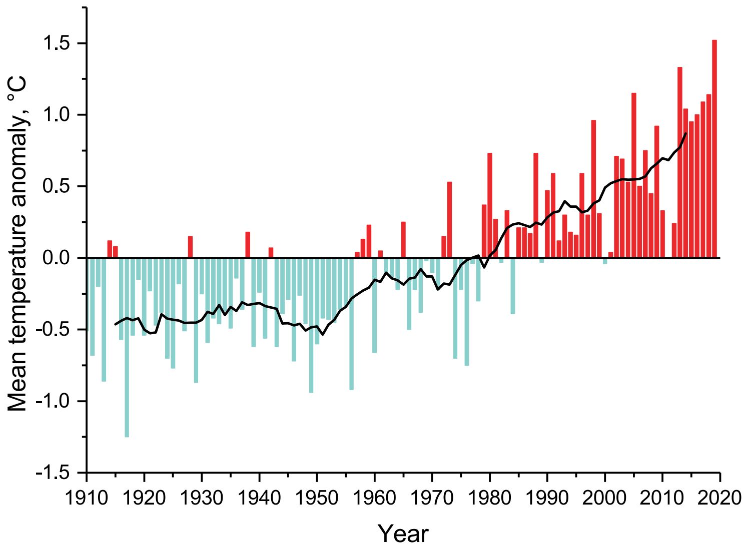

Fig. 7.3 Mean temperature anomalies averaged over Australia. The black line shows the 11-year moving average [175]. (Source: This figure was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020)

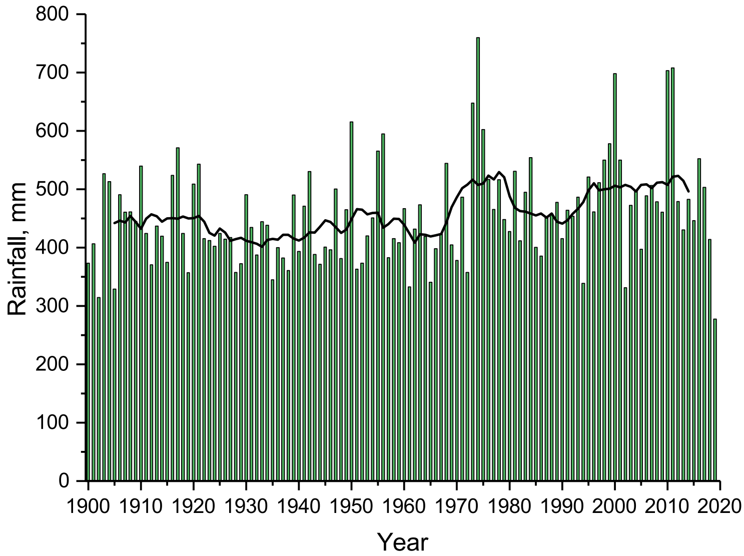

Fig. 7.4 Annual mean rain. The black line shows the 11-year moving average [175]. (Source: This figure was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020)

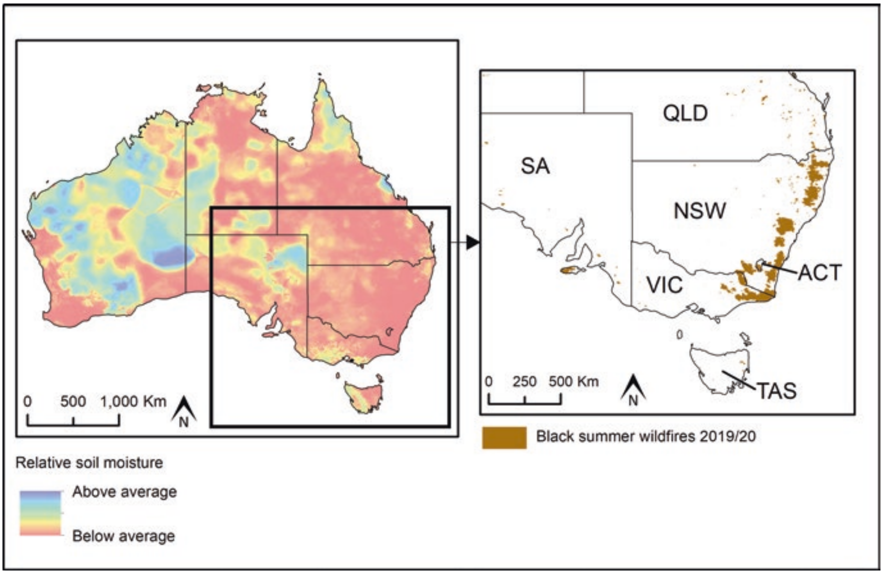

Fig. 7.5 Modelled soil moisture on 30th December 2019 relative to historic patterns (data acquired from AWRA-L water balance model [177]) and wildfire extent in south-eastern Australia for the Black Summer wildfires (data acquired from [178])

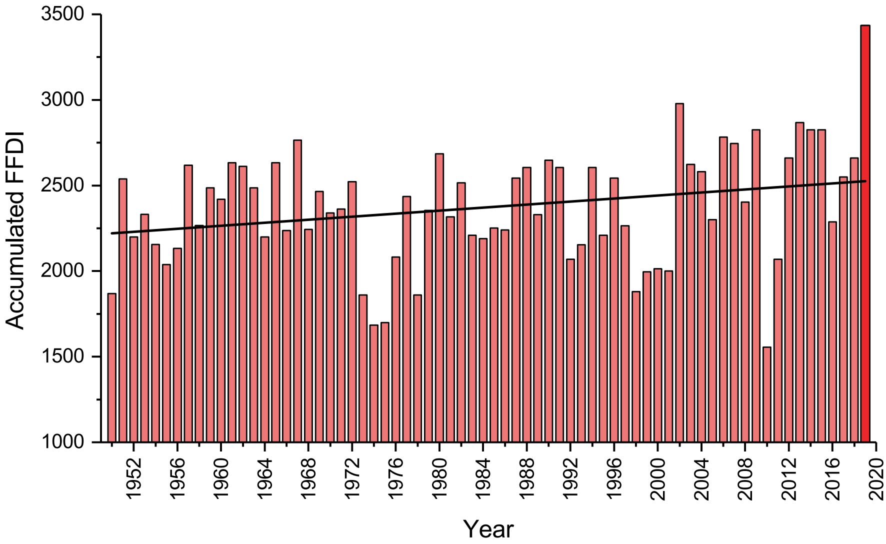

Fig. 7.6 Spring accumulated FFDI values for Australia from 1950 to 2019 [181]. Accumulated FFDI for spring 2019 shown in dark red. Linear trend line shown in black. (Source: This figure was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020)

Impacts on Communities

New South Wales (NSW), Victoria (VIC), and South Australia (SA) were the most impacted States in terms of lives and houses lost [23]. The fires impacted many coastal towns and parks during the peak summer holiday season, when many tourists were visiting the area.

NSW. A total of 10,520 fires were recorded during the 2019/2020 fire season in NSW (Table 7.3). These fires resulted in 5,595,739 hectares burnt, 25 lives lost, and 2475 houses damaged or destroyed (Table 7.3). Two mega-blazes were recorded. The Gospers Mountain fire started on 26 October 2019 and burned approximately 512,626 hectares, becoming the largest forest fire in Australian history [176]. By 11 January, three fires on the border of NSW and Victoria, the Dunns Road fire, the East Ournie Creek, and the Riverina's Green Valley merged and created a second mega-fire which burned through 895,744 hectares. Fires in NSW burned more area than any single fire season in NSW during the last 20 years (Fig. 7.7).

VIC. 3500 fires in Victoria resulted in 1,505,004 hectares burnt, 5 lives lost, and 396 houses damaged or destroyed (as of 20 March 2020) (Table 7.3). The number of fires and the burned area were one of the biggest in Victorian history. One of the most destructive fires was around the town of Mallacoota in the far east of the State, where 300 homes were lost. A small fire started on 29 December 2019, 30 kilometres west of the coastal town of Mallacoota. The fire spread rapidly in the following

Table 7.3 Fire statistics for 2019/2020 wildfire season across Australia

State	Burned area, ha	Number of fires	Houses lost	Lives lost
Victoria	1,505,004	3500	396	5
New South Wales	5,595,739	10,520	2475	25
Queensland	2500,000	NA	48	0
Tasmania	36,000	NA	2	0
Western Australia	2,200,000	NA	1	0
South Australia	286,845	1324	186	3
Northern Territory	6,800,000	NA	5	0
Australian Capital Territory	60,000	NA	0	0
Total	18,983,588	15,344	3113	33

NA = data is not available
Source: This table was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020
These figures are preliminary and may be revised when official statistics are released at the end of the 2019/2020 financial year [23]. Statistics for areas burnt in northern Australia are included, however, these areas are not considered part of the Black Summer fires. The fire season in the northern parts of Australia is typified by frequent, low intensity fires during the dry season (April to November) and vast areas burnt annually

Fig. 7.7 After bushfire. Armidable Road, Clouds Creek, NSW. (Photo is taken on January 4, 2020. ©Photo by Elena Filkova, used with permission)

days, leaving thousands of people (both locals and tourists) stranded on the boat ramp and in the surrounding water as the fire reached the water's edge [182]. Roads to Mallacoota were blocked for 37 days due to wildfires and fallen trees and as a result, many people had to be evacuated on two naval vessels.

SA. The 2019/2020 fire season resulted in a total of 1324 wildfires in South Australia. These fires caused 286,845 hectares burnt, 3 lives lost, and 186 houses damaged or destroyed (Table 7.3). On 20 December 2019, a series of lightning strikes ignited the Cuddle Creek fire in the Adelaide Hills [183]. This fire killed one person, burned 23,295 hectares, destroyed 84 homes and hundreds of other buildings and thousands of livestock. This fire also burnt through world famous viticulture and winery areas, and large parts of the water catchment for Adelaide, the state's capital city.

On 30 December 2019, another band of lightning in the remote Ravine de Casoars Wilderness Area on Kangaroo Island ignited fires that became known as The Kangaroo Island Fire [184]. Two people were killed, 89 homes destroyed and hundreds of other buildings including high visitation tourism assets. There were significant livestock losses for local farmers [185] and $100 to $900 million of plantation timber burnt [186]. The Kangaroo Island fires were officially contained on 21 January 2020 after burning 210,000 hectares and lasting for more than three weeks [185].

Impacts on Biodiversity

The scale and intensity of the black summer fires have resulted in a range of impacts on the biodiversity of eastern Australia. Approximately three billion vertebrate animals were estimated to have been killed in the fires [187], not to mention the countless invertebrates, plants, fungi and microorganisms directly affected.

Fires have occurred in many areas that have previously burnt in recent wildfires. For example, in Victoria the fires have led to a dramatic increase in the area of forest that has been burnt more than twice since 2003 (Fig. 7.8). This includes obligate seeder Alpine Ash forest, that is vulnerable to regeneration failure with short intervals (<20 years) between high intensity fires [71]. Such high frequency and high intensity fire regimes may also lead to a decrease in resprouting success and regeneration of trees in fire-tolerant mixed-species Eucalypt forests [188].

The extremely low soil and fuel moistures resulted in the fires affecting large areas of vegetation types that rarely experience fire, especially high intensity fire, such as subtropical and temperate rainforest. About 37% of the total area of NSW rainforests were affected, including 54% of the extent of the Gondwana Rainforests of an Australia World Heritage Area [190]. While some rainforest plants have adaptations that allow them to survive or reproduce after a single fire, repeated high intensity fires at short intervals may result in shifts towards open forest and promotion of more flammable vegetation [191].

The effects of the fires on many individual species are not yet clear, but ecologists fear some endangered species have been driven to extinction [192]. Forty-nine species listed as threatened under the national Environment Protection and Biodiversity Conservation Act have more than 80% of their distribution within the fire boundary [193]. While there is yet to be extensive post-fire monitoring, 486 plants, 213 invertebrates, 92 terrestrial vertebrates and 19 threatened ecological communities are considered to be at increased risk of extinction due to the wildfires and require urgent management intervention according to the Department of Agriculture, Water and the Environment [193].

The scale and severity of the fires has resulted in large impacts on many species with restricted spatial distributions (Fig. 7.9). This is exemplified by the species that

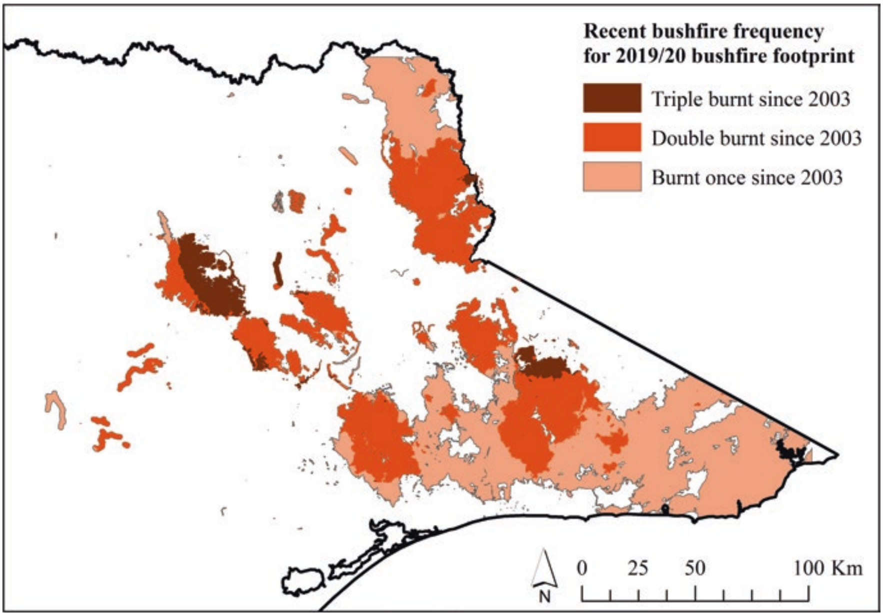

Fig. 7.8 The footprint of the Black Summer Bushfires in Victoria, Australia showing areas that have been affected by recent wildfires [189]

were impacted by the wildfire on Kangaroo Island off the coast of South Australia. More than a third of the island was burnt including most of the native vegetation reserved in protected areas. Experts have expressed concerns over the survival of several endemic endangered species on the island including the Kangaroo Island Dunnart (*Sminthopsis aitkeni*) and a subspecies of the Glossy Black-Cockatoo (*Calyptorhynchus lathami*) [194] that already had small population sizes prior to the fire.

Impacts on Soil and Water

Heavy rainfall following the Black Summer bushfires resulted in elevated levels of surface runoff and erosion in burnt areas, with downstream impacts for water supply and aquatic ecosystems (Fig. 7.10). In Lake Burragorang (Warragamba Dam), Sydney's major water supply, sediment, ash and debris were seen floating on the water surface following heavy rainfall [195]. Water authorities took precautionary action to minimize potential water quality impacts including installing two booms with silt curtains to limit the amount of ash and debris near the dam's supply off-take point [195, 196] and switching the water supply for Sydney to an alternative source following heavy rainfall.

Fig. 7.9 Impacted forest in north-eastern Victoria following the Black Summer fires. (©Photo by Rowhan Marshall, Department of Environment, Land, Water and Planning, used with permission)

Fig. 7.10 High sediment load in the Upper Buffalo river in north-eastern Victoria after the 2019/2020 Black Summer fires. (©Photo by John Costenaro, Department of Environment, Land, Water and Planning. Used with permission)

Numerous measures had to be taken to maintain water supply to towns in the Bega Valley on NSW's south coast following the bushfires [197]. Turbidity levels in the Brogo river and reservoir, a key water supply in the region, were more than 100 times above the safe limit for drinking. The local water authority responded by implementing water restrictions, trucking water into the region at a cost of AUD$30,000 per day, recommissioning water supply from alternative sources and installing additional water treatment facilities [198].

There were severe impacts on aquatic fauna. Tens of thousands of fish were killed in the Macleay River in northern NSW and hundreds of fish killed in Tilba Lake on the south coast of NSW [199]. Critical habitats for threatened aquatic species were damaged by the fires, e.g. Macquarie perch in Mannus Creek [200]. These impacts on fish populations were caused by elevated levels of suspended sediment, which can clog fish gills and smother physical habitat [134] as well as reduced level of dissolved oxygen. Fisheries officers undertook rescue efforts in some catchments to remove threatened fish species from these waterways to repopulate these waterways after water quality conditions improve [200]. However, the combined effect of drought, fire and flood on these systems is expected to have a long-lasting impact on some fish populations [201].

Impact on Air Quality

Smoke from the wildfires shrouded much of Australia's south-eastern coast (Fig. 7.11). According to early estimates from the Global Fire Emissions Database, the wildfires likely contributed 900 million metric tons of carbon emissions [202, 203]. Borchers Arriagada et al. [204] estimated population exposure to $PM_{2.5}$ for NSW, Queensland, the ACT and Victoria between 1 October 2019 and 10 February 2020 and found that $PM_{2.5}$ concentrations exceeding the 95th percentile of historical daily mean values were recorded in the study area on 125 of 133 days. Wildfire smoke was estimated to be responsible for 417 excess deaths, 1124 hospitalisations for cardiovascular problems, 2027 for respiratory problems and 1305 presentations to emergency departments with asthma. Liu et al. [205] estimated that such increases in daily $PM_{2.5}$ concentration could induce an increase of at least 5.6% in daily all-cause mortality, 4.5% in cardiovascular mortality, and 6.1% in respiratory mortality.

Thick smoke covered populated areas of coastal New South Wales and Victoria (Fig. 7.12), including Sydney and Melbourne, particularly from November through to January. Westerly winds continued to blow smoke from fires burning further inland towards the coast, resulting in poor air quality in the Sydney Basin and many

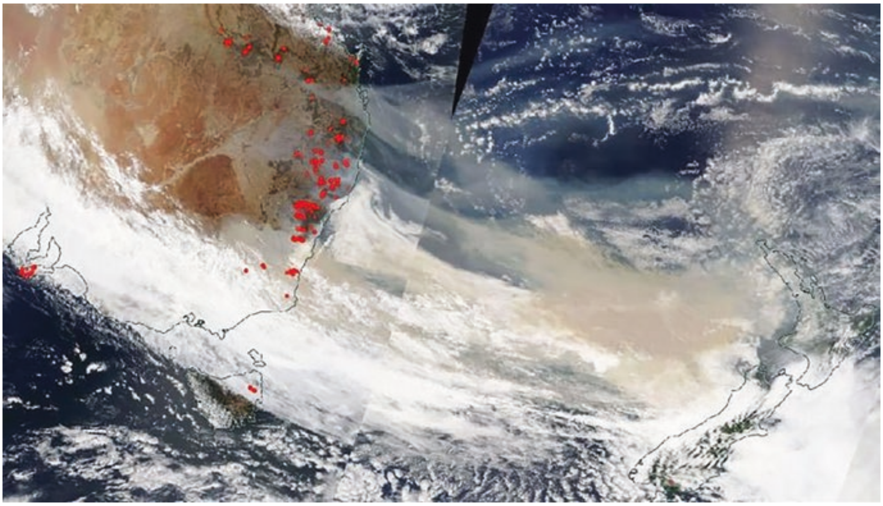

Fig. 7.11 Smoke from wildfires. Red areas represent active fires. This image was taken by NASA's Aqua satellite using the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument on 05 January 2020 [206]. (Open access from https://earthdata.nasa.gov/learn/toolkits/wildfires)

other areas along the New South Wales coast. Sydney experienced 81 days of poor (above 100 μg/m^3) or hazardous air quality in 2019, more than the last 10 years combined. According to Yu et al. [207], in most areas of Sydney, 24-h average of $PM_{2.5}$ concentrations in December 2019 exceeded 100 μg/m^3 (5 times lower before wildfires), which is four-times higher than the World Health Organisation guideline value of 25 μg/m^3. The national capital, Canberra, was also impacted by thick smoke. It experienced poor air quality for 33 days (Civic station) and at one point it had the world's worst 24-h average of $PM_{2.5}$ concentration (714 μg/m^3) [208].

Smoke from the Australian fires covered the whole South Island of New Zealand on 1 January 2020 [209]. The smoke moved over the North Island the following day and affected glaciers in the country, giving a brown tint to the snow. By 7 January 2020, the smoke was carried approximately 11,000 kilometers across the South Pacific Ocean to Chile, Argentina, Brazil, and Uruguay [210].

Impact of Extreme Wildfires

Unprecedented weather conditions and prolonged drought resulted in multiple extreme wildfires. They caused several dynamic fire behaviours, e.g. formation of pyro-convective events, dry thunderstorms and lightning, massive spotting, and fire whirls. At least 18 PyroCb were recorded between 29th December and fourth January in south-eastern Australia [211]. Massive spotting and lightning resulted in two mega fires (>500,000 hectares each) [23]. In NSW flames with 60–70 m height and fire tornados were recorded [212]. One of them flipped a 10-ton fire truck, killing a firefighter. Fast and unpredictable propagation of extreme wildfires resulted in tremendous environmental impact. Further research is being undertaken to fully understand the occurrence and impact of these behaviours.

Fig. 7.12 View of smoke plume from Ovens fire complex in north-eastern Victoria on 16th January 2020. (©Photo by John John Costenaro, Department of Environment, Land, Water and Planning. Used with permission)

Economic

Damage from the wildfires is estimated to have had a $20 billion impact to the economy, greatly exceeding the record A$4.4 billion set by 2009s Black Saturday fires [213, 214]. According to AM Best credit rating agency, wildfires resulted in A$1.7 billion in insurance losses and this is expected to rise [215]. Consulting firm SGS Economics estimated that smoke produced by wildfires caused between A$12 million and A$50 million worth of daily disruption of Sydney [216]. All of the above is likely to make a record impact to the Australian economy.

7.8 Summary

Australia's 2019/2020 wildfire season showed a new level of impact on the environment. Every year in different parts of the world the weather breaks new high temperature and rainfall deficit records. Climate projections show further increases in occurrence and intensity of wildland fires [51, 161].

The effects of wildfire on biodiversity are nuanced and often involve complex interactions between fire regimes and species traits. Fire is in principal, a positive force for biodiversity that has directly driven the evolution of many plants and to a lesser extent animals [217], continuing to be a crucial driver of the life cycles of many species. The greatest risks to biodiversity conservation in fire-prone ecosystems is the emergence of novel fire regimes with climate change and human activities that may push species to extinction and leave certain ecosystems at risk of collapse. Furthermore, interactions between wildfires and other threatening process such as drought, fragmentation and invasive species may compound deleterious effects in the future.

Runoff and erosion from areas burnt by wildfire can have significant impacts on downstream water quality. However, substantial effects are only evident in some instances, particularly when a high severity wildfire intersects with intense rainfall in steep terrain. Streamflow and water yield can also be impacted by the initial loss of vegetative cover and its subsequent regeneration. The level of impact depends on a range of factors including the vegetation type and the severity of the fire.

Smoke from wildfires is seen a significant problem in the future [157, 158]. It impacts on people with cardiovascular and respiratory problems and increases mortality. It also has indirect impact on the economy resulting in disruption of settlements [216] and climate change [147].

Recent increases in the number of extreme fire events [16, 159, 169] and the rapid expansion of the WUI areas [50] is likely to increase their impact. Multiple DFBs in extreme events can manifest simultaneously and at any scale [8] contributing disproportionately to damage and environmental impacts.

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