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Introduction

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Fire is an integral part of the Australian landscape. Over a long history, including tens of thousands of years under Indigenous use and management, it has shaped most of Australia's terrestrial environments and moulded its plant and animal assemblages (Bowman 1998; Bowman *et al*. 2009).

Yet in 2019–20, much of eastern and southern Australia was burnt in 'megafires' at high severity, across an unprecedented extent and over an unusually long duration (Collins *et al*. 2021). The term and incidence of megafire is relatively new: reflecting a global increase in fire sizes, it is recognised as 'an emerging concept' (Linley *et al*. in press). Here we apply it to fires that are more than 100 000 ha in extent, although we note that others have advocated applying the term megafire to fires > 10 000 ha and have coined the terms *gigafire* for fires > 100 000 ha, and *terafire* for fires > 1 000 000 ha (Linley *et al*. in press).

This season of fires was a landmark event in the country's post-colonial history, a year of exceptional loss. For many, these megafires provided a stark demonstration that the consequences of global climate change are occurring now. This was a frightening glimpse of a dystopian future, of a world beyond our control (Fig. 1.1).

The 2019–20 wildfires exacted a considerable toll on people and the economy. They killed 33 people directly and in fire-fighting operations, led to the death of approximately another 430 people through smoke pollution, imposed a $2 billion impost on the Australian health budget (Johnston *et al*. 2021), destroyed many homes and livelihoods and caused significant damage to the national and regional economies. However, in this book our focus is on the environmental impact of these fires.

Australians, and the global community more broadly, watched on as images of burnt koalas and kangaroos haunted the nightly news footage, and experts estimated that billions of animals may have been killed (van Eeden *et al*. 2020). But the dead or injured animals represented only the most conspicuous margins of the impacts of these fires on wildlife. Places of outstanding biodiversity significance, such as World Heritage areas, were damaged. Some environments intolerant of fire, such as rainforests, burnt for the first time in living memory (Kooyman *et al*. 2020). A preliminary analysis estimated that, over the period of 6–8 months, the fires burnt the habitat or range of 107 of Australia's 436 threatened terrestrial and freshwater vertebrate species. The fires rapidly pushed many already imperilled species further to the brink, and caused hundreds of other species formerly considered secure to now be threatened (Ward *et al*. 2020). Scientists have begun

Fig. 1.1. The 2019–20 wildfires were exceptional in scale and duration, burning large areas at high severity. Here, flames from the fires rolling over the ridges of Tidbinbilla Nature Reserve and Namadgi National Park. (Photo: Markus Dirnberger)

documenting likely extinctions as a result of the fires (Moir 2021) – we will learn more in the coming years. However, because of decades of chronic underfunding of survey and monitoring efforts, the actual number of such extinctions may never be known (Scheele *et al*. 2019; Wintle *et al*. 2019).

The fires galvanised an extraordinary response by the Australian community, governments, Indigenous groups and conservation organisations. Record sums of money were contributed to wildlife rescue and recovery efforts. The Australian Government established a $200 million wildlife recovery fund, for urgent and short-term actions designed to limit biodiversity losses and support post-fire recovery – this one-off funding initiative was almost twice that of the normal annual expenditure by the Australian Government on management of all threatened species (Wintle *et al*. 2019). Rapid responses – often heroically undertaken in dangerous situations and with great urgency – helped save some species and constrain some losses (Morton 2020). These responses showed how much the Australian community valued our nature, and were concerned and moved by its potential loss.

But while many of these responses were admirable and achieved some successes, these fires also highlighted the *ad hoc* status, and inadequacies, of planning, management, policy and legal settings for the protection of biodiversity. Emergency management for biodiversity was not previously given prominence by government agencies, and these fires exposed the limited capacity to deal with situations that were beyond what was previously thought to be the extreme limit. Established soon after the fires, a series of government inquiries probed these revealed weaknesses, and proposed some major changes to attempt to reduce fire (Collins *et al*. 2020; Gibson *et al*. 2020). Four fire severity classes are generally considered: (1) understorey burnt with low levels of canopy scorch (< 20% scorch; Low); (2) understorey burnt with moderate levels of canopy scorch (20–80% scorch; Moderate); (3) high levels of canopy scorch with some canopy consumption (> 80% scorch; High); and (4) complete canopy consumption (Extreme).

Fire severity patterns were highly heterogeneous across the extent of the 2019–20 fires (Table 2.1; Fig. 2.3), reflecting the complex interplay between antecedent drought, fire weather, topography, vegetation structure and past management (Bowman *et al*. 2021).

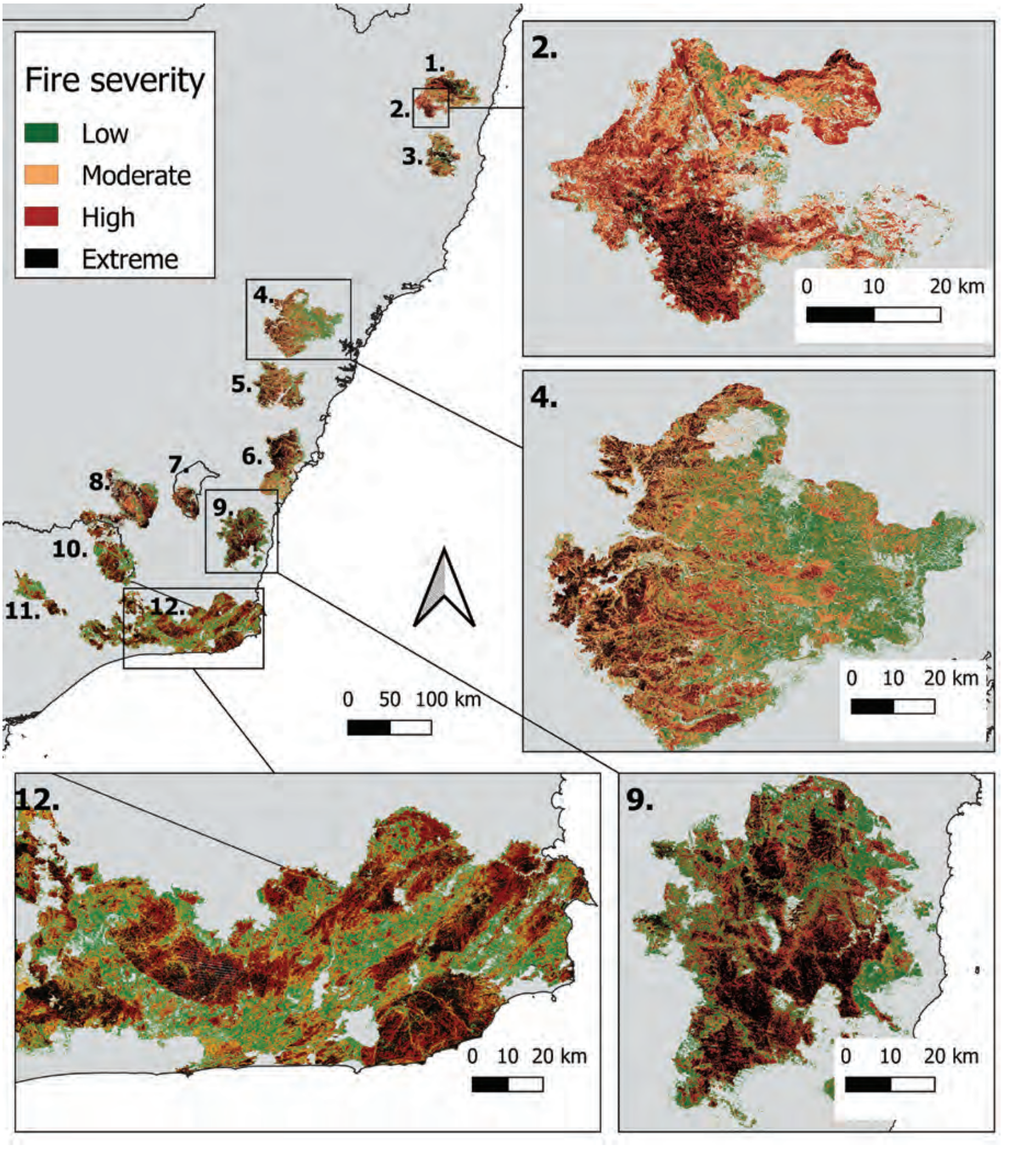

Fig. 2.3. Fire severity maps for 12 major fires in eastern Australia. Fire severity maps were produced using satellite imagery from either Landsat (Collins *et al.* 2020) or Sentinel 2 (Gibson *et al.* 2020). Insets show the severity maps for select fires in greater detail.

Box 4.1. Protected areas in Victoria: impacts and consequences for management

The 2019–20 wildfires burnt ~1.5 million ha across Victoria, including 30 national parks and nature conservation reserves that had over 80% of their area within the fire extent (DELWP 2020). This comprised some of Victoria's best-known national parks, including Croajingolong (87%), Snowy River (76%) and Errinundra (66%). National parks such as the Burrowa-Pine Mountain National Park and the Lind National Park had their entire extents burnt (DELWP 2020). Across Victoria's reserve system, over 280 000 ha were impacted by high-severity fire in the 2019–20 fire season (DELWP 2020).

The 2019–20 wildfires disproportionately affected areas of Victoria's highest biodiversity value (DELWP 2020), much of which occurs in Victoria's protected areas. Species such as spotted tree frog (*Litoria spenceri*) and eastern bristlebird (*Dasyornis brachpterus*) have important populations within Victoria's protected areas that were affected by the 2019–20 wildfires. These wildfires also compounded the effects of other recent large fires (e.g. 2003 and 2006–07), meaning some parts of Victoria's protected areas have been burnt multiple times in the last 20 years, severely impacting species and environments such as Victoria's alpine ash (*Eucalyptus delegatensis*) ecosystems (Fig. 4.2) (Geary *et al.* 2022). Since the fires, management of impacted species has focused on facilitating recovery through management of threats (e.g. invasive predator and herbivore control), as well as proactive actions that can help to reduce the risks of future extreme fires to these species such as emergency extraction (Selwood *et al.* 2021), translocation to new areas and captive breeding.

Fig. 4.2. Long unburnt (1939 regrowth) alpine ash forest in Victoria's Central Highlands (A), and alpine ash forest burnt by successive fires between 2007 and 2019–20 leading to population collapse (B). (Photos: Tom Fairman, University of Melbourne)

Sites set aside for biodiversity: World Heritage listings

Of the 18 terrestrial Australian World Heritage listings, six were impacted by the 2019–20 wildfires (Fig. 4.3; Table 4.3). The World Heritage listing with the largest impact was the Greater Blue Mountains Area, with ~680 000 ha burnt (of which 362 000 ha was high and very high severity and 321 000 ha was low and moderate severity) (see Box 4.2). This represents more than 65% of the entire Greater Blue Mountains Area. The Budj Bim Cultural Landscape, located in the traditional Country of the Gunditjmara people in south-eastern Australia, was also greatly impacted with ~54% of its extent affected by the 2019–20

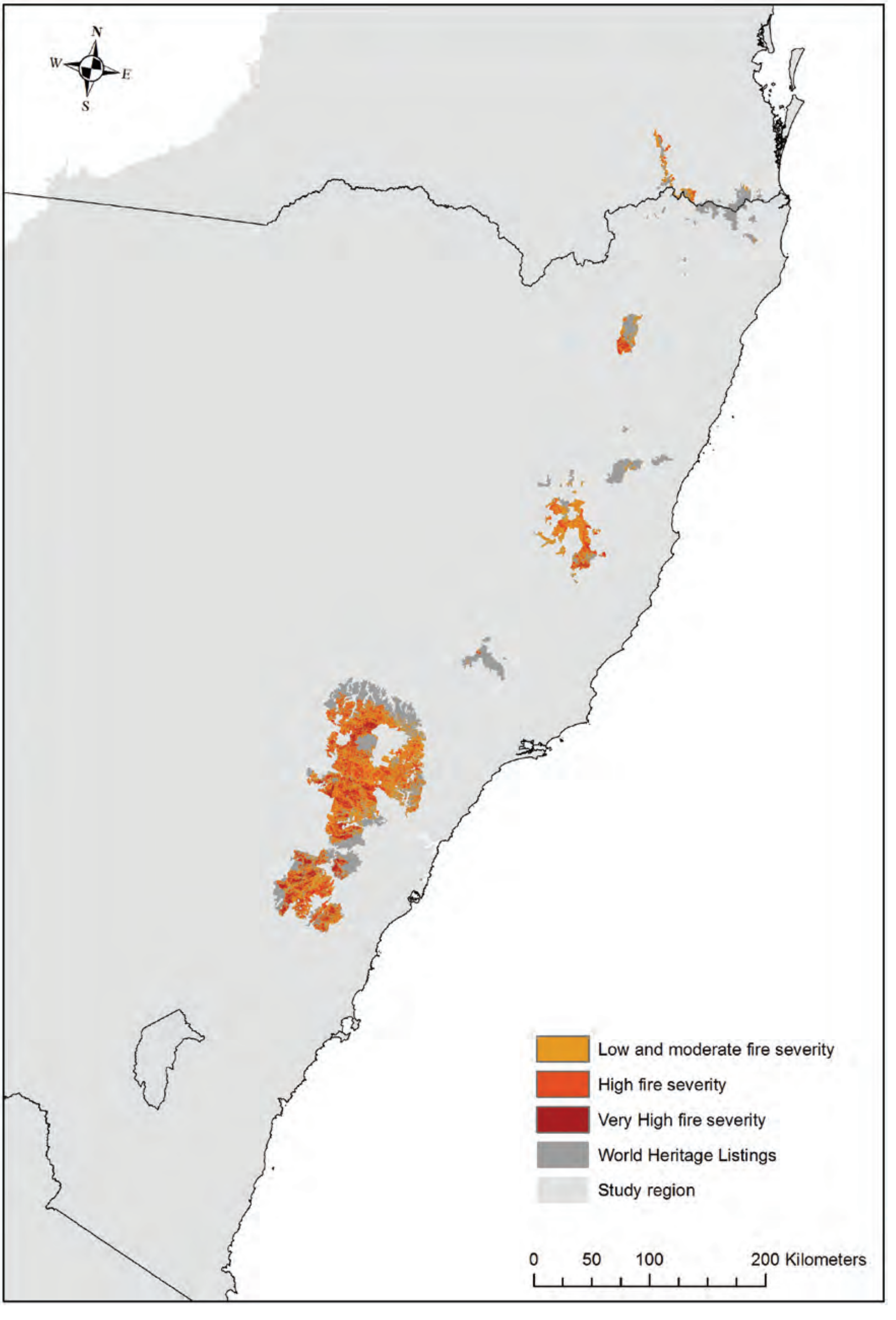

Fig. 4.3. Extent and severity of wildfires between July 2019 and February 2020 and impacts on World Heritage listings. Yellow indicates low and moderate fire severity, orange indicates high fire severity, and red indicates very high fire severity. Dark grey shows all terrestrial World Heritage listings, while light grey shows the study region.

Table 4.4. Overview of the top 10 KBAs with the highest proportion of total extent and severity of the 2019–20 wildfires.

Name	Total area (ha)	Extent burnt – low and moderate fire severity (ha)	Extent burnt – high severity (ha)	Extent burnt – very high severity (ha)	Extent burnt – high and very high severity (ha)	Cumulative extent burnt (ha)	Proportion of total extent burnt (%)
Jerrawangala	4024	2100	1300	600	1900	4000	99
Gibraltar Range	36 563	10 000	12 600	2200	14 800	24 800	68
Werrikimbe	1 074 505	9000	1800	1700	14 500	23 500	67
Greater Blue Mountains	35 127	322 600	286 700	68 800	355 500	678 100	63
Nadgee to Mallacoota Inlet	38 171	11 200	5400	1300	6700	17 900	47
Fitzroy Falls and associated hydrobasin	12 395	1500	2000	1800	3800	5300	43
Palmgrove	25 188	9600	200	–	200	9800	39
Kangaroo Island	441 672	27 600	40 700	94 700	135 400	163 000	37
Stirling Range	112 580	7000	15 300	15 800	31 100	38 100	34
Ulladulla to Merimbula	138 357	34 400	22 200	6200	28 400	62 800	29

Box 4.3. Stirling Range KBA

Not only eastern states were affected by the 2019–20 wildfires – large areas of south-west Western Australia were also impacted. This is a region famous for its high levels of biodiversity and endemism (Beard *et al.* 2000). Stirling Range KBA is internationally recognised as important for the persistence of 15 bird species (DPaW 2014) and also contains 80 endemic plant species, 13 species of endemic trapdoor spiders, an isolated subpopulation of quokkas (*Setonix brachyurus*), and a threatened ecological community (Parks and Wildlife Service 2017) (Chapter 8). Over a third of Stirling Range KBA (37 826 ha) burnt in December 2019 during two blazes ignited by lightning strikes. Aided by drought and hot, windy weather, 37 826 ha of vegetation burnt with very high intensity, scorching the canopy and leaving few unburnt refuges (Fig. 4.6; Roff 2020). Impacts were compounded by a large fire having occurred the previous year, leaving a combined scar covering 43% of the KBA. While both Carnaby's (*Zanda latirostris*) and Baudin's black-cockatoo (*Z. baudinii*) feeding habitat in Stirling Range KBA were badly damaged by the 2019–20 wildfires, most of their known roosting and nesting habitat remained

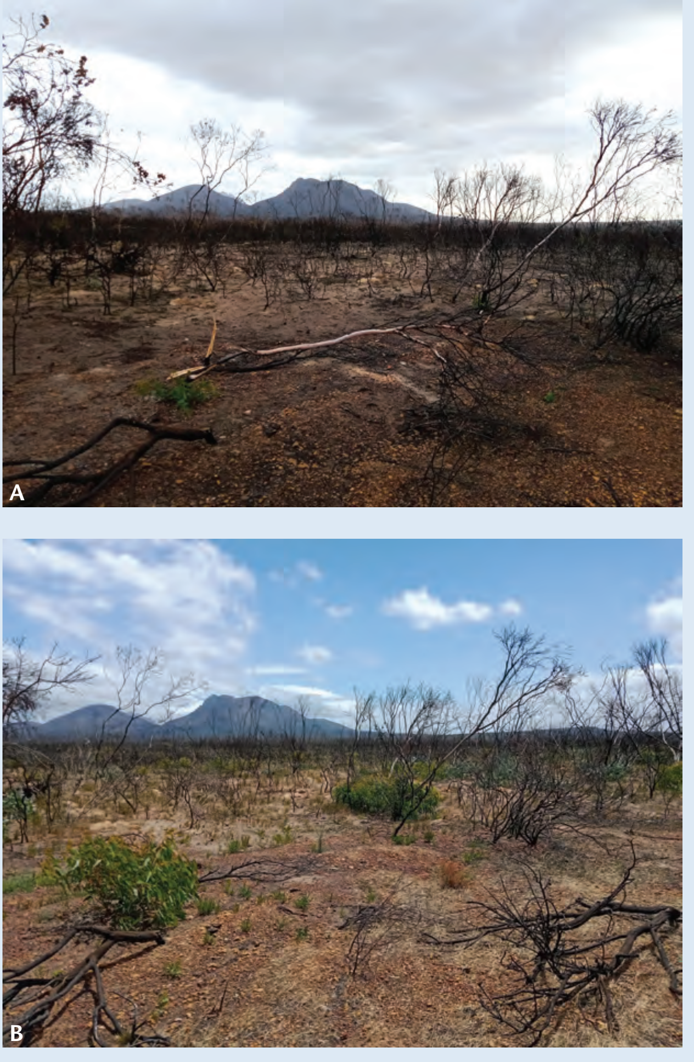

Fig. 4.6. Stirling Range KBA 3 months post-fire (A) and one year post-fire (B) showing severely burnt areas are slow to recover. (Photos: Vicki Stokes)

intact (BirdLife Australia 2021), and breeding hollows were confirmed active in spring and summer 2020 (V. Stokes, *pers. comm.*). Other species did not get away so lightly. The fire sensitive wheatbelt western whipbird (*Psophodes nigrogularis oberon*), for which Stirling Range KBA is one of two remaining strongholds (McNee 1986; Birdlife International 2016), had ~30–40% of its habitat burnt in 2019, mostly with high severity. Record densities of calling whipbirds found in habitat adjacent to burnt areas suggests individuals immigrated from severely burnt areas, now uninhabitable (Stokes *et al.* 2021). Unfortunately, these refuges are unlikely to sustain whipbirds in the long term and burnt areas will take many years to regrow suitable whipbird breeding habitat.

Patterns of fire

We explored the patterns between forest integrity, measured using the global 'forest integrity' metric (Grantham *et al.* 2020) and 2019–20 wildfire severity for each protected area, World Heritage listing and KBA. The statistical analysis suggests that for every unit increase in forest integrity, the odds of an increase in fire severity decreased by 13.7% (CI: 13.5–13.8) in KBAs and 3.1% (CI: 3.0–3.2) in protected areas (Fig. 4.7A, C). More simply, the higher the forest integrity in a KBA or protected area, the less likely that area will experience very high severity fires.

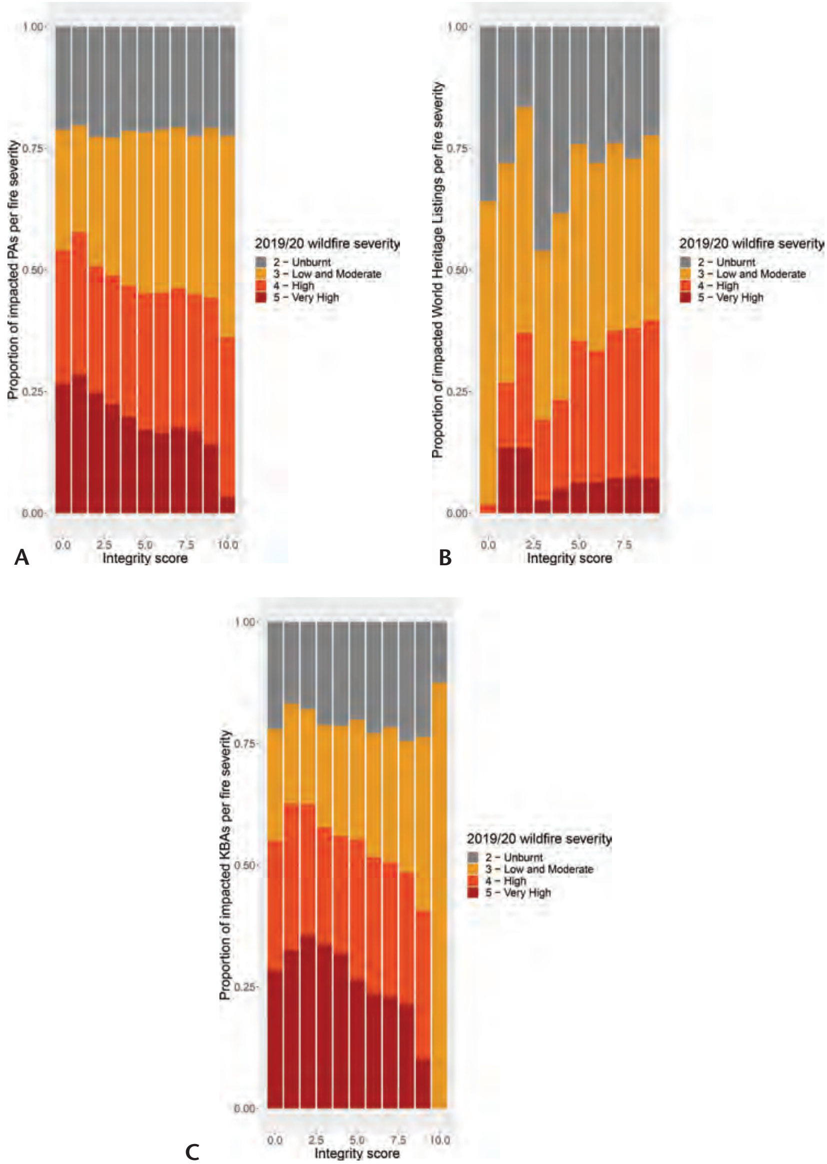

Fig. 4.7. Broad patterns between forest integrity and 2019–20 wildfire severity for each protected area (PA), World Heritage listing and KBA.

deeper into sands), but also because they contain less organic matter, often occur on steep land and are more poorly structured, and therefore erode more easily.

Soil surface temperatures range from ~100°C during mild fire, to 800°C in moderate to high-intensity fires, to 1500°C during extreme fire events, such as many of the 2019–20 wildfires (DeBano *et al*. 1998). While a low to moderate fire will leave some litter and organic matter on the surface, high to intense fires can cause total canopy loss, and the complete combustion of litter and soil organic matter to several centimetres depth. These impacts have the potential to physically alter soil properties that influence infiltration, runoff and erodibility of soil (Fig. 5.1).

In general, organic matter loss commences at temperatures exceeding 100°C. The temperature at which soil constituents (e.g. nutrients and cations) are vaporised depends on their temperature tolerances. Carbon, sulphur and nitrate are volatilised by 200°C, and by ~450–500°C almost all organic matter has been combusted (De Bano *et al*. 1998). Substantial soil physical and chemical changes occur once the surface reaches temperatures of 400–600°C. Most temperature effects occur within a few centimetres of the surface, with values rarely exceeding 150°C at depths of 50 mm (DeBano *et al*. 1998).

Soil temperatures also affect biological processes. Low-intensity fires (e.g. hazard reduction burns) may fail to heat the surface above 40°C at 50 mm depth, thereby failing to break seed dormancy for the germination for some plants (Penman and Towerton 2008). High-intensity fires are therefore critical for the germination of many plant species (Chapter 9).

Ash deposition on the fire ground

Ash comprises charred, loose material < 1 cm in size and is formed from the complete oxidation of vegetation and soil organic matter. Ash loads increase with fire intensity, with values of 1 to 35 t ha^{-1} recorded for low to severe fires (respectively) in Australia

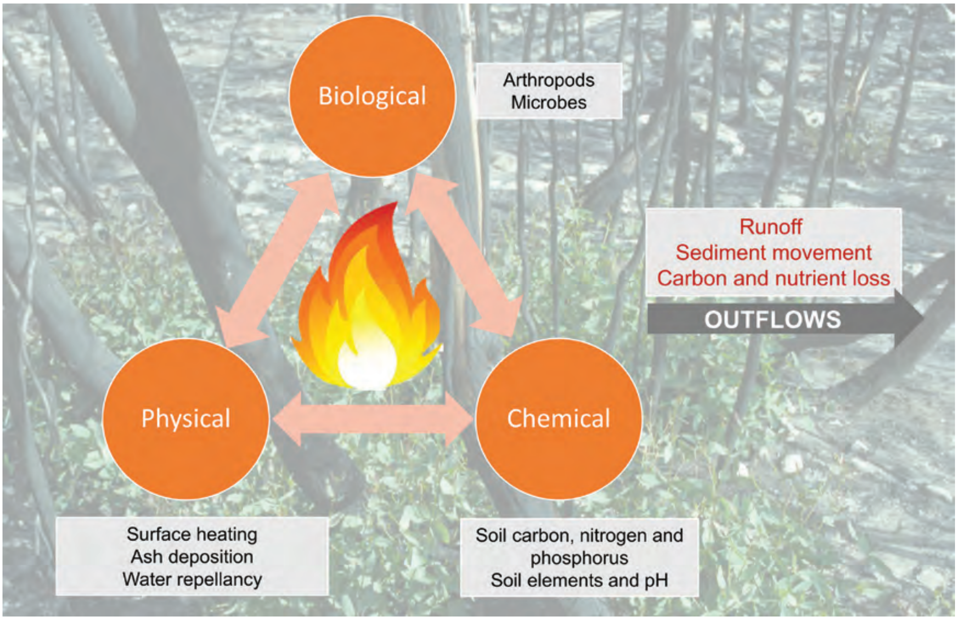

Fig. 5.1. Conceptual model of the direct effects of fire on biological, physical and chemical properties and processes, and resultant outflows.

Fig. 5.2. Surface of the soil after the 2013 Warrumbungles fire showing the complete removal of the surface soil layers by fire and exposure of the B horizon. (Photo: Sally McInnes-Clarke)

(Chapter 11). For instance, soil arthropods and microbes process organic matter and release carbon and nitrogen. Like many faunal groups (Chapters 13–16), arthropods vary greatly in their susceptibility to fire, and the magnitude of impacts of fire on invertebrate communities is influenced by fire severity and fire regimes, and environmental settings. For example, collembola may take many years to return to pre-fire levels (Driessen and Greenslade 2004), affecting the ability of soils to process organic matter. Fire can suppress litter processing taxa such as cockroaches (Arnold *et al*. 2017) and alter predator–prey relationships among litter-dwelling invertebrates (Dawes-Gromadzki 2007).

Recovery of hydrological function and surface stability generally occurs 18–36 months after fire, depending on vegetation regrowth, reductions in soil repellency and reduced soil erodibility (Smith *et al*. 2011). However, recovery of infiltration capacity may depend on the reinstatement of animal-created pores and burrows of ants and spiders, and even the passages around plant roots (macropores; Holden *et al*. 2014), which drive hydraulic conductivity.

The effect of fire on invertebrates also varies widely among ecosystems, and with fire severity and fire regimes. For example, few differences were found in collembolan communities 12–24 years after fire in a Tasmanian buttongrass community (Driessen and Greenslade 2004) whereas ants were more abundant in burnt sites in arid mallee woodlands (Kwok and Eldridge 2015), suggesting a rapid response to fire in this ecosystem. In contrast, the impact of even a single wildfire may still be evident in some invertebrate communities for at least 50 years (Henry *et al*. 2022). Though the 2019–20 occurred predominantly across forested systems, there is a real opportunity to explore the impacts of