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The 2019–20 Australian wildfires: precursors, characteristics and implications for the future

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Summary

- Extensive severe wildfires are occurring more frequently across much of the world, driven by changes in land use and management, and especially by climate change.
- There were exceptional precursors to the 2019–20 Australian wildfires, notably a 3-year drought. The calendar year of 2019 was the hottest and driest year on record for the country, resulting in exceptionally low moisture levels in forest fine fuels.
- Extending from August 2019 to March 2020, the wildfires in southern and eastern Australia burnt 10.3 million ha, mostly of temperate forests.
- The 2019–20 Australian fires were globally exceptional. Since 2000, no forest biome anywhere on Earth has had a higher percentage of its area burnt in a single season than the 21% reported for forest biome burnt in the 2019–20 Australian fires.
- The 2019–20 wildfires also impacted many vegetation communities that are typically too wet to burn, such as peatlands and Gondwanan rainforest.
- A feature of many of the megafires of the 2019–20 season was their unusually long duration, with one fire burning for 108 days.
- Extreme fire activity was largely driven by complex dynamics of fire coupling with atmospheric conditions, resulting in an unusually high incidence of violent pyrocumulonimbus storms.
- The 2019–20 fires set Australian records for area burnt at high severity, houses lost and the largest individual fire originating from a single ignition.
- Estimates of economic impacts from the fires are more than $10 billion.

Introduction

The size and frequency of wildfires has increased across many forested regions globally (Pausas and Fernández-Muñoz 2012; Kelly *et al.* 2013; Bradstock *et al.* 2014; Hanes *et al.* 2019; Williams *et al.* 2019). Increased extent of wildfire is broadly caused by two key factors – changing human practices increasing the structure and load of fuels, and climate change altering the occurrence of weather conducive to fire spread (Abatzoglou and Williams 2016). In many countries, a cessation of Indigenous burning has altered vegetation communities favouring systems with high fuel levels (Mariani *et al.* 2022). Similarly, the abandonment of agriculture in many Mediterranean countries has resulted in grass-dominated agricultural areas being replaced with shrubby systems that carry higher-intensity fires (Pausas and Fernández-Muñoz 2012). Contemporary fire management practices such as fire suppression aim to reduce the impact of wildfires, but policies of wildfire exclusion have increased fuel levels, leading to large high intensity fires (Brotons *et al.* 2013; Calkin *et al.* 2015). The most consistent cause for shifting fire regimes is the effect of global climatic change. Increases in weather conducive to fire spread have been observed in fire-prone systems around the world (Westerling and Bryant 2008; Moritz *et al.* 2012; Abram *et al.* 2021). Further, the incidence of severe drought is increasing across forests globally under climate change (Miralles *et al.* 2019; Brodribb *et al.* 2020), leading to increased forest flammability through changes to fuel structure and declines in fuel moisture content (Ruthrof *et al.* 2016; Abatzoglou *et al.* 2018).

Major fire events must be taken as a time of learning and reassessment of current knowledge. Each major fire prompts new calls for a re-evaluation of policy and practice, attitudes, understanding and expectations of future fire regimes (Moritz *et al.* 2014; Moreira *et al.* 2020). The Black Summer fire season in Australia began in August 2019 and finished in March 2020. The area burnt by these fires was the largest on record for south-eastern Australia (Boer *et al.* 2020; Bowman *et al.* 2020a): the total area burnt in the study area (see Fig. 2.2) of eastern and southern Australia was 10.3 million ha. The devastating impacts of these fires will be felt for years to come by those that lived through them and by the environment. It is therefore vital that we learn to reduce the impacts of future extreme fire seasons. In this chapter, we look at the environment before Black Summer and the weather during the season, and describe the extent and behaviour within each of the fires and the impact of the fires. Finally, we compare these data with preceding fire seasons and extreme fire seasons across the globe to place the fires in both a global and climate change context.

Environmental precursors

Wildfire occurrence is strongly determined by the biomass and moisture content of fuels. The temperate forests of Australia typically have enough fuel biomass, but it is not until periods of drought that sufficient quantities of fuels become dry enough to facilitate large wildfires (Bradstock 2010). In the winter of 2019, much of eastern Australia was in the grip of a third consecutive year of drought (Bureau of Meteorology 2019a). In the latter half of 2019, many regions were subject to a flash drought (Nguyen *et al.* 2021), which is the rapid intensification of an extreme drought event (Pendergrass *et al.* 2020). As the season progressed, there were multiple heatwaves, with record-breaking temperatures recorded across Australia (Bureau of Meteorology 2020). The calendar year of 2019 was the hottest and driest year on record for the country (Fig. 2.1) (Bureau of Meteorology 2019a, 2020). These conditions triggered widespread canopy die-back in many forests across eastern

Australia (Fig. 2.1) (De Kauwe *et al*. 2020; Nolan *et al*. 2021b) and primed the landscape for fire.

A key metric of forest fire danger is the moisture content of fine fuels (plant biomass < 6 mm diameter, such as leaves and twigs) (Hines *et al*. 2010). Estimates of fine fuel

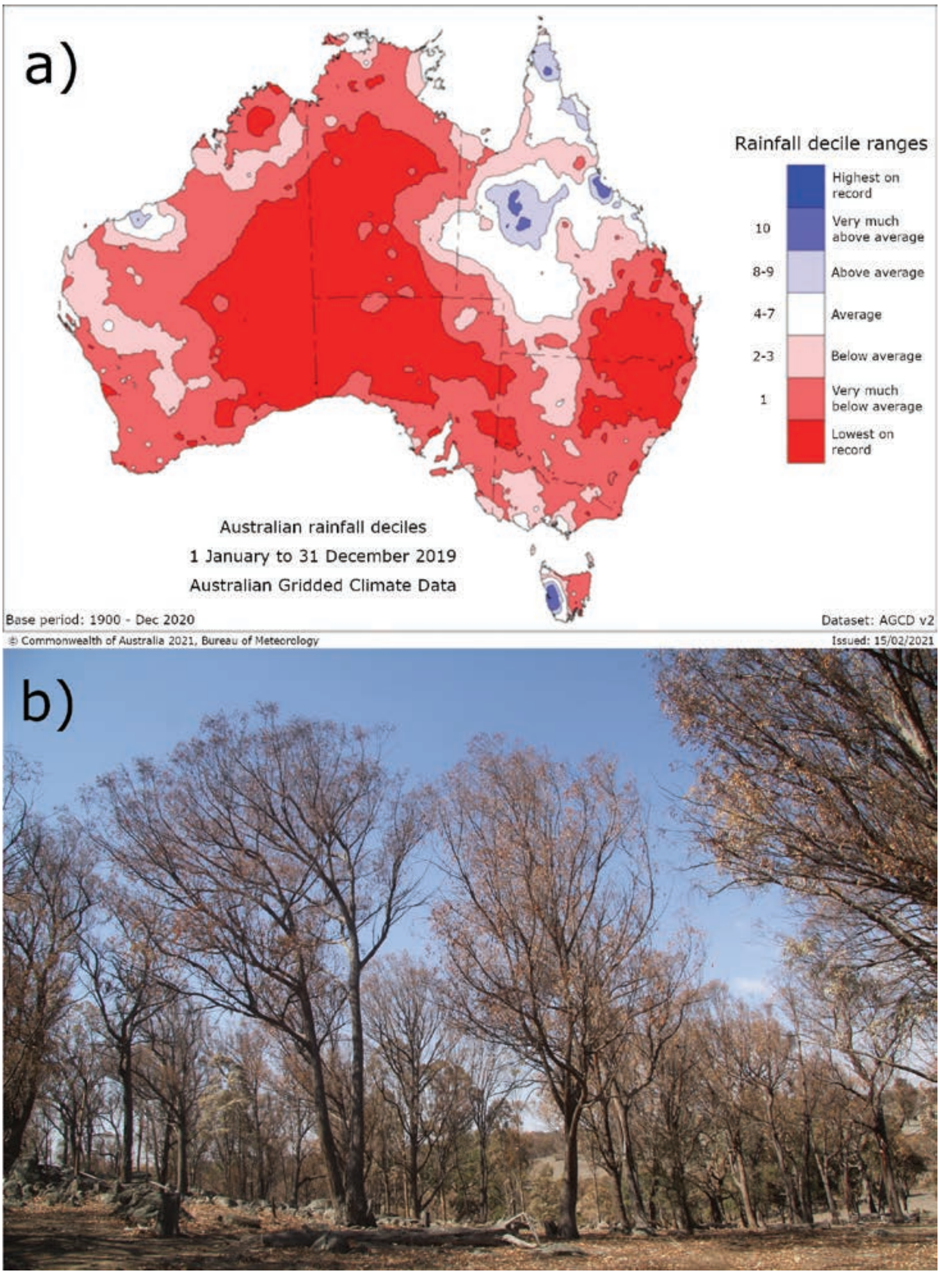

Fig. 2.1. a) 12-month rainfall deciles for Australia in 2019 (source: https://www.bom.gov.au); and b) an example of a drought-stressed forest experiencing canopy dieback in eastern Australia in late 2019. (Photo: Rachael Nolan)

moisture content over the 2019–20 fire season indicated that values were very much below average, or the lowest on record, across much of eastern and southern Australia (Nolan et al. 2020; Abram *et al.* 2021). The canopy die-back in eucalypt forest triggered by the drought also probably resulted in an increase in the ratio of dead fuels to live fuels, which would have further amplified the flammability of the temperate forest estate. The combination of an influx of dead fuels to the forest floor and the opening of the forest canopy, as the forests responded to severe drought stress, may have contributed to increased rates of fire spread (Ruthrof *et al.* 2016).

The biomass of fine fuels in a forest is another key predictor of fire behaviour (Gould *et al.* 2011; McCaw *et al.* 2012). Analyses of fine fuel load and structure in the lead-up to the 2019–20 fires in New South Wales indicated that, on average, fine fuel load and structure were no higher than historical values (Nolan *et al.* 2021a). This is not to say that fuel load and structure were not important drivers of the fires at particular locations, but the overriding influence on the 2019–20 fire season was climate, not fuel load and structure.

Fire weather during the fire season

Fire weather conditions during the 2019–20 season were unquestionably extreme and by many (but not all) measures unprecedented. The McArthur Forest Fire Danger Index (FFDI; Luke and McArthur 1978) is computed from standard meteorological observations or model predictions of precipitation, relative humidity, wind speed and temperature (Noble *et al.* 1980). Mean monthly FFDI was the highest ever recorded (since records began in 1950) over parts of northern New South Wales and south-east Queensland in September 2019 (Bureau of Meteorology 2019a; Clarke *et al.* 2020). These conditions continued through spring, with New South Wales, Queensland, Northern Territory, Western Australia and Tasmania all setting new records for mean spring FFDI (Bureau of Meteorology 2019b). December 2019 saw the highest ever average FFDI for Australia as a whole, with the majority of the country setting new record highs (Bureau of Meteorology 2020). Many locations in New South Wales set new records for highest minimum monthly FFDI values, indicating a lack of reprieve from elevated conditions and likely contributing to the severity and extent of the overall season.

During December 2019, FFDI values exceeding 100 ('Catastrophic') were observed in every mainland state and the Northern Territory (Bureau of Meteorology 2020). Much of eastern Tasmania recorded its highest ever December FFDI on 30 December. Australian Capital Territory set new records for maximum daily temperature in December, January and February (Bureau of Meteorology 2020). In South Australia there were days of FFDI exceeding 50 in November, December and January, including 3 days where multiple regions recorded FFDI values > 100 (Government of South Australia 2020). Southern Western Australia recorded near Catastrophic conditions on multiple days in December (Bureau of Meteorology 2020). Multiple regions in eastern New South Wales set records for the number of days exceeding FFDI of 25 (Clarke 2020). These same regions recorded high but not record-setting numbers of days with FFDI greater than 50.

Fire weather conditions experienced during the 2019–20 season were extreme but, in many cases, fitted within a long-term increasing trend of FFDI values (Clarke *et al.* 2013; Dowdy 2018; Abram *et al.* 2021) and atmospheric instability (Dowdy and Pepler 2018). While interannual variability is expected to persist, unmitigated climate change is expected to lead to further, substantial increases in FFDI and atmospheric instability (Clarke and Evans 2019; Di Virgilio *et al.* 2019; Dowdy *et al.* 2019). This would imply an increase in fire extent and likelihood of extreme fire seasons.

Timing, ignitions, spread and severity

In Australia, fire seasons typically coincide with broad latitudinal bands, occurring in spring in southern Queensland and northern New South Wales, spring to summer in southern New South Wales and summer to early autumn in southern regions (i.e. Victoria, South Australia, south-west Western Australia and Tasmania) (http://www.bom.gov.au/weather-services/fire-weather-centre/bushfire-weather/index.shtml). The start of the 2019–20 fire season was earlier than average (Filkov *et al.* 2020). Ignition dates followed the typical pattern of commencing earlier in the north and progressing through the season towards the south (Fig. 2.2). Numerous different ignition sources were reported over the 2019–20 fire season, including lightning and anthropogenic ignitions (e.g. arson, power-lines). Fires originating from suspected lightning ignitions accounted for the greatest amount of area burnt (Nolan *et al.* 2021a). Most of the fires across southern Australia were extinguished or declared under control by the end of February 2020 (Fig. 2.2).

A notable aspect of the 2019–20 fire season was the duration of many of the larger fire events across south-eastern Australia. Numerous megafires (as defined in Chapter 1, fires > 100 000 ha) burnt through forested terrain for several months (Table 2.1), the longest

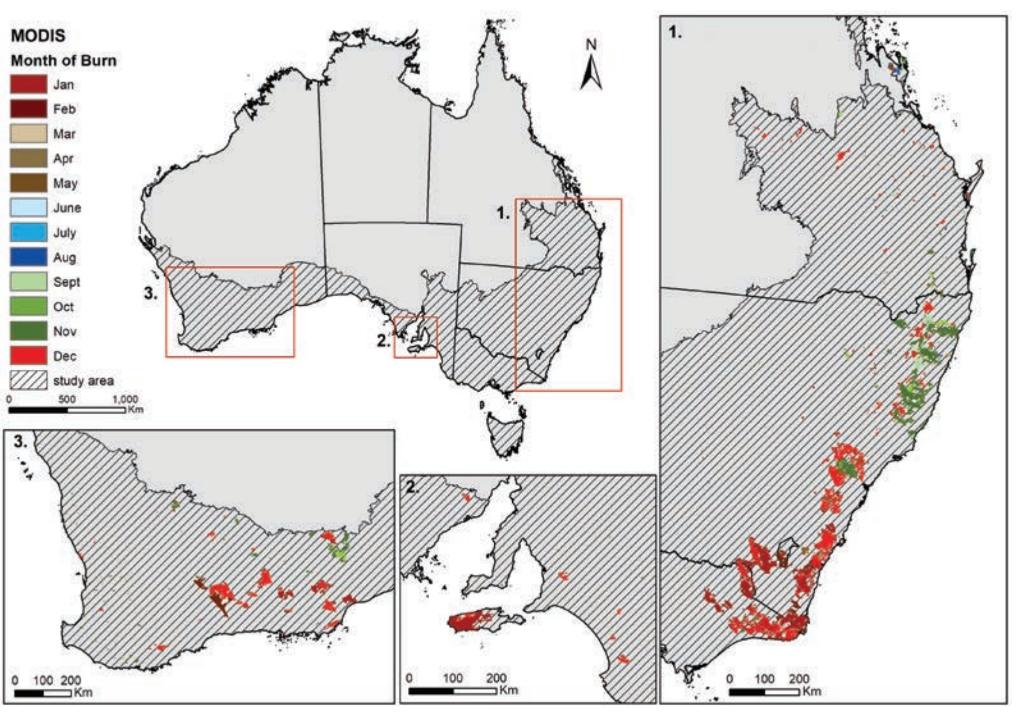

Fig. 2.2. The month of burn for the study area. Insets show a detailed view of areas of significant fire activity in (1) eastern Australia, (2) South Australia, and (3) Western Australia. Month of burn was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) day of burn product (https://modis.gsfc.nasa.gov/).

Table 2.1. Details of the start date, duration, size and the contribution (%) of each fire severity class for megafires (> 100 000 ha) occurring in south-eastern Australia.

The area burnt and severity statistics only consider native forest, woodland and shrublands. Fire severity classes are: unburnt canopy or low canopy scorch (Low); partial canopy scorch (Moderate); full canopy scorch with partial consumption (High); full canopy consumption (Extreme). The fire numbers align with those presented in Fig. 2.3. (Fires 1–9 occurred in New South Wales; fires 10–12 in Victoria)

Fire name	Start date	Duration (days)*	Area burnt (ha)	Severity statistics			
				Low	Moderate	High	Extreme
1. Liberation Trail	04/11/2019	51	218 995	16.3	32.0	27.0	24.7
2. Bees Nest	31/08/2019	75	108 551	6.1	34.5	44.9	14.5
3. Carrai East	17/10/2019	95	155 950	16.1	37.2	22.7	24.1
4. Gosper Mtn	26/10/2019	108	479 560	30.1	40.0	19.3	10.6
5. Green Wattle Ck	27/12/2019	46	282 279	19.0	34.8	24.4	21.7
6. Currowan	26/11/2019	75	318 792	16.7	30.1	22.5	30.7
7. Orroral	27/01/2020	32	92 313	10.7	16.9	31.2	41.2
8. Dunns Rd	28/12/2019	50	221 817	17.5	22.9	32.0	27.7
9. Badja Forest	27/12/2019	69	331 214	28.7	14.1	27.2	30.1
10. Upper Murray	29/12/2019	46	230 031	28.8	20.3	32.3	18.5
11. Ovens	30/12/2019	31	126 468	35.0	23.7	26.2	15.1
12. Gippsland	21/11/2019	91	1 070 341	25.1	23.9	33.2	17.8

* In the absence of published end dates, MODIS hotspots were used to calculate fire duration.

being the Gospers Mountain fire, which burnt for 108 days across complex terrain in largely inaccessible eucalypt forest west of Sydney. The duration of this and other fires in the Black Summer season exceeded that of notable megafire events occurring in south-eastern Australia in the 2003 (59 days) and 2007 (2 months) fire seasons (McCarthy *et al.* 2012; Tolhurst and McCarthy 2016).

Strong surface winds drove very rapid fire spread and long-range spotting in southern Queensland and northern New South Wales (Sharples 2020). In contrast, extreme fire activity in the southern regions was largely driven by complex dynamics of fire coupling with atmospheric conditions, resulting in violent pyrocumulonimbus (pyroCb) storms. PyroCB events generate extreme fire behaviour, including rapid rates of fire spread and long-range spotting, facilitating very rapid fire growth (Dowdy *et al.* 2017). An estimated 29 pyroCBs occurred during the 2019–20 season, which greatly increased the number of previously recorded pyroCB events for southern Australia (i.e. 60; Bowman *et al.* 2020b; Abram et al. 2021). The combination of extreme drought, frequent episodes of elevated fire danger and a high number of pyroCB events resulted in periods of rapid fire growth across eastern Australia. For example, 18 pyroCB storms occurring in southern New South Wales and Victoria over the period from 29 December 2019 to 4 January 2020 burnt an estimated 530 000 ha in a non-consecutive 51-hour period (Kablick *et al.* 2020; Peterson *et al.* 2021).

Satellite derived measures of fire severity have provided important insight into the impact of fire intensity on vegetation across the 2019–20 fires. In Australian forests, woodlands and shrublands, fire severity is quantified based on the degree of scorch and consumption of canopy and understorey foliage recorded in the days and months following 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).

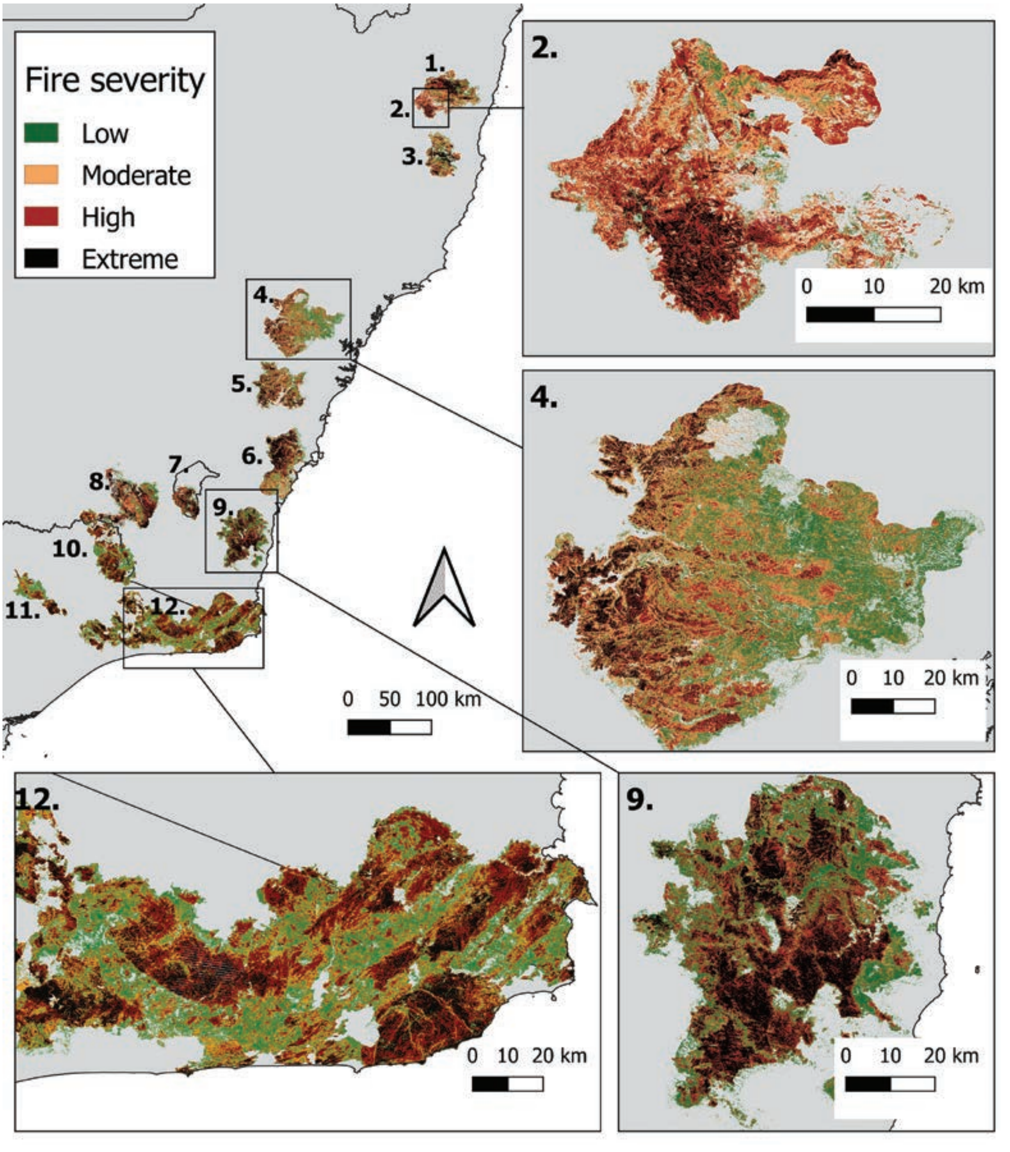

Fig. 2.3. Fire severity maps for 12 major fires in eastern Australia. Fire severity maps were produced using satellite imagery from either Landsat (Collins *et al.* 2020) or Sentinel 2 (Gibson *et al.* 2020). Insets show the severity maps for select fires in greater detail.

Analysis of fire severity patterns indicates that the proportional contribution of severity classes to fire extent typically fell within the historic range (1988–2018) for forests and shrublands in south-eastern Australia (Collins *et al*. 2021). Notable exceptions were rainforest and woodland communities, which experienced a proportionally greater extent of extreme severity fire (Collins *et al*. 2021). The 2019–20 fires impacted many vegetation communities that are typically considered too wet to burn, such as peatlands and Gondwanan rainforest (Nolan *et al*. 2020). Given the unprecedented size of the 2019–20 fires, the overall extent of high and extreme severity fire is likely to be a new record within a single fire season (Collins *et al*. 2021).

Fire severity that exceeded the resistance of canopy plants accounted for a considerable proportion (~44%) of the total extent of the temperate woody vegetation communities impacted by the 2019–20 fires (Bowman *et al*. 2021; Collins *et al*. 2021). This included many very large (> 10 000 ha) contiguous patches of high and extreme severity fire that were associated with extreme fire behaviour occurring during pyroCBs (Collins *et al*. 2021; Peterson *et al*. 2021). Unburnt vegetation and low severity fire were also common across the fire grounds (e.g. ~9% unburnt and 28% low severity) (Collins *et al*. 2021), with large (> 5000 ha) unburnt patches being observed across several megafires (Godfree *et al*. 2021). Areas that remain unburnt or burnt at low severity offer areas for survival, post-fire persistence and *in situ* recolonisation by plants and animals (e.g. Banks *et al*. 2011; Godfree *et al*. 2021).

Emissions

Climate change was a contributor to the magnitude of the 2019–20 wildfires, but these (and comparable future) fires may themselves contribute to ongoing climate change through the exceptional amounts of greenhouse gas emissions that they produce. Satellite measurements of trace gases were used to estimate that 715 Tg (million tonnes) (range 517–867) of carbon dioxide were emitted by these wildfires between November 2019 and January 2020 (van der Velde *et al*. 2021). As context, this vastly exceeds the (16-year) average of 9 Tg from fires in south-eastern Australia (van der Velde *et al*. 2021), and exceeds Australia's typical annual fossil fuel emissions (e.g. 531 Tg CO_{2e} in 2019: Commonwealth of Australia 2020a). In some environments, fire-derived emissions are expected to be compensated for when vegetation regrows, but such offsetting is unlikely to be realised in the future if comparable severe fires recur with shorter intervals (van der Velde *et al*. 2021).

Global comparisons

Placing the 2019–20 Australian fires in context is challenging as there is a continually growing list of internationally significant fire events. In the 2 years since the start of Black Summer, there have been extreme fire seasons across the globe including the United States of America, Canada, Greece and Russia. Although they may differ in properties like fire size, dominant fuel type, severity and impact, together they illustrate the depth of the worldwide wildfire problem (Gill *et al*. 2013).

The lengthy record of major Australian fires since European colonisation provides a natural point of comparison for the 2019–20 Australian fires. The 2019–20 fires set records for area of temperate forest burnt (Nolan et al. 2020), area burnt at high severity (Collins *et al*. 2021), houses lost (Filkov *et al*. 2020) and the largest individual fire originating from a single ignition (Boer *et al.* 2020). Several previous fire seasons have caused greater loss of life, including the Black Saturday fires of 2009 (173 lives, > 2000 houses). However, the Black Saturday fires burnt a much smaller area (~400 000 ha) and impacted primarily on a single day rather than months (Blanchi *et al.* 2014).

The 2019–20 Australian fires were globally remarkable. Since 2000, no forest biome anywhere on Earth has ever had a higher percentage of its area burnt in a single season than the 21% reported for forest biome burnt in the 2019–20 Australian fires (Boer *et al.* 2020). This figure also represents a massive departure from typical annual values of well below 5% in this and other forest biomes.

While comparisons between different major fires are commonplace, they are generally informal and limited to a few fires. Three exceptions are Filkov *et al.* (2020) (n = 14), Duane *et al.* (2021) (n = 18) and Williams *et al.* (2011) (n = 8). Across the three studies, the only fires of comparable size to the Australian 2019–20 season were the 1997–98 Indonesian peat fires (9.7 Mha), and the Siberian boreal forest fires of 2019 (13 Mha) and 2020 (14 Mha). In contrast, the number of people killed by the 2019–20 Australian fires was below many of the examples listed, which included 112 (Portugal 2017), 102 (Greece 2018) and 85 (USA 2018). Other fires that destroyed multiple thousands of houses were the 2017, 2018 and 2020 fire seasons in the USA (~10 000, ~19 000 and ~10 000 structures respectively). Clearly, these types of impacts are a complex function of the interaction between fire and human settlements, which can vary considerably in their size, density and other factors that influence their exposure and vulnerability to fire.

Human and economic costs

Thirty-three people lost their lives directly as a result of the fires (Filkov *et al.* 2020). Smoke exposure is estimated to have caused an additional 417 deaths and 3230 hospitalisations for cardiovascular and respiratory problems, and 1523 presentations to emergency departments due to asthma (Johnston *et al.* 2021). The cost of these health impacts from the fires are estimated at $1.95 billion (Johnston *et al.* 2021). The fires are also likely to have caused mental health issues associated with the trauma of evacuation and loss of family, friends, livestock, pets, properties and livelihoods (Zhang *et al.* 2020). Frontline workers, particularly firefighters, may have similarly experienced mental health impacts from exhaustion, emotional trauma, smoke exposure and, for volunteer firefighters, loss of income (Zhang *et al.* 2020). Further, the fires particularly affected many Indigenous communities in relation to their relationships with Country (Williamson *et al.* 2020). At a larger societal level, media coverage of the catastrophic nature of the fires, in combination with coverage of the COVID-19 pandemic shortly thereafter, may have affected mental health across Australia and beyond (Looi *et al.* 2020).

Over 3100 houses were destroyed by the fires (Filkov et al. 2020). In New South Wales, which was subject to the largest loss of houses, 2476 were destroyed and 1034 damaged (NSW Government 2020). In addition to house loss, 3 schools and 284 facilities were destroyed by fire in New South Wales, along with losses of critical agricultural and telecommunication infrastructure (NSW Government 2020). Fire damage of power poles, powerlines and the telecommunications network are estimated to have resulted in power outages to over 280 000 customers and over 800 telecommunications outages (Commonwealth of Australia 2020b). In New South Wales alone, over 88 000 km of agricultural fencing and 600 000 ha of pasture were damaged by the fires (NSW Government 2020).

The loss of lives and property was disproportionately borne by regional and socially disadvantaged communities (Nolan *et al*. 2021a).

Estimates of economic impacts from the fires are upwards of $10 billion (Commonwealth of Australia 2020b). Many of the fire-affected communities are reliant on tourism (Schweinsberg *et al*. 2020), which was heavily impacted by COVID-19 travel restrictions immediately following the Black Summer fires (Pham *et al*. 2021). The compound effect of loss of income from the fires and COVID-19 may delay social and economic recovery from the fires. Another important factor likely to affect recovery of fire-affected communities is the pace of rebuilding, which is often linked to insurance coverage (Eriksen and de Vet 2020). However, many homes in fire-affected areas are likely to have been underinsured, as was found following the 2013 fires in the Blue Mountains area of New South Wales (Eriksen and de Vet 2020). Thus, the socio-economic impacts of the fires and compounding effects of COVID-19 may take many years to become apparent.

Conclusions

The 2019–20 Black Summer set Australian records for a range of fire and weather statistics. However, of greatest concern is that the seasons fits within a global trend of worsening fire weather and fire impacts. Whatever records the 2019–20 Australian fire season set may not last long, given the continuing effects of climate change. This places fire and conservation managers in a difficult position as the main driver of change – rising global temperatures and increasing occurrence and intensity of drought – is beyond their control and subject to national and international decision making.

The heart of the worldwide wildfire problem is its complexity. Across diverse ecosystems and stakeholders, at multiple spatial and temporal scales, simple solutions are elusive (Gill *et al*. 2013). Improving the evidence base of national fire history datasets and associated impacts remains critical, regardless of policy directions (Syphard and Keeley 2019; Coops *et al*. 2020; Bowman *et al*. 2020a; Collins et al. 2021). Estimates of environmental impact have been hampered by limited baseline information from which to compare and the limitations created by the COVID 19 global pandemic. Bringing together the available data is important for scientists to interpret the Black Summer season, but is vital for predicting, measuring and evaluating future change across Australia's diverse ecosystems.

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