Impact of the 2019-20 Mega-Fires on the Greater Blue Mountains World Heritage Area, New South Wales

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The 2019-20 'Black Summer' mega-fires burnt an unprecedented 79% of the Greater Blue Mountains World Heritage Area, which is more than three times greater than the area burnt in any of the previous 48 fire seasons. The fires were not proportionally more severe than previous large fires but their huge scale meant that an unprecedented 29% of the World Heritage Area was burnt at high to extreme severity. The fires were particularly extensive and severe in parts of the World Heritage Area that are rarely burnt by wildfires, notably in cooler areas over 1000 m in the south-west. The vegetation type least impacted by the fires was grassy woodland, an important bird habitat, of which 48% was burnt. However, grassy woodland covers less than 2% of the World Heritage Area and extensive areas of grassy woodland were burnt elsewhere in 2019-20. Rainforest and shrubby wet sclerophyll forest in sheltered gullies have played an important role in past fires as unburnt fauna refuges but were unusually heavily impacted in 2019-20, with 82% and 79% burnt, respectively. The fauna and flora of the World Heritage area are likely to eventually recover from the Black Summer fires if this was an exceptional event that will not recur for many decades. However, a change in the Australian fire regime to more frequent, more extensive, more severe wildfires as a result of climate change has long been predicted. If the Black Summer fires are a harbinger of this change, the long-term impact on the environment and biota of the World Heritage Area would be catastrophic.

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KEYWORDS: climate change, fauna habitat, fire history, fire regime, landscape types, prescribed burns, vegetation types, wildfire.

INTRODUCTION

The year 2019 was Australia's hottest and driest on record (Abram et al. 2021) and culminated in the catastrophic 'Black Summer' mega-fires of spring and summer 2019-20. More than 23% of the temperate forests of south-eastern Australia were burnt in this one fire season, making the scale of the fires unprecedented both for Australia and globally (Boer et al. 2020). The 2019-20 fires were a dramatic example of a world-wide trend that has seen extremely destructive fires occurring with increasing frequency over the last 20 years, driven chiefly by anthropogenic climate change but with other factors also having an influence (Brotons et al. 2013, Jolly et al. 2015, Fonseca et al. 2017, Williams et al. 2019).

The Greater Blue Mountains World Heritage Area, which encompasses over one million hectares of native bushland in the ranges west of Sydney, was one of the areas worst affected by the 2019-20 fires. The area's exceptional floral and faunal biodiversity is the reason for its recognition as a World Heritage Area of international conservation significance. The impact of the 2019-20 fires on its flora and fauna is of great concern.

In the 2019-20 fire season, the World Heritage Area was burnt by the Gospers Mountain Fire (479,514 ha burnt in and around the World Heritage Area; NSW National Parks and Wildlife Service records), Green Wattle Creek Fire (277,882 ha), Kerrys Ridge Fire (183,647 ha), Little L Complex Fire (136,286 ha), Three Mile Fire (48,216 ha), Erskine Creek Fire (22,497 ha), Grose Valley Fire (19,896 ha) and Ruined Castle Fire (17,043 ha). These contiguous fires clearly satisfy the recent definition of a mega-fire in south-eastern Australia as a wildfire or wildfire complex that encompasses more than 100,000 ha of native woody vegetation (Collins *et al.* 2021).

Across south-eastern Australia, the 2019-20 fires burnt over 50% of all known locations for a total of 816 native vascular plant species (Godfree et al. 2021). Most of the affected species are resilient to fire and, given time, are likely to recover. However, rainforest

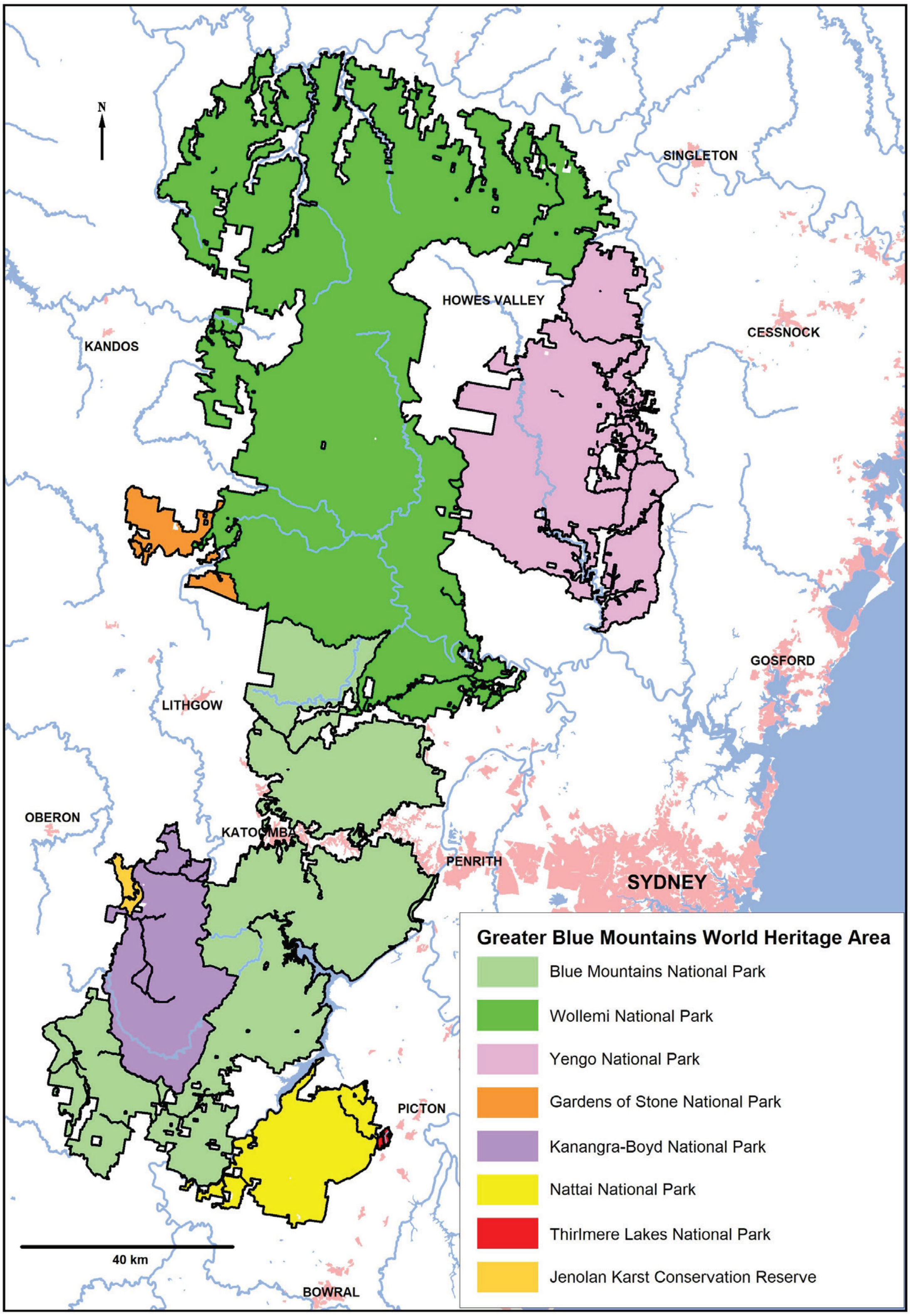

Figure 1. The eight conservation reserves that make up the Greater Blue Mountains World Heritage Area. Reserve boundaries as at July 2021, including additions since inscription of the World Heritage Area in 2000. The additions are not yet officially part of the World Heritage Area.

vegetation and plant species, which are rarely if ever subjected to fires, were widely and severely impacted in 2019-20 and may be unable to recover effectively, resulting in a landscape-scale decline of this ecosystem (Godfree et al. 2021), although results from a recent study by Baker et al. (2022) suggest that most rainforest plants may be more resilient to rare fires than expected. In a separate analysis, Gallagher et al. (2021) identified 595 plant species from various ecosystems that will be slow to recover after the 2019-20 fires and will be at risk of extinction because of the likelihood that future fires will be too frequent because of climate change to allow them to recover.

Among the native vertebrate fauna of south-eastern Australia, Ward et al. (2020) identified a total of 70 taxa for which a substantial proportion (>30%) of their known or potential habitat was impacted by the 2019-20 fires, including 51 species for which 30-50% of their habitat burned, 16 species for which 50-80% of their habitat burned and 3 species for which over 80% of their habitat burned.

In 2021, we described the extent and severity of the 2019-20 mega-fires in the Greater Blue Mountains World Heritage Area using the NSW Government's fire mapping (Smith 2021). Here, we expand the analysis to examine fire extent and severity in relation to various factors, including elevation, temperature, rainfall, geomorphological landscape types, vegetation types and fire history (both wildfires and prescribed burns), using publicly available datasets. Our particular interest is the impact of the 2019-20 fires on fauna habitats in the World Heritage Area (Smith et al. 2019).

METHODS

This study was a desktop review that did not involve field inspections. However, we have carried out extensive fieldwork in the World Heritage Area for other post-fire studies (Smith and Smith 2022a, 2022b), as well as many pre-fire studies (e.g. Smith and Smith 2017, 2018, Smith et al. 2019).

Study area

The Greater Blue Mountains World Heritage Area consists of eight adjoining conservation reserves, including Wollemi, Blue Mountains, Yengo, Kanangra-Boyd, Nattai, Gardens of Stone and Thirlmere Lakes National Parks and Jenolan Karst Conservation Reserve (Fig. 1). The reserves are managed by the NSW National Parks and Wildlife Service, which is part of the NSW Department of Planning and Environment. In 2000, when the Greater Blue Mountains was inscribed on the World Heritage List, the eight reserves had a total area of 1,043,825 ha. Since that time, additions have been made to the reserves and their total area in July 2021 was 1,082,810 ha, an increase of 38,985 ha since inscription. The additions are not yet officially part of the World Heritage Area but they are effectively managed as if they were. We have therefore chosen to use the current reserve boundaries (as at July 2021) for our analyses rather than the official World Heritage Area boundary.

Fire extent and severity

Spatial data on the extent and severity of the 2019-20 mega-fires in the Greater Blue Mountains World Heritage Area was obtained from the NSW Government's Fire Extent and Severity Mapping (FESM) project Version 3 (last updated 18/12/2020). The data are available as a Geographic Information System (GIS) layer at https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm. FESM is a collaborative project between NSW Department of Planning and Environment and NSW Rural Fire Service. It is a semi-automated approach to mapping fire extent and severity through a machine learning framework based on Sentinel 2 satellite imagery enhanced by high resolution aerial photography taken 4-6 weeks post-fire (Department of Planning, Industry and Environment 2020). The FESM project also involved numerous field surveys undertaken shortly after the 2019-20 fire season to validate the mapping. Five fire severity classes were distinguished (Table 1, Fig. 2). The pixel size of the FESM mapping is 100 m^2 (10 x 10 m).

Wildfire and prescribed burn history

Wildfires are unplanned fires from natural causes (such as lightning) or from accidental human ignitions or arson. Prescribed burns are planned fires intentionally ignited to meet management objectives, usually to reduce fuel loads and hence wildfire hazard. GIS mapping of wildfires and prescribed burns in the World Heritage Area before the 2019-20 fires was available from the NSW National Parks and Wildlife Service at https://datasets.seed.nsw.gov.au/dataset/fire-history-wildfires-and-prescribed-burns-1e8b6. The mapping shows the extent of previous fires but not their severity nor unburnt areas within the fire boundary. In the present analysis, fire extent and severity in 2019-20 was compared among areas unburnt by wildfire in the previous 48 fire seasons (July to June, 1971 to 2019) and areas burnt by wildfire in one, two, three, four and five-eight previous fire seasons (no areas were burnt more often). For prescribed burns, fire extent and severity in 2019-20 was compared among areas unburnt by prescribed burns between 1971 and 2019, areas

Severity class	Description	% foliage fire affected
Unburnt	Both canopy and understorey unburnt	0% canopy and understorey burnt
Low	Burnt understorey with unburnt canopy	>10% burnt understorey >90% green canopy
Moderate	Partial canopy scorch	20-90% canopy scorched
High	Complete canopy scorch (+/- partial canopy consumption)	>90% canopy scorched <50% canopy consumed
Extreme	Complete canopy consumption	>50% canopy consumed

Table 1. Fire severity classification used in the NSW Government's Fire Extent and Severity Mapping (FESM Version 3) of the 2019-20 fires. Canopy scorch is when the leaves are killed by the heat of the fire but not consumed.

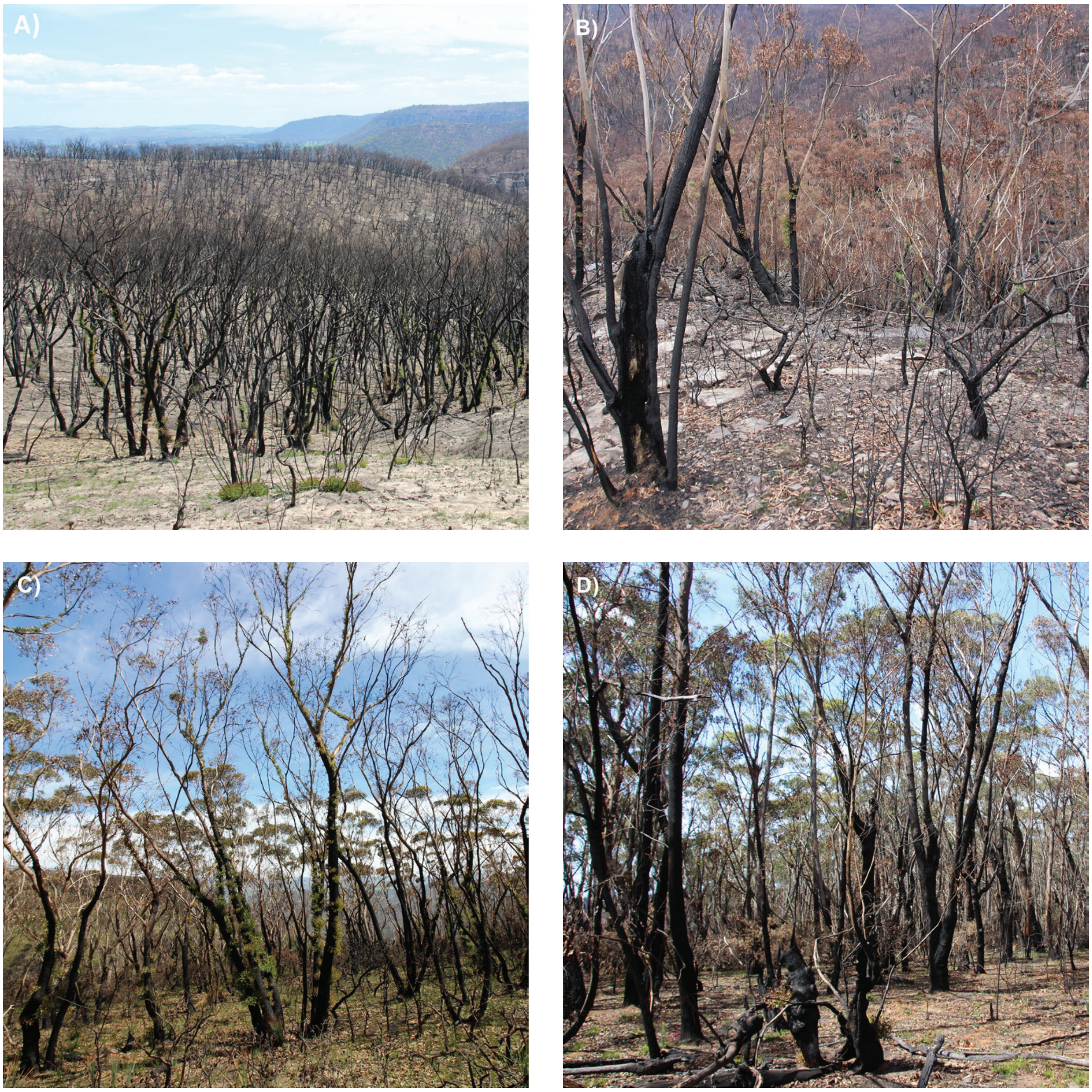

Figure 2. Examples of the fire severity classes. (A) Extreme severity fire, Bell (complete canopy consumption). (B) High severity fire, Mount Tomah (complete canopy scorch). (C) Moderate severity fire, Narrow Neck Plateau (partial canopy scorch). (D) Low severity fire, Evans Lookout (understorey burnt, canopy unburnt).

last burnt between 1971 and 1999, areas last burnt between 1999 and 2014, and areas last burnt between 2014 and 2019. Records of wildfires and prescribed burns before 1971 are incomplete and insufficient to allow analysis.

Elevation

Elevation in the World Heritage Area ranges from about 10 m beside the Nepean River to 1334 m on Mount Emperor on the Great Dividing Range. In the present analysis, fire extent and severity in 2019-20 was compared among three elevation zones: 10-500 m, 500-1000 m and 1000-1334 m. The zones were mapped using the 500 m and 1000 m contour lines on 1:250,000 topographic map GIS layers available from Geoscience Australia at https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/63999.

Temperature and rainfall

The Australian Bureau of Meteorology distinguishes three average annual daily mean temperature zones in the World Heritage Area, based on temperature records from 1961 to 1990: 12-15^{o}C, 15-18^{o}C and 18-21^{o}C (www.bom.gov.au/jsp/ncc/climate_averages/temperature/index.jsp). The Bureau distinguishes two average annual rainfall zones based on rainfall records from 1981 to 2010: 600-1000 mm and 1000-1500 mm (www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp). In the present analysis, fire extent and severity in 2019-20 was compared among the three temperature zones and between the two rainfall zones, using GIS layers provided by the Bureau with a resolution of approximately 2.5 km for temperature and 5 km for rainfall.

Landscape type

Mitchell Landscapes (Mitchell 2002a, 2002b, Eco Logical Australia 2008) is a classification of New South Wales landscapes that is used by the NSW Department of Planning and Environment. A GIS map layer of Version 3.1 (2016) Mitchell Landscapes is available at https://data.nsw.gov.au/data/dataset/nsw-mitchell-landscapes-version-3-1. Mitchell Landscapes are based primarily on geomorphology: each landscape represents a particular combination of geology, topography and soils (Mitchell 2002a). The individual landscapes are described by Mitchell (2002b) and grouped into 'meso' categories (the term 'meso' is not defined), which in turn are grouped under the bioregions identified in the Interim Biogeographic Regionalisation for Australia (Thackway and Cresswell 1995). In the present analysis, fire extent and severity in 2019-20 was compared among 14 'meso' landscape types and between two bioregions.

Vegetation type

The NSW Department of Planning and Environment has mapped the plant community types of NSW and the mapping is available as a GIS layer at https://datasets.seed.nsw.gov.au/anzlic_dataset/nsw-state-vegetation-type-map. The plant community types are grouped under the vegetation formations and sub-formations distinguished by Keith (2004). In the present analysis, fire extent and severity in 2019-20 was compared among the 11 vegetation formations/sub-formations represented in the World Heritage Area.

Analysis

For each factor (wildfire history, prescribed burn history, elevation, temperature, rainfall, landscape type and vegetation type), the QGIS Version 3.16 Geographic Information System (QGIS Development Team 2021) was used to determine the area burnt at each level of fire severity in 2019-20 within each of the map units being compared (e.g. the three elevation zones).

RESULTS

Fire extent and severity

The FESM Version 3 fire extent and severity mapping indicates that the 2019-20 mega-fires burnt a total of 855,310 ha in the World Heritage Area (as defined here), representing 79% of its total area (Fig. 3). The breakdown by fire severity was 11% of the World Heritage Area burnt at extreme severity, 18% burnt at high severity, 28.5% burnt at moderate severity, 21.5% burnt at low severity, and 21 % was unburnt. The fires were far more extensive than in any of the previous 48 fire seasons, 1971-2019 (Fig. 5). The worst fire seasons prior to 2019-20 were 2001-02, when 24% of the World Heritage Area burnt, and 1993-94, when 23% burnt.

Wildfire history

Over the 48 fire seasons prior to the 2019-20 mega-fires, 22% of the World Heritage Area had not been burnt by wildfire, 28% had been burnt by one wildfire, 23% by two wildfires, 17% by three wildfires, 7% by four wildfires and 3% by five-eight wildfires (Fig. 4). The 2019-20 Black Summer fires burnt large areas in all these categories but were less extensive in the less frequently burnt areas: 70% of the previously unburnt parts of the World Heritage Area were burnt in 2019-20, 75% of the parts that had been burnt by one wildfire, 80% of the parts that had been burnt by two wildfires, and 86-91% of the parts that had been burnt by 3-8 wildfires (Fig. 6).

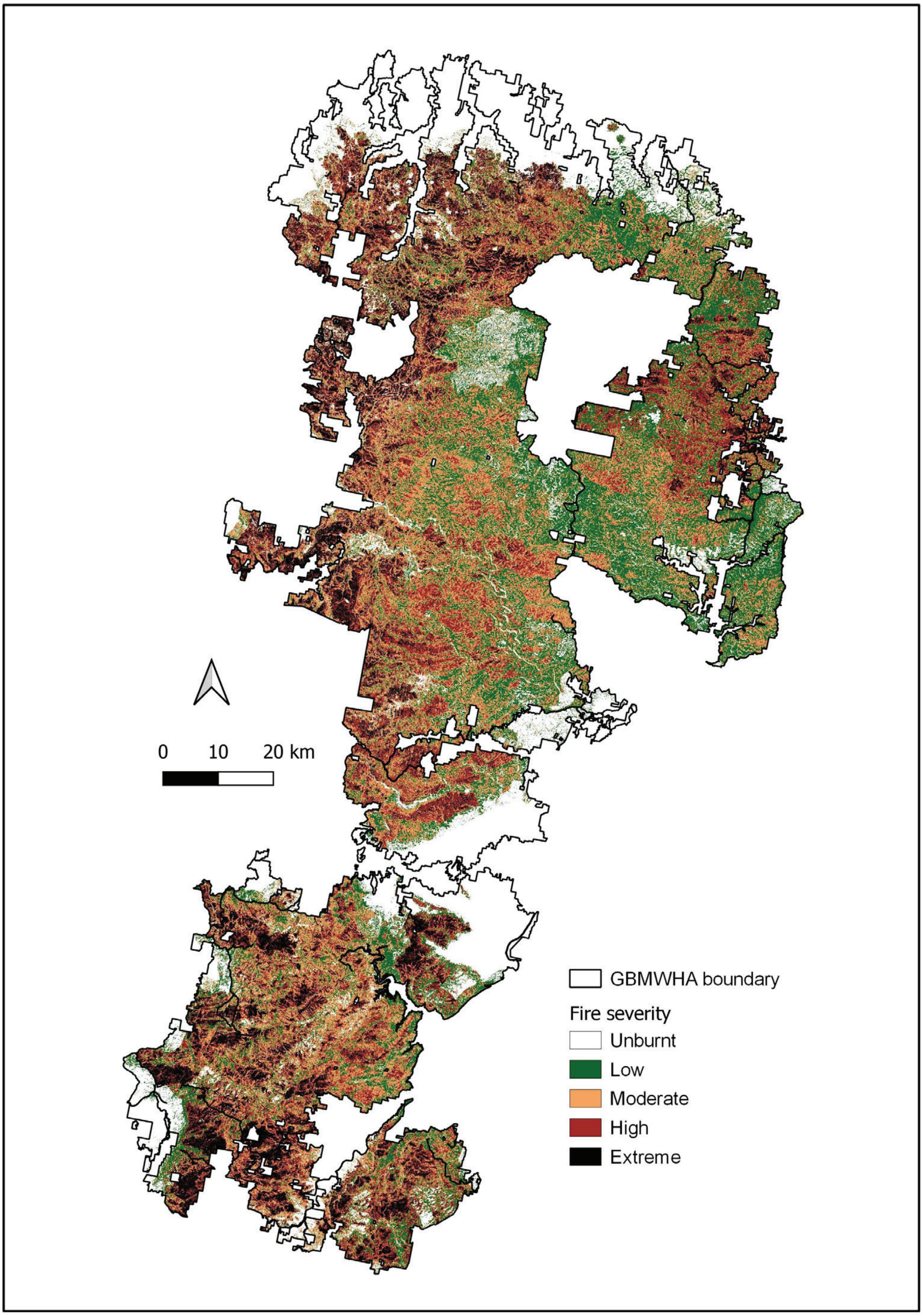

Figure 3. Extent and severity of the 2019-20 mega-fires in the Greater Blue Mountains World Heritage Area (data source FESMv3, 18/12/2020).

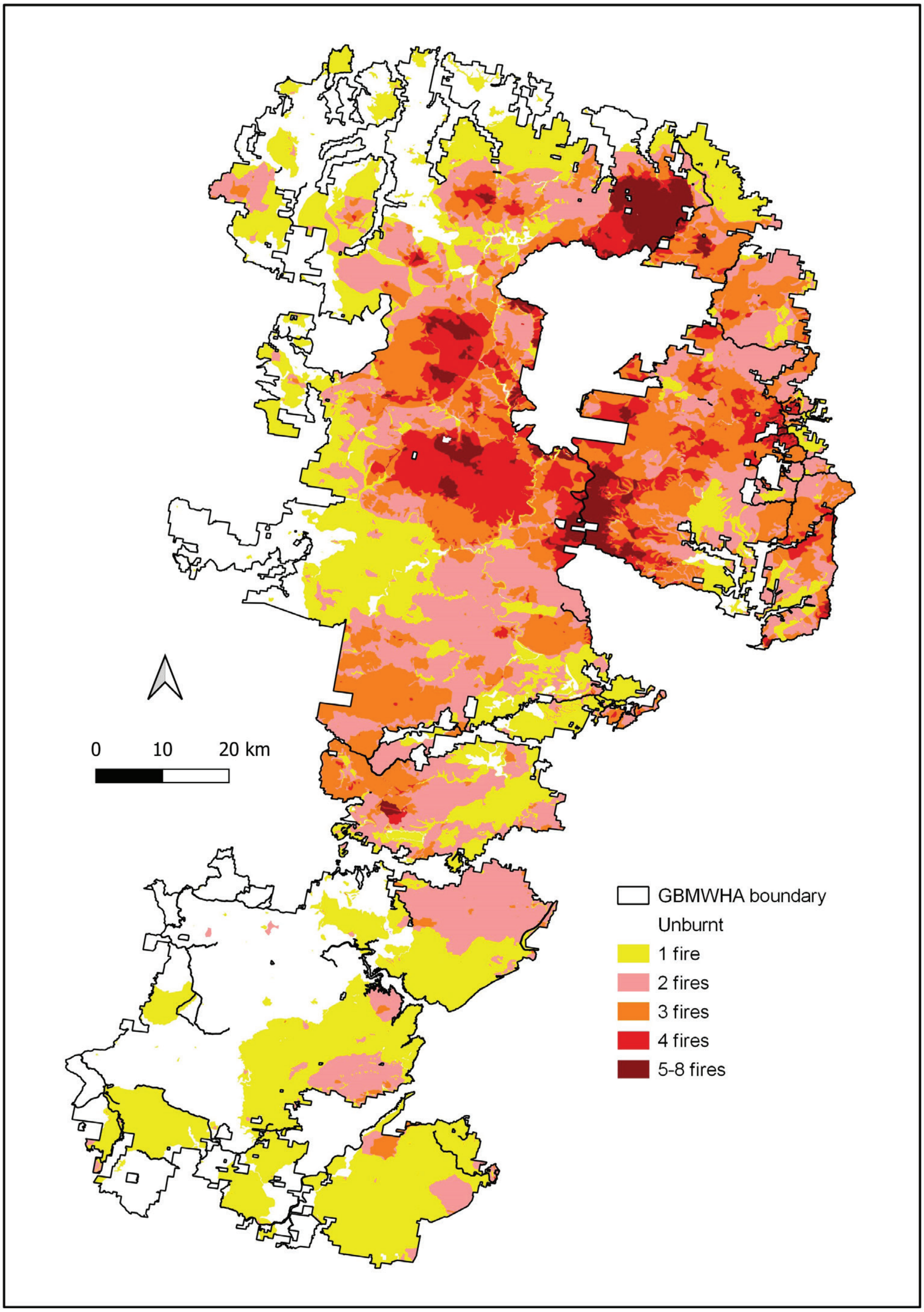

Figure 4. Wildfire history of the Greater Blue Mountains World Heritage Area 1971-2019 (48 fire seasons) prior to the 2019-20 mega-fires.

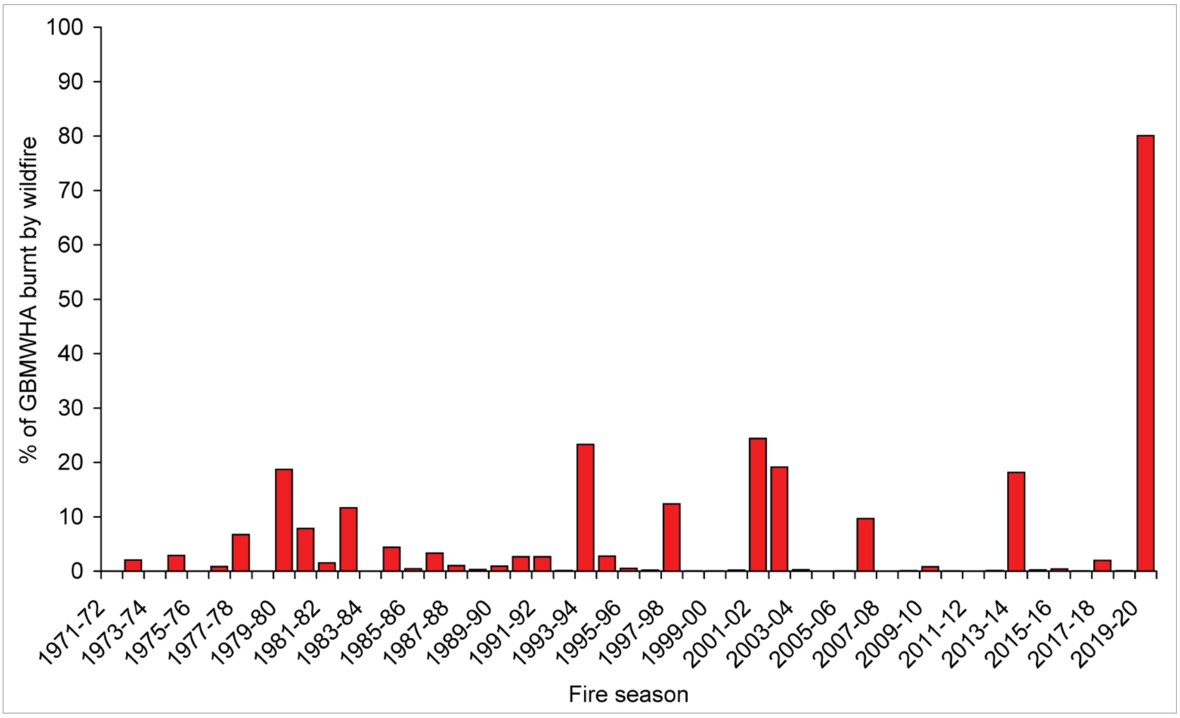

Figure 5. Area burnt by the 2019-20 fires compared with areas burnt in previous fire seasons in the Greater Blue Mountains World Heritage Area.

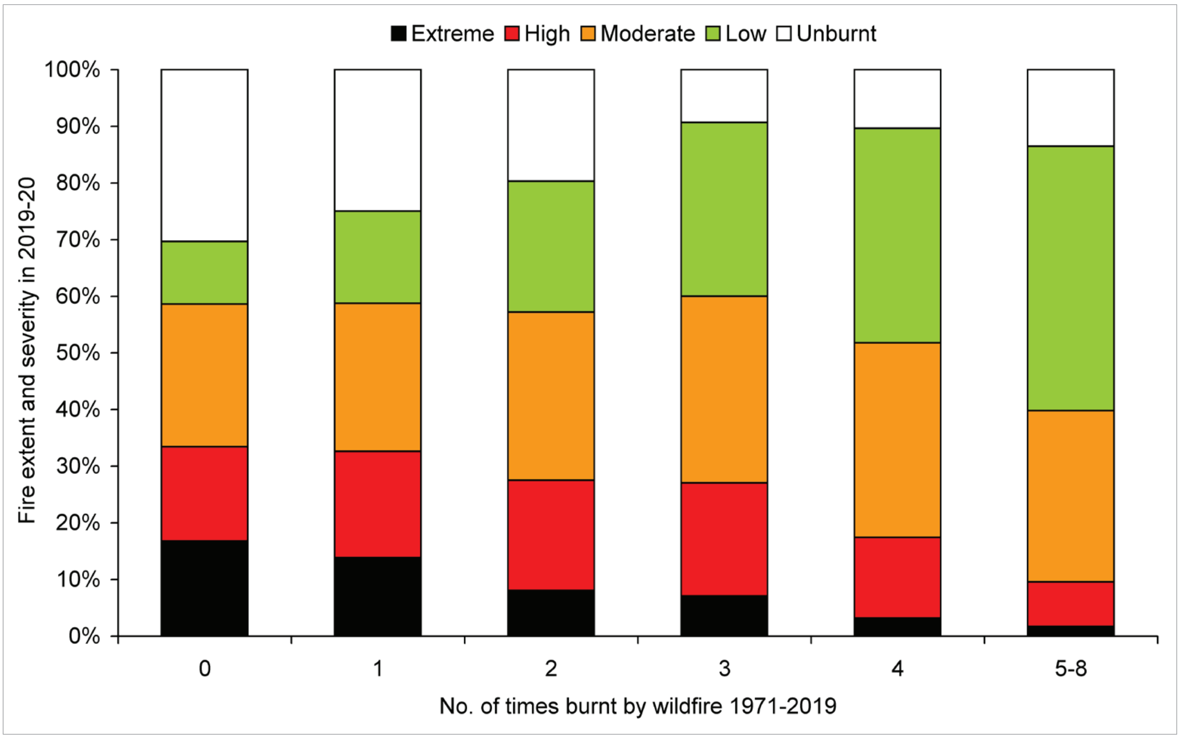

Figure 6. Fire extent and severity in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to wildfire history 1971-2019.

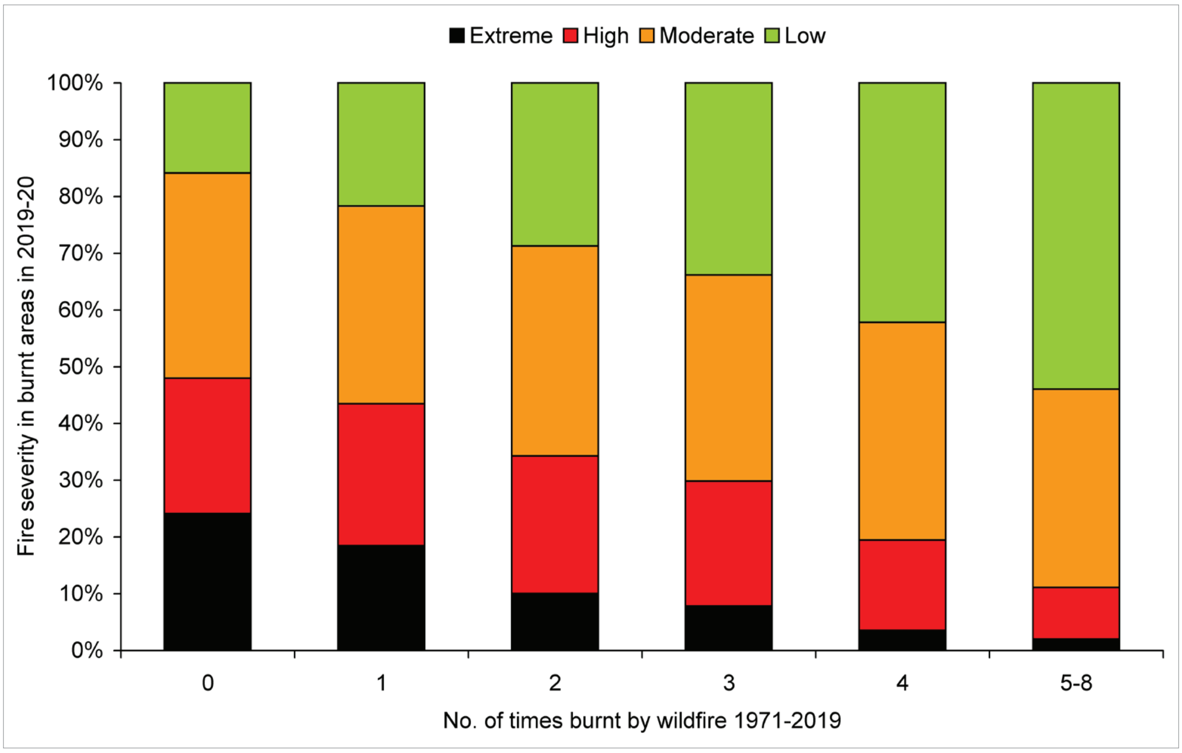

Figure 7. Fire severity in burnt areas in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to wildfire history 1971-2019. This figure repeats Figure 6 but with unburnt areas excluded in order to show the fire severity patterns more clearly.

Although less extensive in areas unburnt in the previous 48 fire seasons, the 2019-20 fires were proportionally more severe in these areas, with 48% of the burnt areas in the previously unburnt category burnt at high to extreme severity in 2019-20. The proportion of the burnt areas that were burnt at high to extreme severity declined progressively with increasing frequency of previous wildfires and was only 11% in the parts of the World Heritage Area that had been burnt by 5-8 wildfires since 1971 (Fig. 7).

Prescribed burn history

Prior to the 2019-20 mega-fires, most of the World Heritage Area (74%) had not been burnt by prescribed burns since at least 1971; 9% had been last burnt between 2014 and 2019 (i.e. within the previous five fire seasons); 12% had been last burnt between 1999 and 2014; and 5% had been last burnt between 1971 and 1999 (Fig. 8). The 2019-20 fires were less extensive in areas subject to prescribed burns since 1999 than in areas unburnt since 1999 (Fig. 9). The fires were proportionally least severe in areas subject to prescribed burns since 2014 (where 26% of the area burnt in 2019-20 burnt at high to extreme severity) and most severe in areas subject to prescribed burns between 1999 and 2014 (where 45% of the area burnt in 2019-20 burnt at high to extreme severity) (Fig. 10).

Elevation

Three elevation zones were distinguished in the World Heritage Area, with the 10-500 m zone covering 50% of the area, the 500-1000 m zone covering 45.5% and the 1000-1340 m zone covering just 4.5% (Fig. 11). The extent and severity of the 2019-20 fires differed between the zones. The fires were more extensive and severe at elevations above 500 m, especially in terms of the area burnt at high to extreme severity versus the area burnt at low severity or unburnt (Fig. 12). This contrasts with previous wildfire patterns: wildfires had been more frequent between 1971 and 2019 at elevations below 500 m, especially compared with elevations over 1000 m, where 75% of the area had not been burnt by any wildfire in the 48 fire seasons between 1971 and 2019 (Fig. 13).

Temperature

The Bureau of Meteorology distinguishes three average annual daily mean temperature zones in the World Heritage Area, with the 12-15°C zone covering 10% of the area, the 15-18°C zone covering 54% and the 18-21°C zone covering 36% (Fig. 14). The 2019-20 fires were less extensive and severe in the hottest zone (18-21°C) than in the two cooler zones (Fig. 15). This contrasts with previous wildfire patterns between 1971 and 2019, when wildfires were more frequent in the

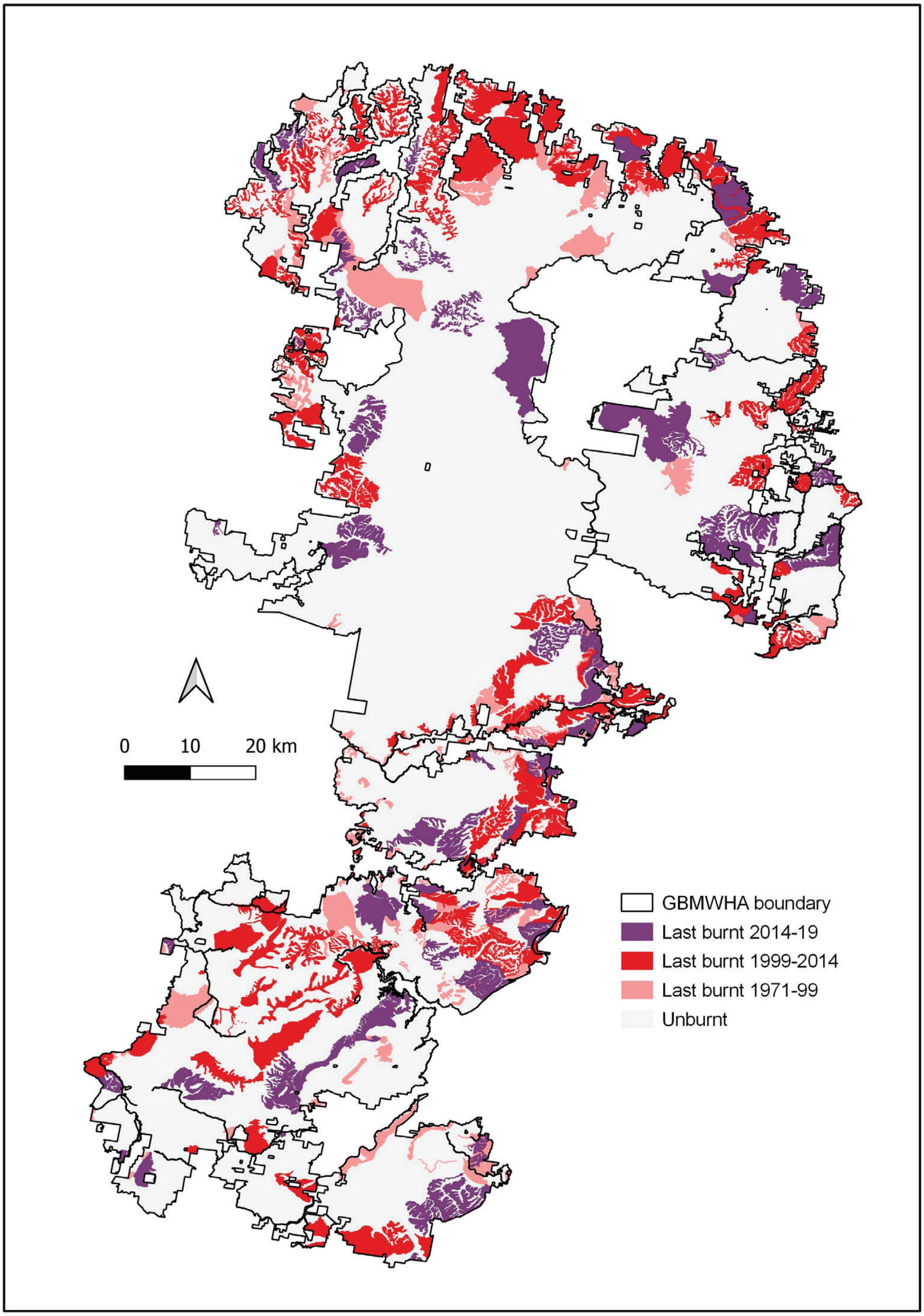

Figure 8. Prescribed burn history of the Greater Blue Mountains World Heritage Area 1971-2019 (48 fire seasons) prior to the 2019-20 mega-fires.

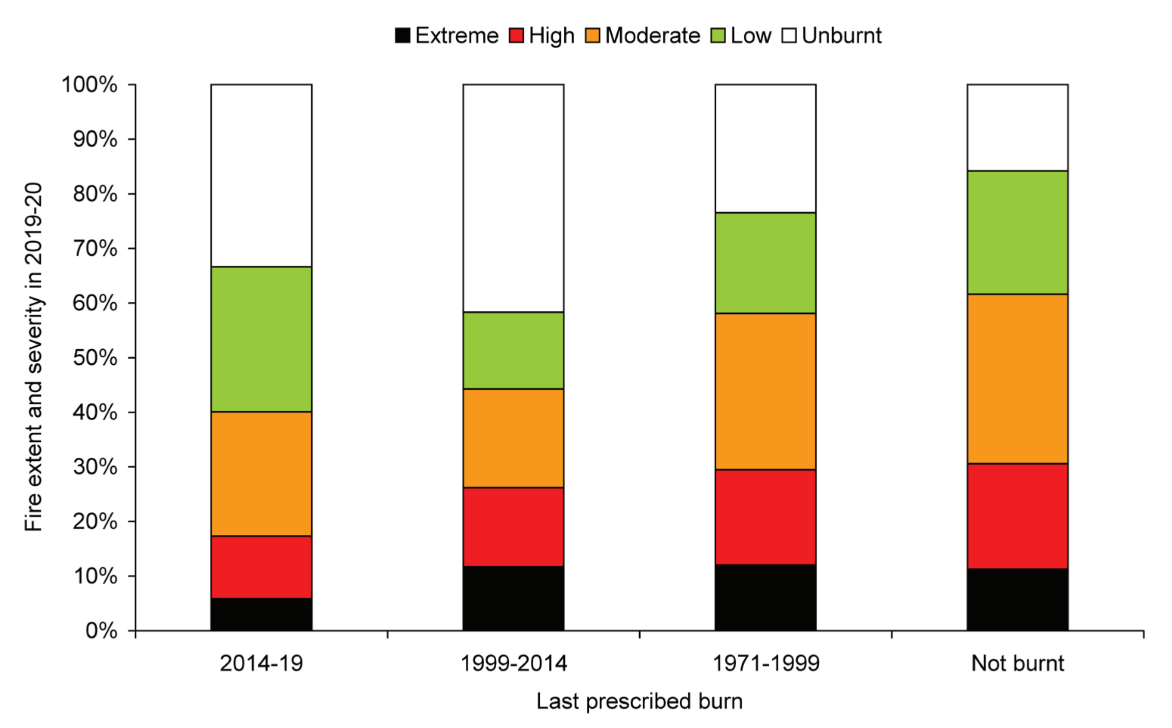

Figure 9. Fire extent and severity in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to prescribed burn history 1971-2019.

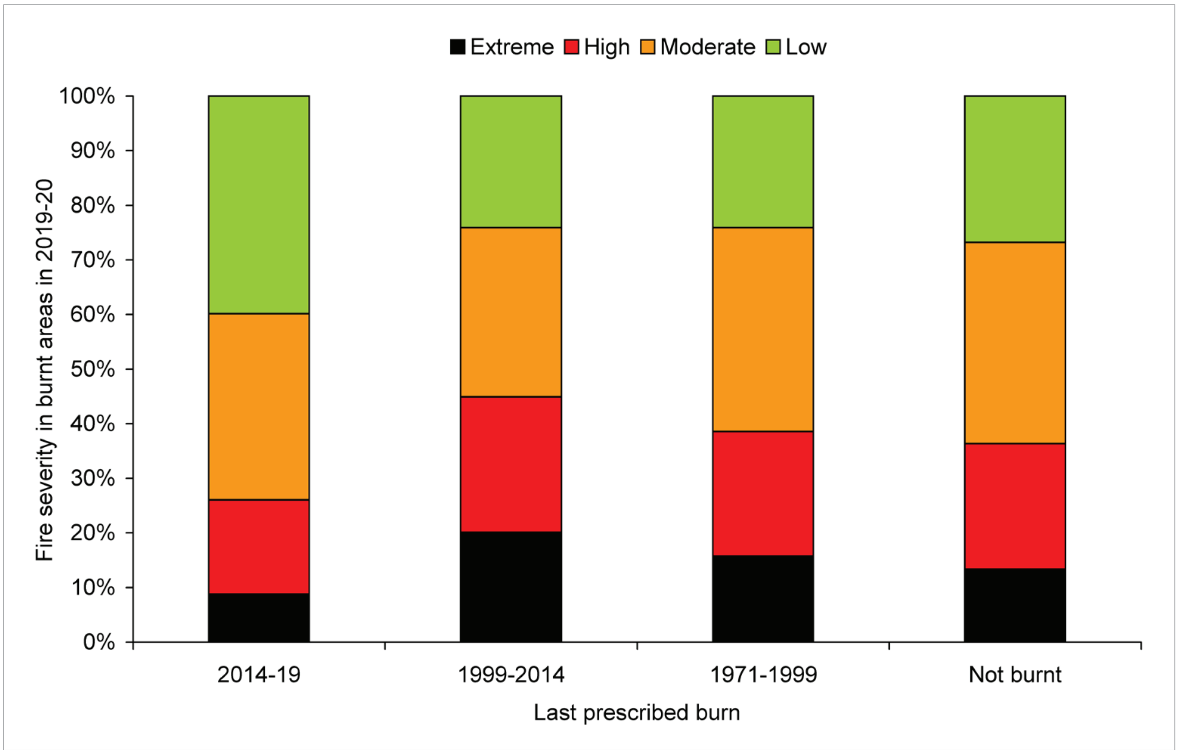

Figure 10. Fire severity in burnt areas in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to prescribed burn history 1971-2019. This figure repeats Figure 9 but with unburnt areas excluded in order to show the fire severity patterns more clearly.

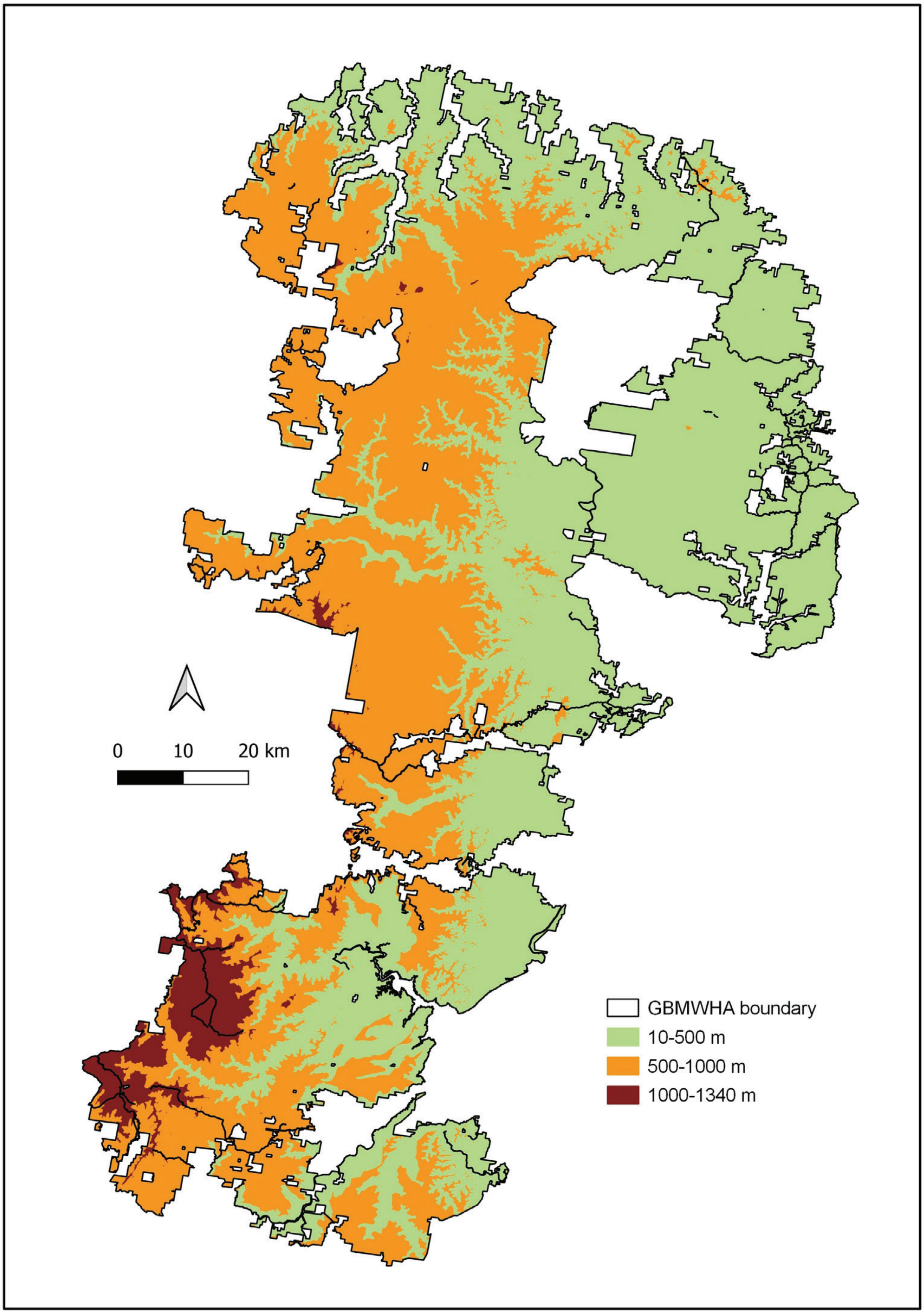

Figure 11. Elevation zones in the Greater Blue Mountains World Heritage Area.

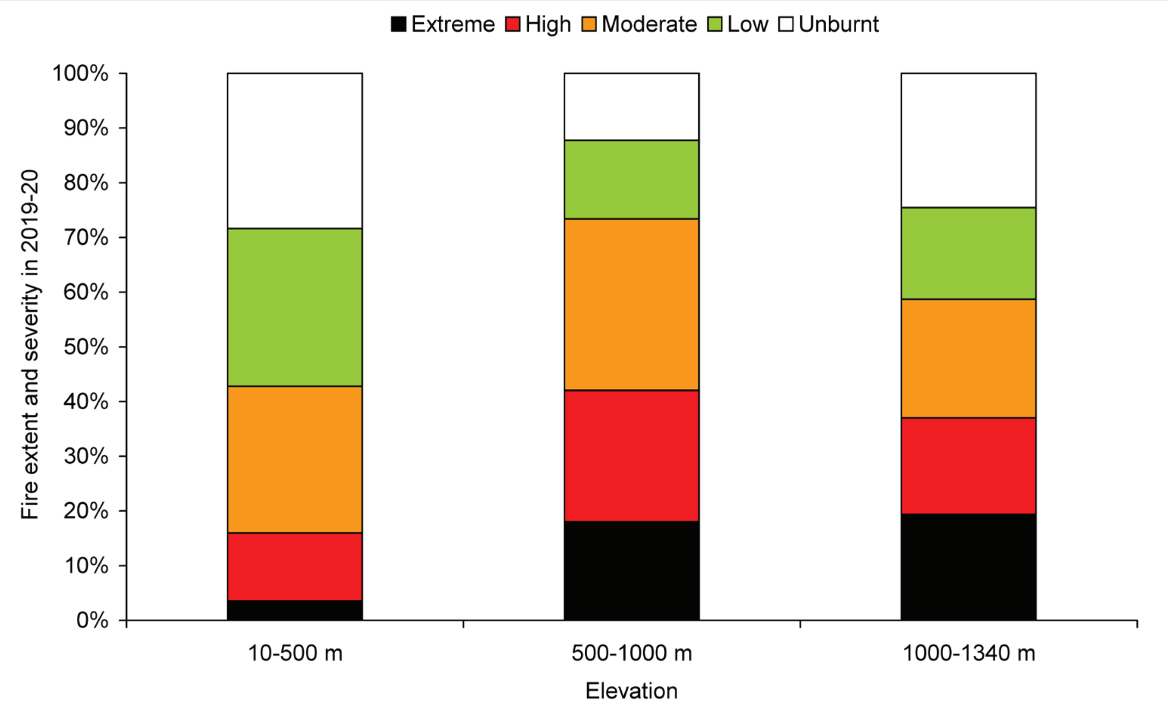

Figure 12. Fire extent and severity in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to elevation zones.

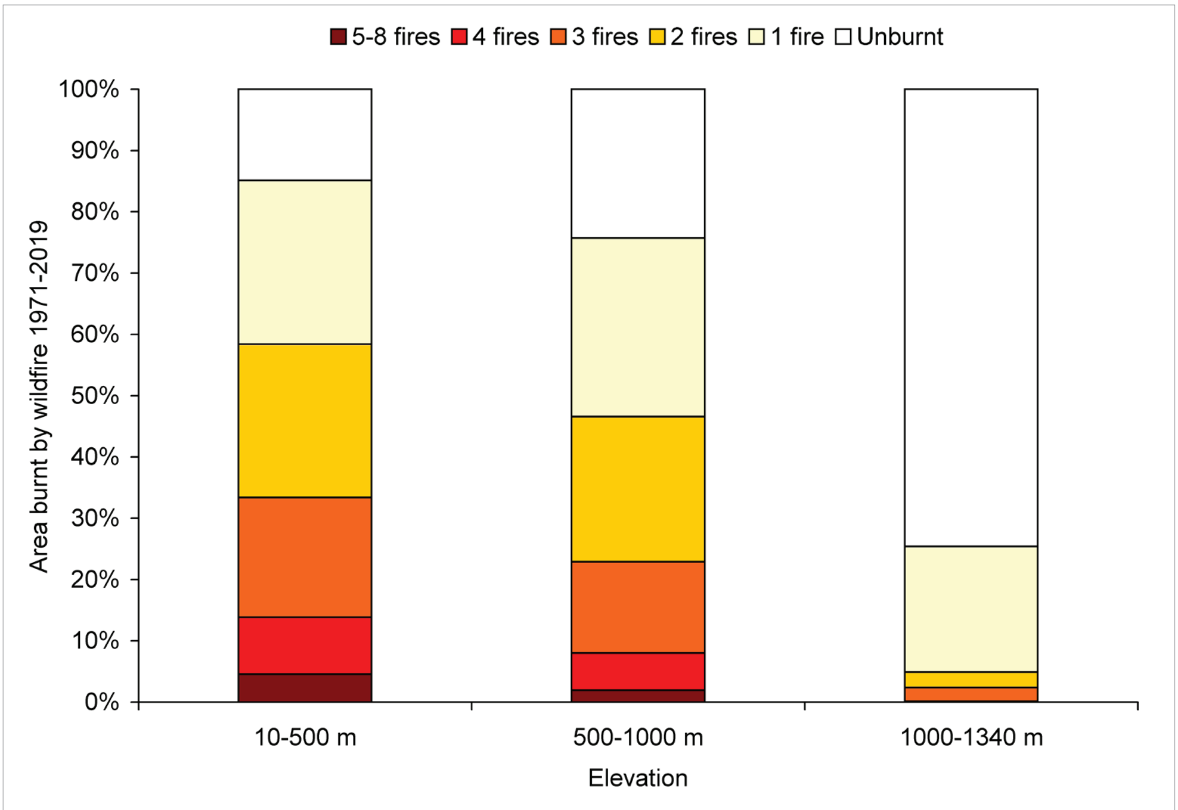

Figure 13. Frequency of wildfires in the Greater Blue Mountains World Heritage Area 1971-2019 in relation to elevation zones.

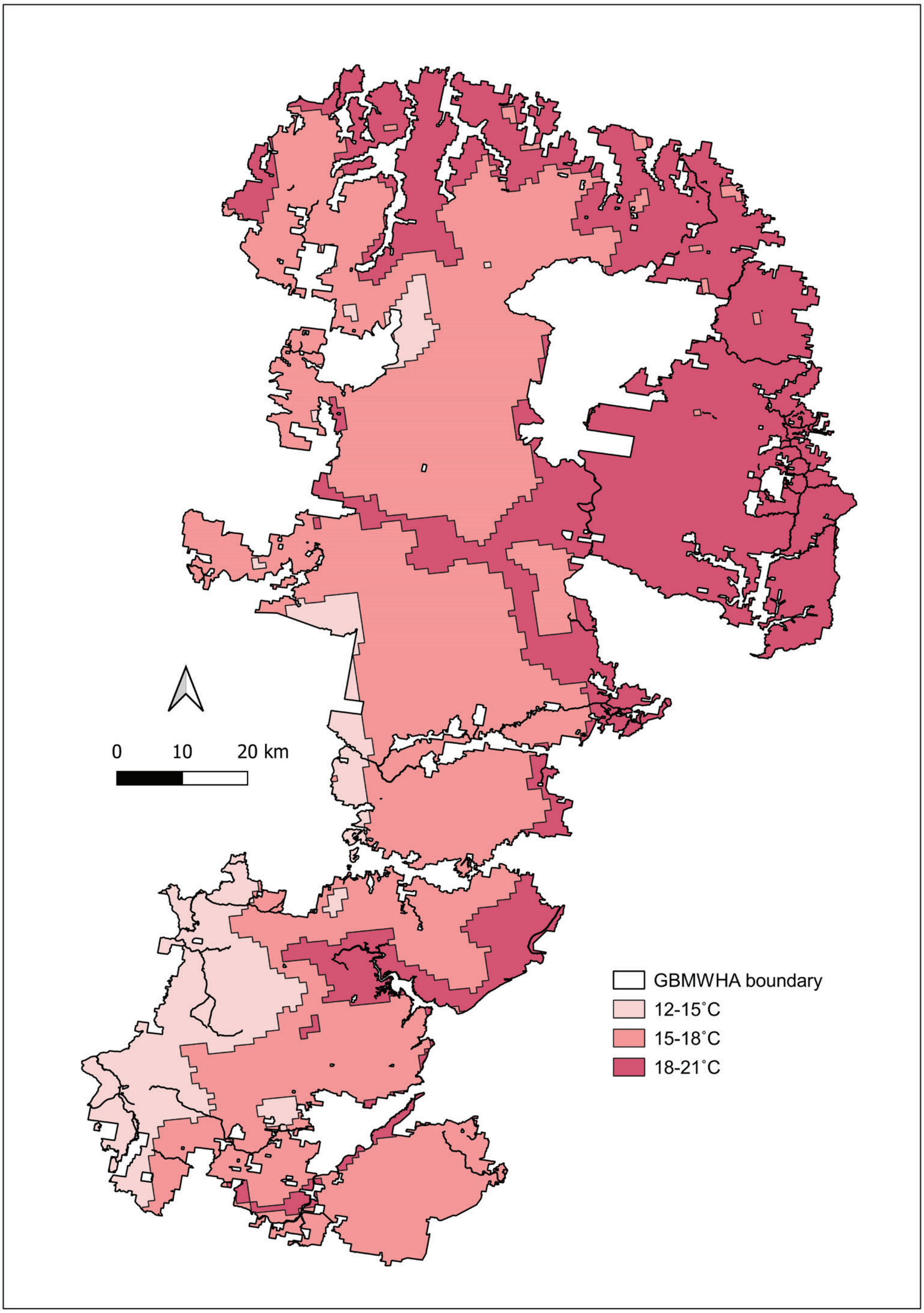

Figure 14. Temperature zones in the Greater Blue Mountains World Heritage Area based on average annual daily mean temperatures, 1961-1990.

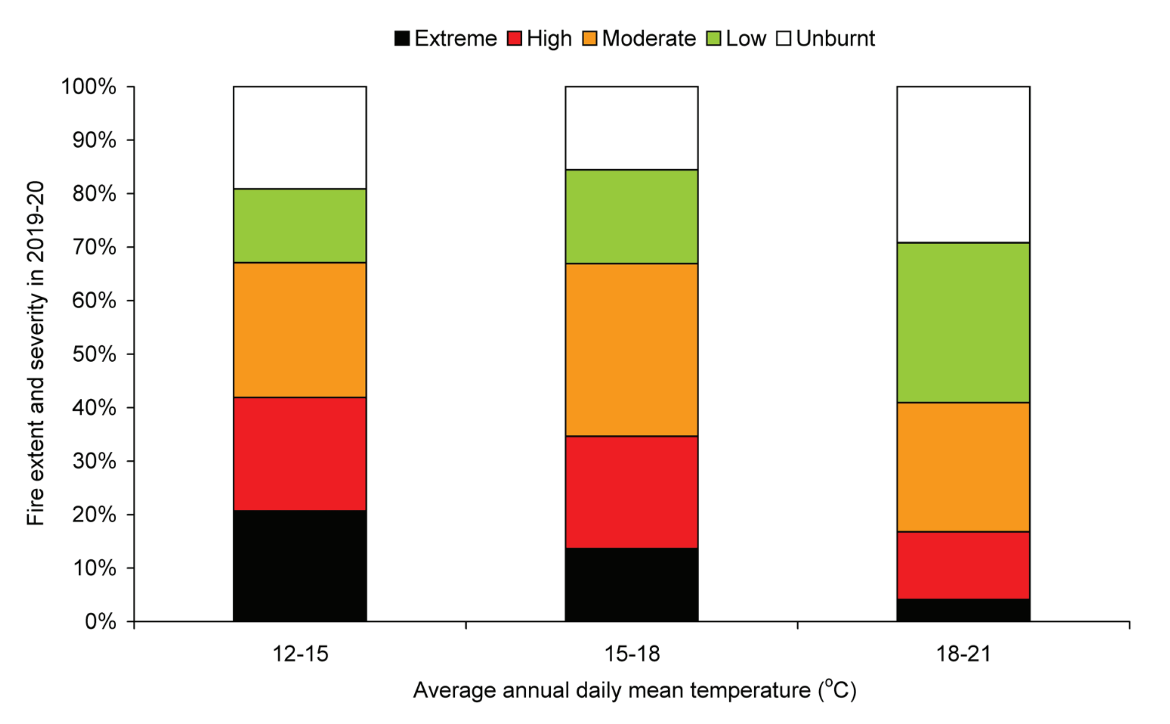

Figure 15. Fire extent and severity in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to temperature zones.

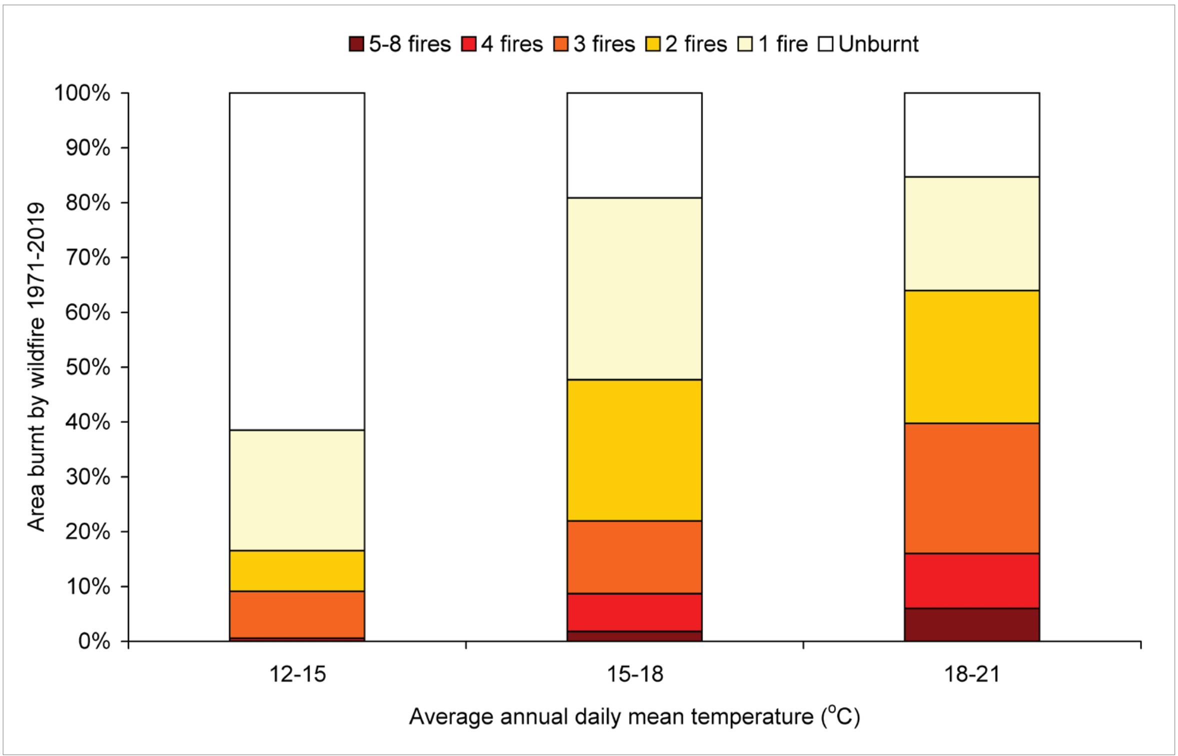

Figure 16. Frequency of wildfires in the Greater Blue Mountains World Heritage Area 1971-2019 in relation to temperature zones.

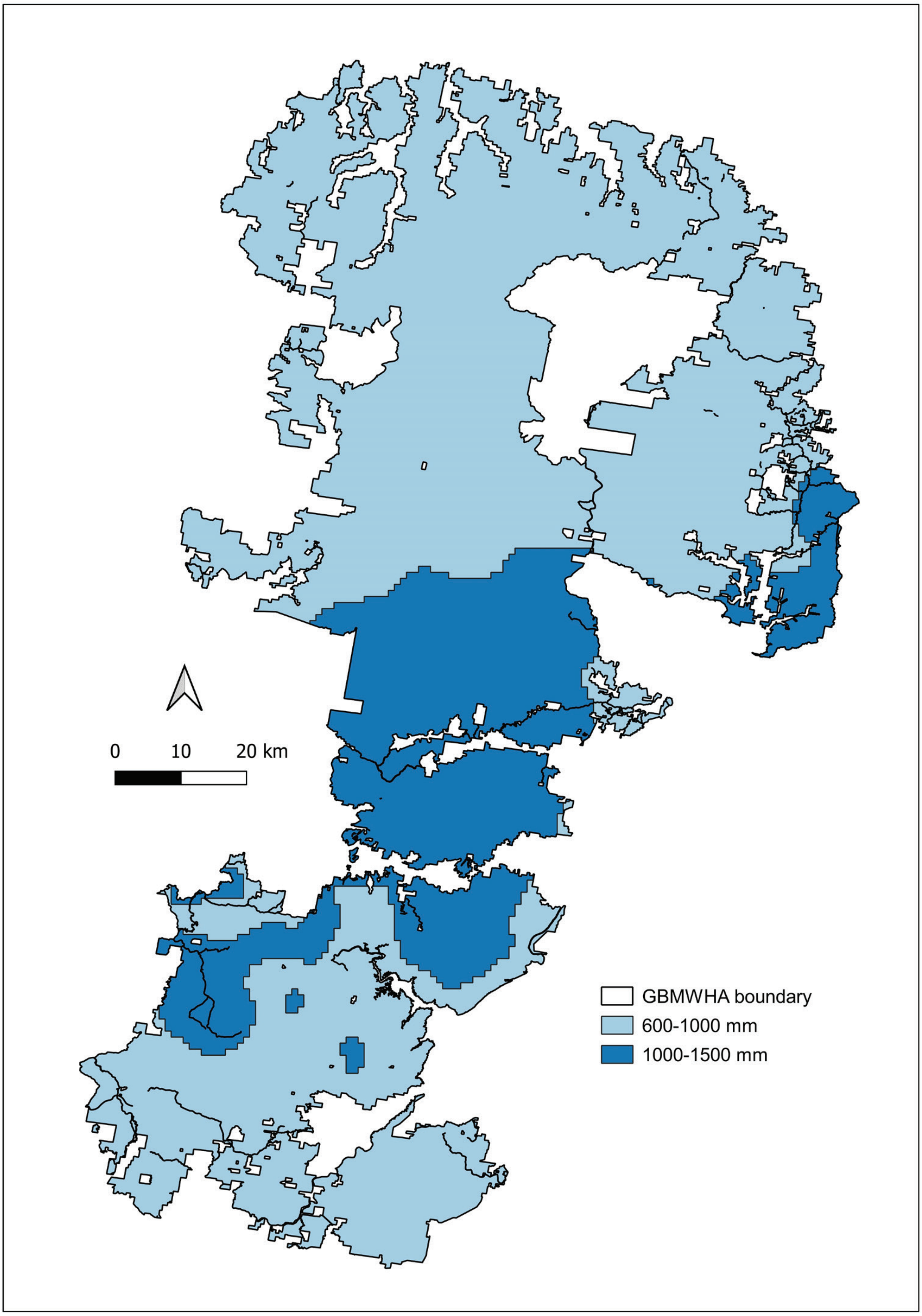

Figure 17. Rainfall zones in the Greater Blue Mountains World Heritage Area based on average annual rainfall, 1981-2010.

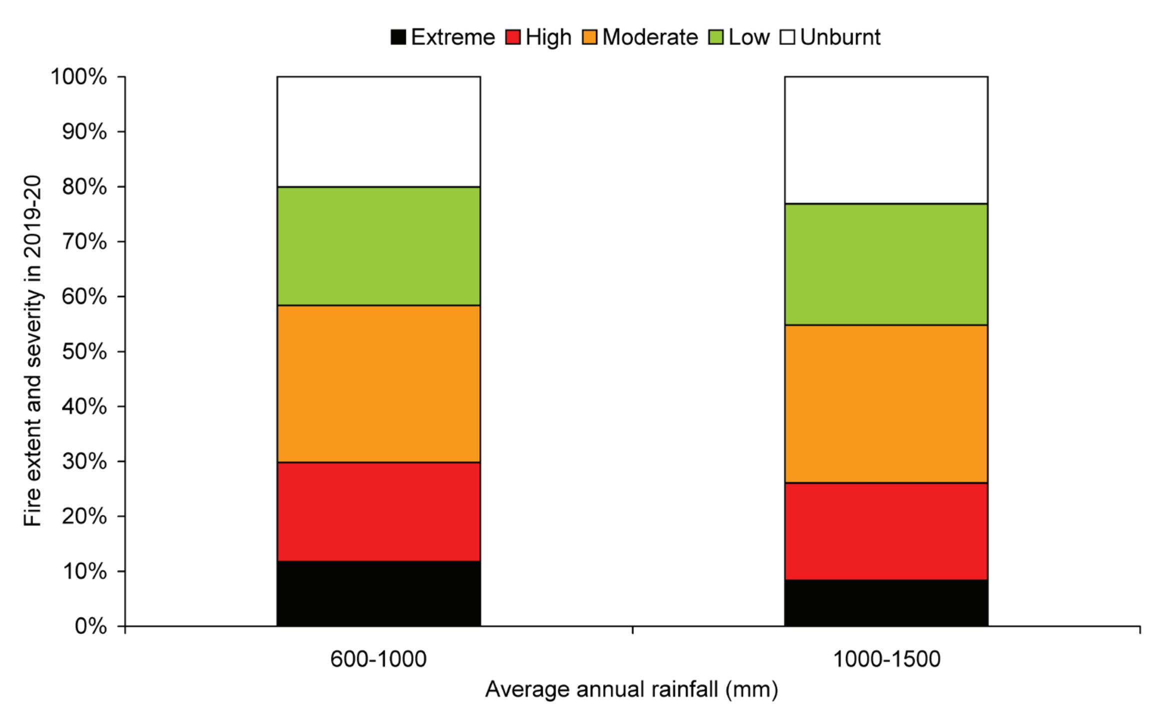

Figure 18. Fire extent and severity in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to rainfall zones.

hottest zone than in the two cooler zones, especially the 12-15°C zone, 62% of which had not been burnt by wildfire since at least 1971 (Fig. 16).

Rainfall

The Bureau of Meteorology distinguishes two average annual rainfall zones in the World Heritage Area, with the 600-1000 mm zone covering 74% of the area and the 1000-1500 mm zone covering 26% (Fig. 17). There was little difference between the two zones in relation to the extent and severity of the 2019-20 fires (Fig. 18).

Landscape type

A total of 19 landscape types have been distinguished in the World Heritage Area, based on Mitchell's (2002b) 'meso' groupings of Mitchell Landscapes (Fig. 19). Five of these (Cumberland, Karst, Moss Vale, Moss Vale Basalts and Pittwater) are minor landscape types with areas less than 330 ha (less than 0.03% of the World Heritage Area) and were not included in the analysis. The other 14 landscape types all have areas over 1500 ha (Table 2). Five of these (Bungonia, Kanangra, Northern Granites, Oberon and Oberon Basalts) are associated with the South Eastern Highlands Bioregion; the other nine are associated with the Sydney Basin Bioregion.

The impact of the 2019-20 fires varied widely between landscape types (Fig. 20). The most impacted landscapes, especially in terms of fire severity, were SEH Kanangra (98% burnt, 51% at high to extreme severity), SEH Bungonia (94% burnt, 66% at high to extreme severity) and SEH Northern Granites (82% burnt, 51% at high to extreme severity), all of which are in the South Eastern Highlands Bioregion in the south-west of the World Heritage Area (Fig. 19). The least impacted landscapes were SB Hunter (2% burnt, 0.04% at high to extreme severity) and SB Kerrabee (19% burnt, 8% at high to extreme severity), both of which are in the Sydney Basin Bioregion at the northern end of the World Heritage Area.

Only four of the 14 major landscape types had been subject to frequent wildfires before 2019-20, with at least 54% of their area burnt by two or more wildfires between 1971 and 2019 (Fig. 21). However, these include the two most extensive landscapes, SB Wollemi and SB Yengo, which together cover 68% of the World Heritage Area (Table 2, Fig. 19). The other 10 landscapes had been infrequently burnt, with at least 85% of their area unburnt or only burnt by one wildfire between 1971 and 2019 (Fig. 21). The infrequently burnt landscapes included the two landscapes least impacted by the 2019-20 fires (SB Hunter and SB Kerrabee) but they also included the three most severely burnt landscapes (SEH Kanangra, SEH Bungonia and SEH Northern Granites) (Fig. 20).

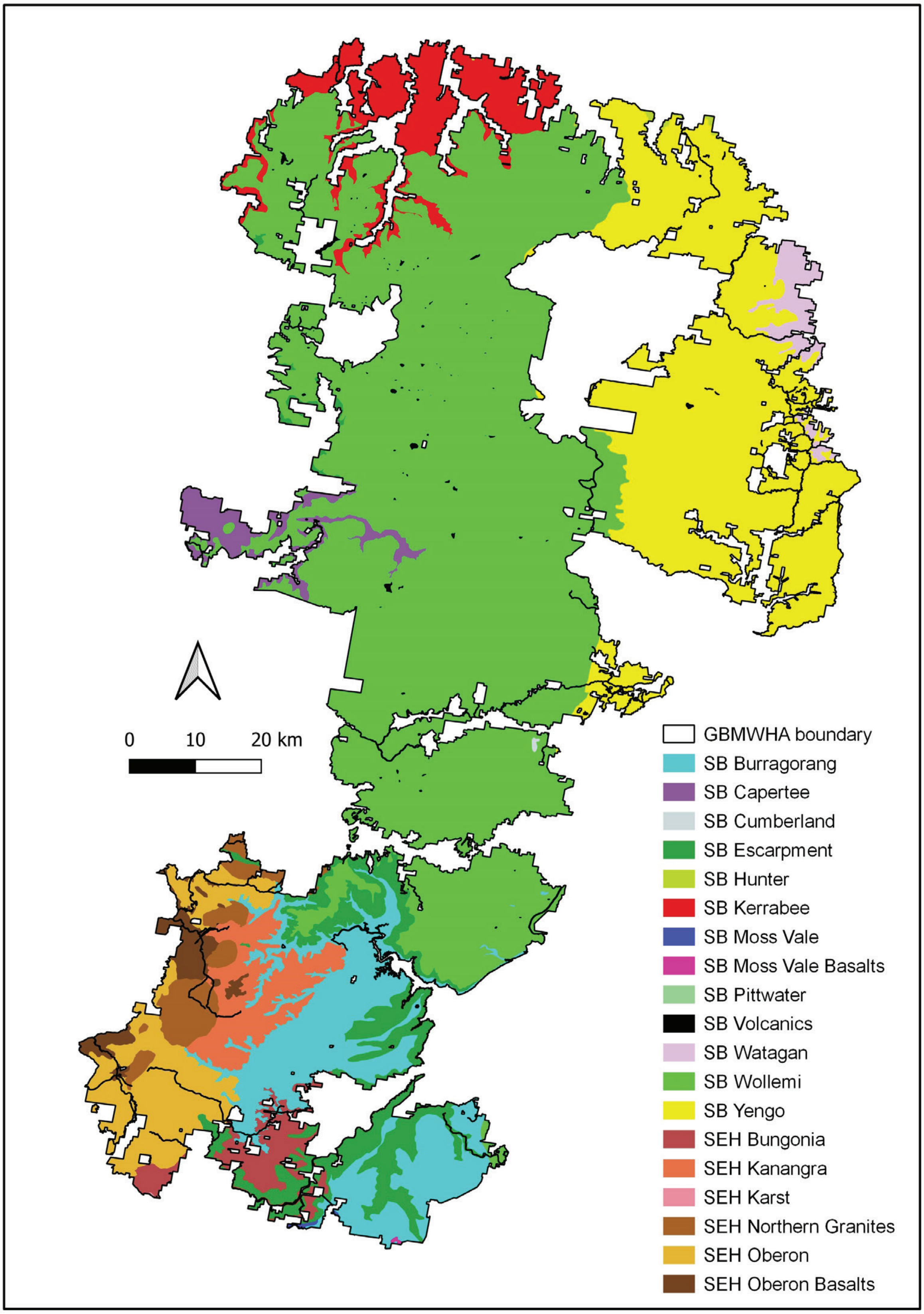

Figure 19. Geomorphological landscape types of the Greater Blue Mountains World Heritage Area. Each landscape type is a 'meso' grouping of Mitchell Landscapes (Mitchell 2002b). SB, Sydney Basin Bioregion; SEH, South Eastern Highlands Bioregion (Thackway and Cresswell 1995).

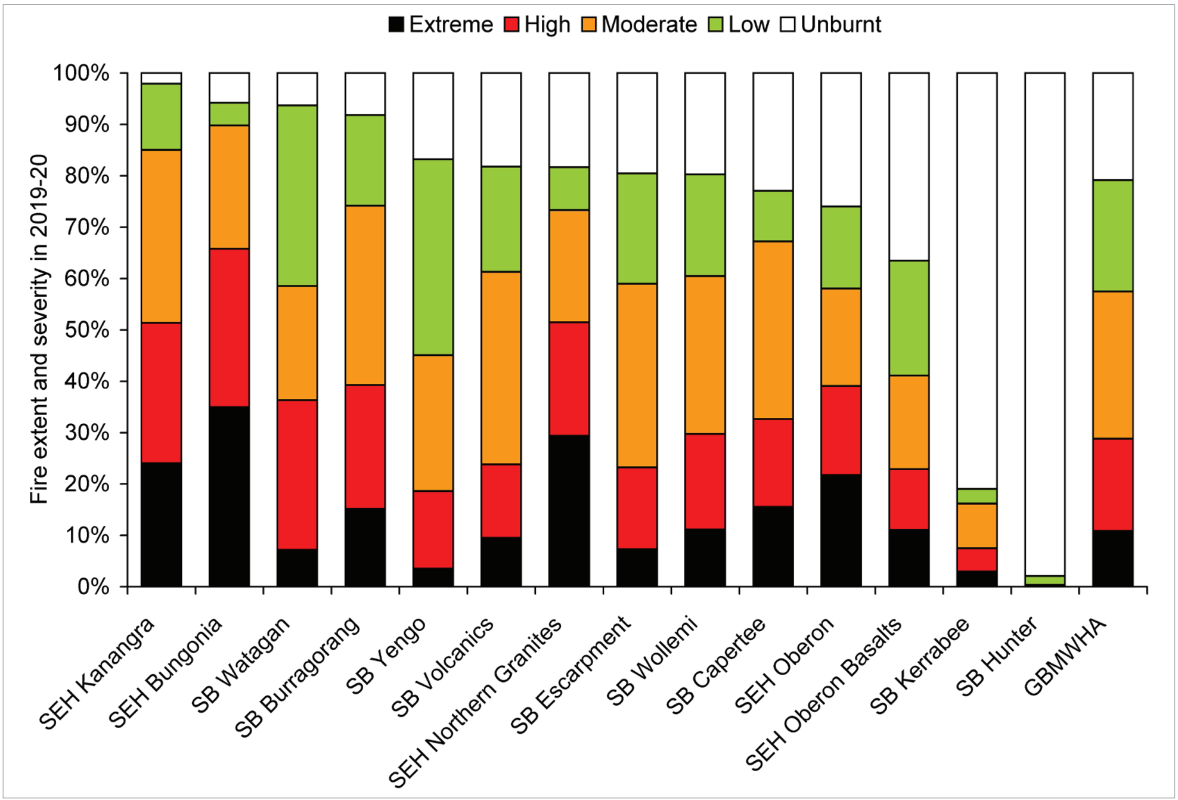

Figure 20. Fire extent and severity in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to landscape types, excluding types less than 330 ha in area.

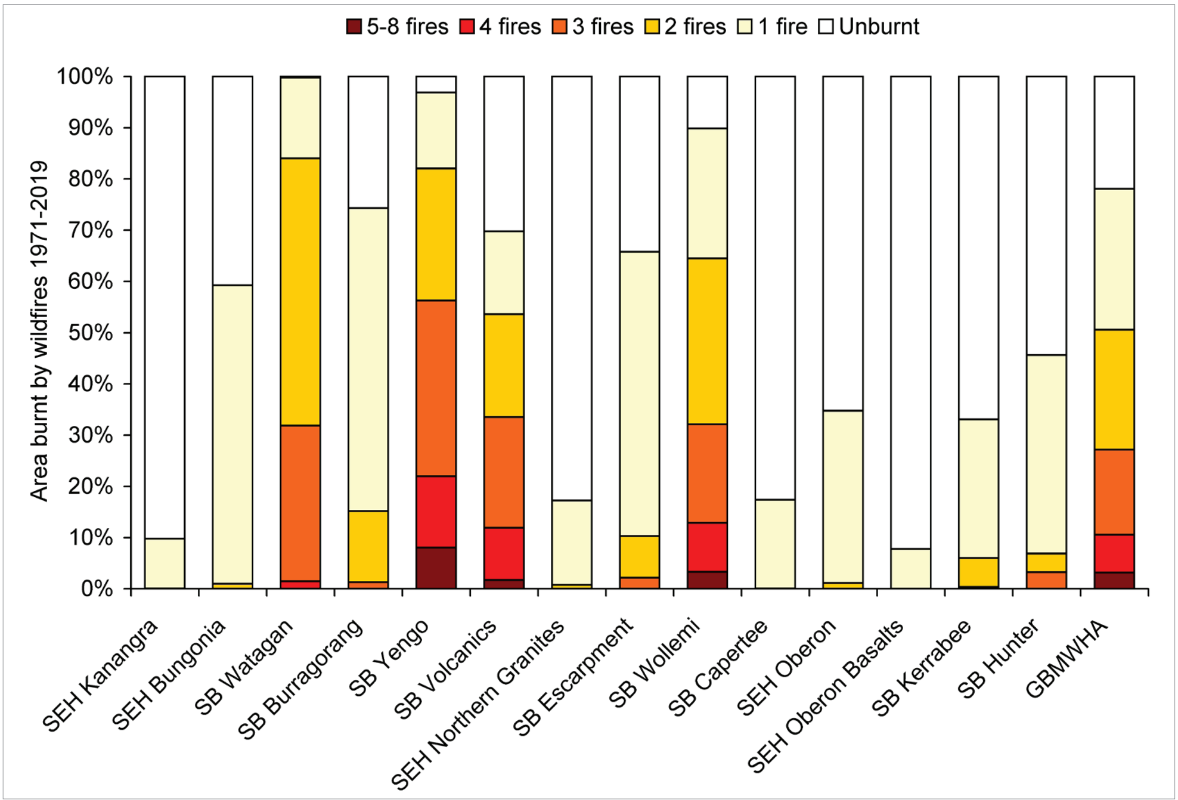

Figure 21. Frequency of wildfires in the Greater Blue Mountains World Heritage Area 1971-2019 in relation to landscape types, excluding types less than 330 ha in area.

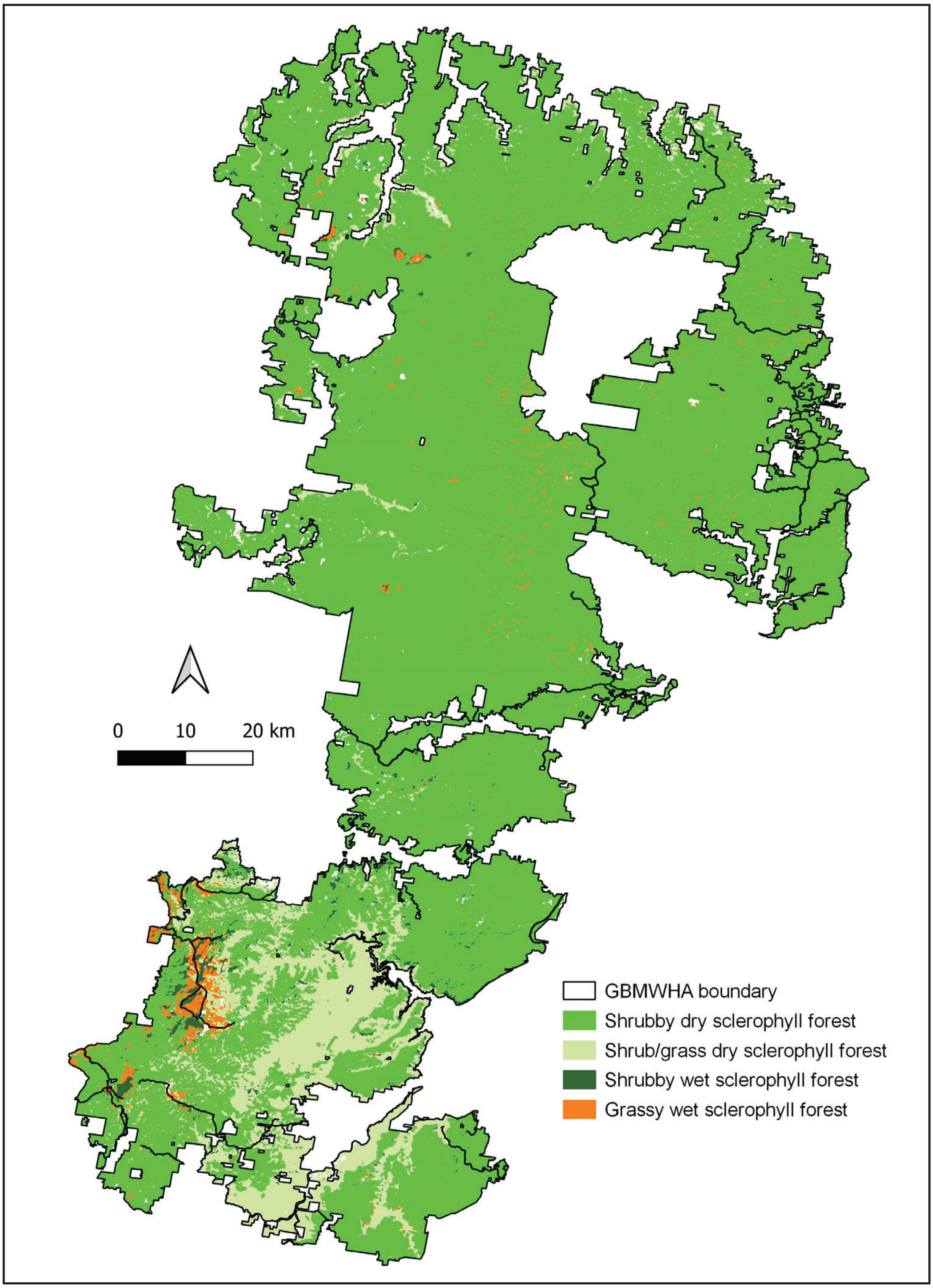

Figure 22. Major vegetation types of the Greater Blue Mountains World Heritage Area. Combined, the four types cover 90% of the World Heritage Area. The types are sub-formations of two NSW vegetation formations, dry sclerophyll forest and wet sclerophyll forest (Keith 2004).

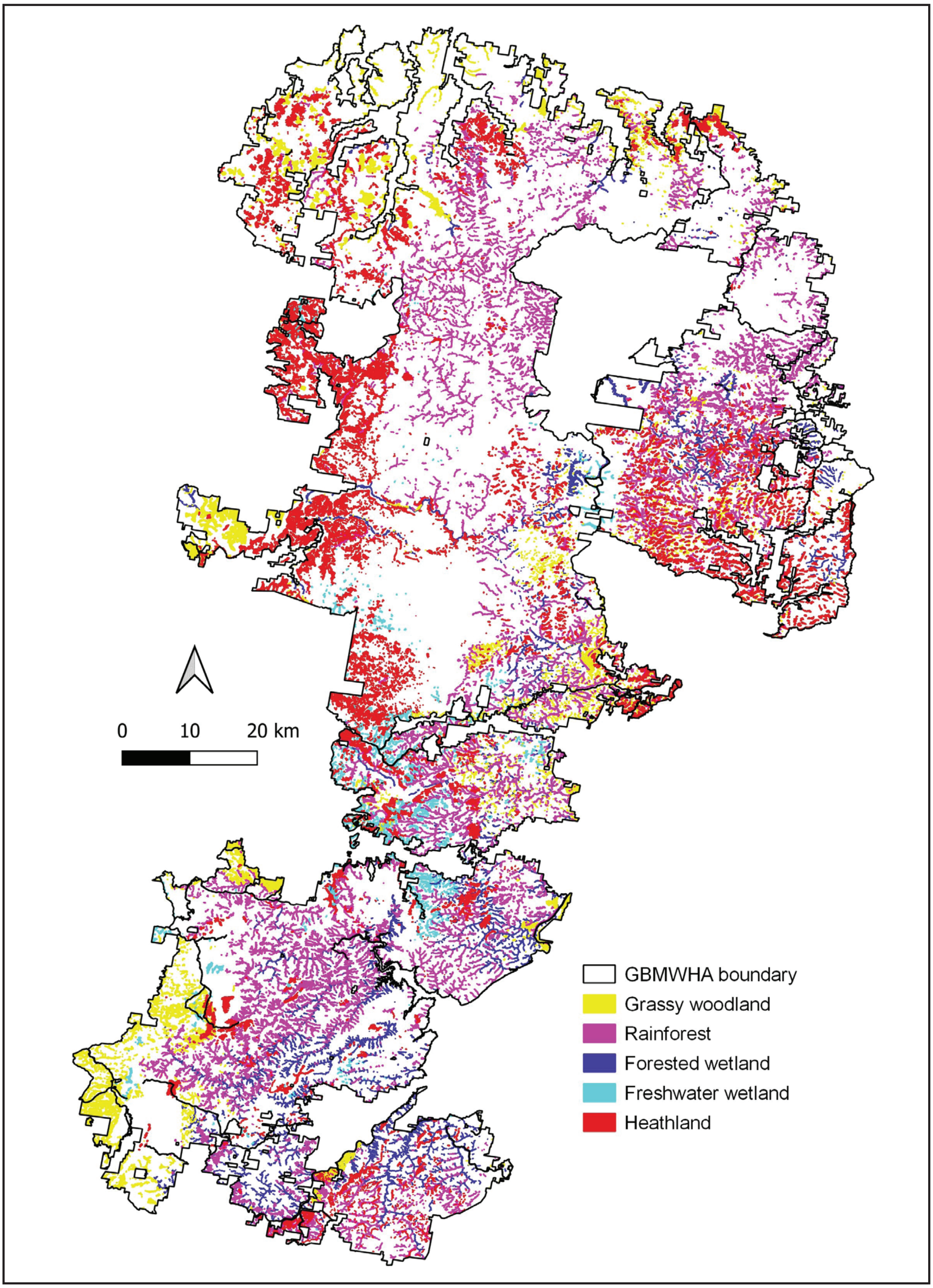

Figure 23. Minor vegetation types of the Greater Blue Mountains World Heritage Area, excluding two types less than 45 ha in area. The map shows the distribution of the vegetation types but gives a misleading impression of their area – combined, they cover only 10% of the World Heritage Area. All are NSW vegetation formations as distinguished by Keith (2004).

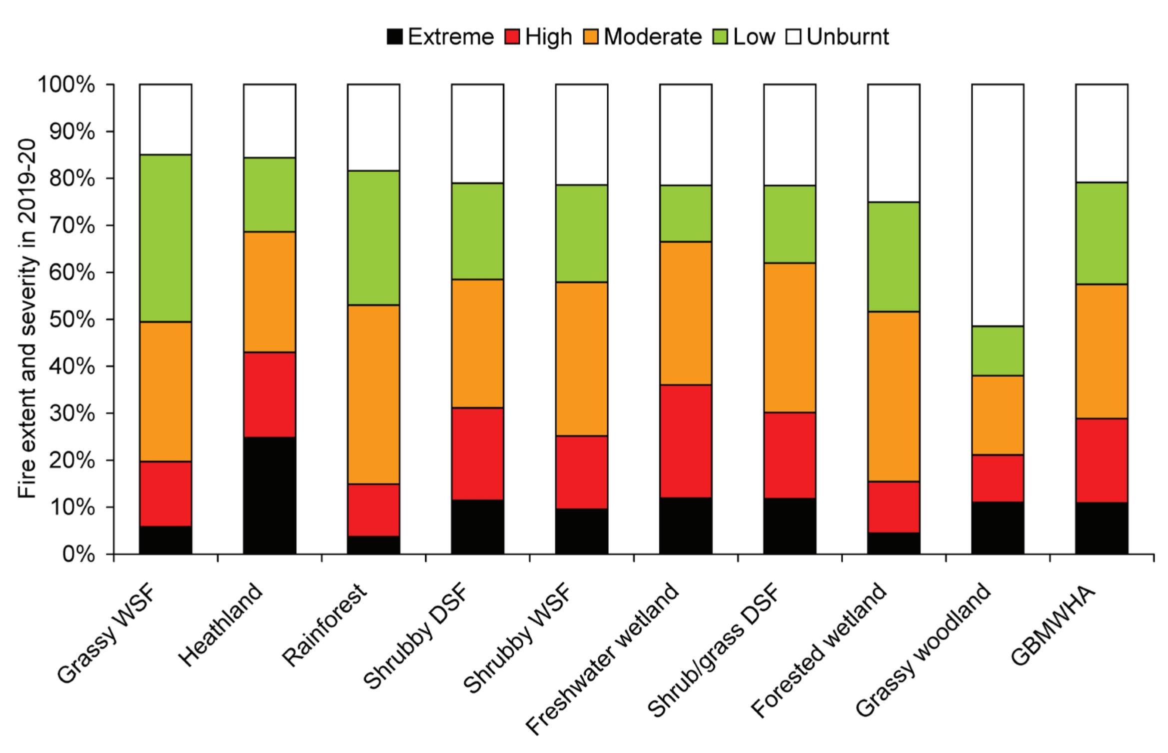

Figure 24. Fire extent and severity in 2019-20 in the Greater Blue Mountains World Heritage Area in relation to vegetation types, excluding two types less than 45 ha in area. DSF, dry sclerophyll forest; WSF, wet sclerophyll forest.

Vegetation type

Eleven vegetation formations and sub-formations (Keith 2004) occur in the World Heritage Area (Table 3). The vegetation consists predominantly of two formations, dry sclerophyll forest and wet sclerophyll forest (each represented by two sub-formations), which cover 90% of the World Heritage Area (Fig. 22). The other seven formations cover only 10% (Fig. 23). Areas with no native vegetation formation (such as rock outcrops, water bodies and cleared areas) cover 0.5%. Two formations, grassland and grassy semi-arid woodland, are very restricted, with a combined area of less than 45 ha, and were not included in the analysis.

The 2019-20 fires burnt a similar proportion (75-85%) of each vegetation type except for grassy woodland, which was only 48% burnt (Fig. 24). Fire severity was more variable. The most severely burnt types were heathland (43% burnt at high to extreme severity) and freshwater wetland (36% burnt at high to extreme severity). These two types lack trees and therefore the fire severity figures reflect impacts on the shrub layer rather than the tree layer as in the other types. The least severely burnt types were rainforest and forested wetland (both 15% burnt at high to extreme severity).

DISCUSSION

The area burnt annually by wildfires in Australian forests has been increasing each decade since the 1970s and especially since 2000 (Canadell et al. 2021). This trend is linked to increased fire weather risk as a result of anthropogenic climate change (Canadell et al. 2021, van Oldenborgh et al. 2021). However, the 2019-20 ‘Black Summer’ mega-fires in south-eastern Australia were a dramatic escalation of the trend, unmatched in the historical record (Abram et al. 2021). They were the culmination of three years of increasingly severe drought and heatwaves, with 2019 the hottest and driest year on record for Australia (Abram et al. 2021). The forest area burnt in the 2019-20 fires was at least three times the maximum area burnt in any of the 32 previous years (Canadell et al. 2021). The extent of the fires in the Greater Blue Mountains World Heritage Area was consistent with this general pattern – the area burnt was more than three times greater than for any of the previous 48 fire seasons (Fig. 5).

The 2019-20 fires were particularly extensive and severe in parts of the World Heritage Area that have rarely been burnt by wildfires in the past, notably in areas over 1000 m with average annual daily mean temperatures less than 15^{o}C in the South Eastern

Landscape type	Area (ha)	% of GBMWHA	Description
SB Burragorang	88,878	8.2	Plateaus, ridges, slopes and gorges on Triassic sandstone, shale, conglomerate and siltstone at 50-850 m
SB Capertee	16,957	1.6	Wide valleys, low rolling hills and debris slopes on Permian sandstone, conglomerate, shale and coal at 500-1000 m
SB Escarpment	53,307	4.9	Steep dissected slopes descending from Triassic rocks into Permian conglomerate, shale and sandstone at 250-1000 m
SB Hunter	1,532	0.1	Undulating lowlands fringing the Hunter Valley on Permian sandstone, conglomerate, shale and coal at 40-300 m
SB Kerrabee	51,185	4.7	Stony plateaus, ridges, slopes, escarpments, valleys and gorges on Permian, Triassic and Jurassic sandstone, shale and conglomerate at 150-750 m
SB Volcanics	3,310	0.3	Undulating to flat peaks and short ridges at 700-1300 m on Tertiary basalt caps above Triassic sandstone, also circular volcanic vents (diatremes) at various elevations
SB Watagan	12,901	1.2	Steep dissected ranges and small plateaus on Triassic sandstone, shale, tuff and claystone at 30-300 m
SB Wollemi	532,213	49.2	Plateaus, ridges, slopes, escarpments, gorges and valleys on Triassic sandstone, conglomerate, siltstone and shale at 100-1100 m
SB Yengo	205,300	19	Plateaus, ridges, slopes, escarpments, gorges and valleys at 0-400 m on Triassic sandstone, shale and conglomerate, also Quaternary and recent sands
SEH Bungonia	15,654	1.4	Plateaus and gorges on Devonian quartz porphyry and small areas of granite at 600-900 m
SEH Kanangra	27,860	2.6	Plateau on Devonian sandstone, siltstone, shale and conglomerate at 1100-1250 m
SEH Northern Granites	17,844	1.6	Undulating to steep hills and swampy plateau on Carboniferous granite and granodiorite at 650-1400 m
SEH Oberon	44,236	4.1	Low hills on plateau at elevations over 1000 m on Silurian and Ordovician slate, phyllite, sandstone and interbedded volcanics
SEH Oberon Basalts	10,863	1	Low rises and hills on Tertiary basalt at 950-1250 m

Table 2. Major landscape types of the Greater Blue Mountains World Heritage Area (Mitchell 2002b). Five minor types with areas <330 ha (<0.03% of the World Heritage Area) are not included. SB, Sydney Basin Bioregion; SEH, South Eastern Highlands Bioregion (Thackway and Cresswell 1995).

Vegetation type	Area (ha)	% of GBMWHA
Shrubby dry sclerophyll forest	631,029	58.3
Shrub/grass dry sclerophyll forest	148,850	13.7
Shrubby wet sclerophyll forest	55,169	5.1
Grassy wet sclerophyll forest	136,769	12.6
Grassy woodland	20,195	1.9
Grassy semi-arid woodland	4	0.0003
Rainforest	26,998	2.5
Forested wetland	13,685	1.3
Freshwater wetland	4,463	0.4
Heathland	39,828	3.7
Grassland	40	0.004

Table 3. Vegetation types of the Greater Blue Mountains World Heritage Area. Each type is a NSW vegetation formation or sub-formation as distinguished by Keith (2004).

Highlands Bioregion in the south-west of the World Heritage Area, especially the SEH Kanangra, SEH Bungonia and SEH Northern Granites landscapes. It is likely that the exceptionally dry, hot conditions of 2019 dried out the normally moist fuel loads in these fire-resistant parts of the World Heritage Area, making them far more susceptible to wildfires than usual.

The 2019-20 fires burnt an unprecedented proportion (over 23%) of the temperate forests of south-eastern Australia (Boer et al. 2020). However, a comparison of the 2019-20 fires and previous large fires (>2500 ha) since 1988 in NSW and Victoria (Collins et al. 2021) has shown that the 2019-20 fires were not proportionally more severe than previous wildfires, especially in the dominant dry sclerophyll forest communities. Collins et al. (2021) reported that fire severity within burnt areas of south-eastern Australia between 1988 and 2020 has averaged 13% extreme, 30% high, 22% moderate and 35% low. By comparison, fire severity in the burnt areas of the World Heritage Area in 2019-20 was 14% extreme, 23% high, 36% moderate and 27% low. The ratio of high-extreme severity fire to low-moderate severity fire in the World Heritage Area in 2019-20 (37% vs 63%) was lower than the long-term average for major wildfires in south-eastern Australia (43% vs 57%). The 2019-20 fires in the World Heritage Area were not proportionally more severe than previous fires.

However, the 2019-20 fires in the World Heritage Area, and south-eastern Australia generally, because they were so extensive, resulted in an unprecedented area being burnt at high-extreme severity. The area of forest burnt at this level of severity in south-eastern Australia in 2019-20 (about 1.8 million ha) accounted for about 44% of the total area burnt by high-extreme severity fire between 1988 and 2020 (Collins et al. 2021).

An example of how higher severity fires can have a disproportionate impact on fauna populations is the Greater Glider (*Petauroides volans*). In the Greater Blue Mountains World Heritage Area, the 2019-20 fires burnt 84% of all known locations of the Greater Glider (Smith and Smith 2022a). The species was also impacted by the severe drought and heatwaves that preceded the fires. The impact was markedly worse in study sites burnt at high-extreme severity, where the species was eliminated, whereas it was able to persist in sites burnt at low-moderate severity. The impact in areas burnt at higher severity was largely responsible for an estimated overall decline of 61% in the Greater Glider population in the World Heritage Area in 2019-20. The impacts of higher severity fires on fauna may be prolonged. For example, Franklin et al. (2022) reported impacts of high-extreme severity fires on forest birds in dry sclerophyll forests in the World Heritage Area that were still evident 16 years post-fire, indicating persistent fire effects on fauna habitat.

The proportion of burnt areas burnt at high-extreme severity in the World Heritage Area in 2019-20 varied in relation to prescribed burn history. The proportion was lowest in areas that had been burnt by prescribed burns since 2014, highest in areas burnt between 1999 and 2014, and intermediate in areas burnt between 1971 and 1999 or unburnt by prescribed burns since at least 1971 (Fig. 10). This is consistent with findings from other studies that a rapid fuel accumulation rate generally limits the effectiveness of prescribed burns in reducing fire hazard to a post-treatment period of 2-6 years (Raison et al. 1983, Fernandes and Botelho 2003, Boer et al. 2009). It is also consistent with indications that fire hazard reaches a peak in forests burnt 6-12 years previously and then declines to lower levels in long unburnt forests (Storey et al. 2016, Dixon et al. 2018). It is likely that the peak in fire hazard is a result of the shrub layer reaching a maximum density at around 10 years post-fire before thinning out as the shrubs senesce.

Hislop et al. (2020) have assessed the effectiveness of recent (2015-19) prescribed burns in mitigating the effects of the 2019-20 mega-fires. They found a significant reduction in fire severity for 48% of the burns but no significant effect for 52% of the burns. Burns in 2019 were more effective (66% of burns reduced fire severity) than burns in 2015 (42% of burns reduced fire severity). It was unclear, however, whether these effects would make wildfires easier to control under extreme conditions, when wildfires are driven mainly by the weather, irrespective of fuel loads (Hislop et al. 2020, Nolan et al. 2021).

The proportion of burnt areas burnt at high-extreme severity in the World Heritage Area in 2019-20 also varied in relation to the frequency of previous wildfires. The proportion was highest in areas unburnt by wildfires since at least 1971 and decreased progressively with increasing frequency of previous wildfires (Fig. 7).

In a study of fire history in the World Heritage Area between 1982 and 2014, Barker and Price (2018) found a relationship between fire severities in consecutive fires, with a crown (extreme severity) fire more than twice as likely after a previous crown fire than after a previous understorey (low severity) fire. This effect, which was most pronounced 10-17 years post-fire, was attributed to more vigorous shrub and sapling regrowth after higher-severity fires (Williams et al. 2012, Clarke et al. 2015, Gordon et al. 2017), resulting in denser vegetation, higher fuel loads and an increased probability of future crown fires in the medium term.

Barker and Price (2018) suggested that this positive feedback effect between fires, where extreme-severity fire increases the likelihood of subsequent extreme-severity fire, has the potential for causing a runaway effect where some areas experience a regime of repeated severe fires and a sustained increase in vegetation density that makes them more prone to extreme-severity fire. The present study shows no evidence of such an effect. The parts of the Greater Blue Mountains World Heritage Area that have been subject to more frequent wildfires in the past were less severely burnt in the 2019-20 fires, not more severely burnt. The severity patterns of previous wildfires were not analysed in this study. There may be areas with a history of repeated severe fires that makes them more prone to extreme-severity fire. However, the fire severity pattern in 2019-20 suggests that such areas are of limited extent. A more general pattern was reduced fire severity in areas that have been burnt repeatedly by wildfires, i.e. repeated burning resulting in a reduction in fuel hazard not an increase.

In Californian forests, Steel et al. (2015) found evidence of a gradation between 'fuel-limited' fire regimes, characterised by frequent lower-severity wildfires, and 'climate-limited' fire regimes, characterised by infrequent, more severe wildfires. In forest types with fuel-limited or intermediate fire regimes, there was strong evidence that fire severity increased as fire frequency decreased. Similar patterns were evident in the present study, with a similar inverse relationship between wildfire severity and frequency, and a similar gradation in the World Heritage Area between landscape types characterised by infrequent but severe wildfires (notably the SEH Kanangra, SEH Bungonia and SEH Northern Granites landscapes) and landscape types characterised by frequent but generally less severe wildfires (notably the SB Wollemi and SB Yengo landscapes, which cover two-thirds of the World Heritage Area).

The vegetation type least impacted by the Black Summer fires in the World Heritage Area was grassy woodland, of which 48% was burnt. It was the only major vegetation type that was markedly less extensively burnt than the 79% burnt in the World Heritage Area as a whole (Fig. 24). Grassy woodland covers less than 2% of the World Heritage Area (Table 3) but it is an important fauna habitat that supports a suite of threatened birds of considerable conservation concern, the 'declining woodland birds' (Bennett and Watson 2011, Smith et al. 2019). The relatively limited impact of the Black Summer fires on this habitat in the World Heritage Area is good news. However, grassy woodland vegetation was extensively burnt outside the World Heritage Area in 2019-20 (Gallagher et al. 2021, Collins et al. 2021, Godfree et al. 2021).

The ability of fauna populations to survive and recover after fires is dependent to a large degree on the presence of unburnt or lightly burnt patches within the fire boundary that serve as fauna refuges (Smith 1989, Robinson et al. 2013, 2014). These fauna refuges are often associated with sheltered, moist locations in gullies, which are rarely if ever burnt, even when there have been extensive fires in the surrounding landscape (Leonard et al. 2014). In the World Heritage Area, two vegetation types associated with gullies, rainforest and shrubby wet sclerophyll forest, are particularly important in providing unburnt fauna refuges in major fires (Hammill and Tasker 2010, Smith et al. 2019).

The amount of vegetation left unburnt within a fire boundary is typically a small but variable proportion of the total fire area (<1-22%; Robinson et al. 2016), depending on factors such as topography, vegetation type and fire severity (Leonard et al. 2014). In the 2019-20 Black Summer fires in the World Heritage Area, about 6% of the vegetation within the fire boundary was unburnt (based on the FESM Version 3 fire extent and severity mapping within the fire boundary as mapped by NSW National Parks and Wildlife Service). This is a low percentage but higher than after the 2009 'Black Saturday' bushfires in Victoria, when less than 1% of the area within the fire boundary was unburnt (Leonard et al. 2014). However, the two vegetation types that have traditionally provided unburnt fire refuges in the World Heritage Area were both heavily impacted by the Black Summer fires, with 82% of the rainforest burnt and 79% of the shrubby wet sclerophyll forest (Fig. 24). These wetter vegetation types also normally play a role as natural firebreaks controlling the spread of wildfires. Because these vegetation types were abnormally dry and more fire-prone in 2019-20, the reduction in natural firebreaks may have contributed to the fires being exceptionally extensive.

Rainforest grows in very moist, sheltered locations and is rarely, if ever, burnt. The Black Summer fires had an unprecedented impact on rainforest vegetation not only in the World Heritage Area but also across south-eastern Australia, resulting in much concern about the threat of widespread regeneration failure and landscape-scale decline in this fire-sensitive ecosystem (Gallagher et al. 2021, Collins et al. 2021, Godfree et al. 2021), although a recent study by Baker et al. (2022) suggests that most rainforest plants may be more fire-resilient than expected. The particular vulnerability of rainforest bird communities to fire has become evident since the fires, compared with bird communities in more fire-prone ecosystems (Lee et al. 2022).

Shrubby wet sclerophyll forest is not as fire-free and fire-sensitive as rainforest but it is rarely burnt, except under unusually dry conditions and extreme fire weather. It is usually an important provider of unburnt fire refuges (Berry et al. 2015). The Black Summer fires in the World Heritage Area were exceptional in that they had a similar impact on shrubby wet sclerophyll forest in sheltered gullies (79% burnt, 25% at high to extreme severity; Fig. 24) as on shrubby dry sclerophyll forest on exposed ridges and slopes (79% burnt, 31% at high to extreme severity). It is worth noting, however, that Robinson et al. (2016) found that after the 2009 Black Saturday fires in Victoria, contrary to predictions, shrubby wet sclerophyll forest in gullies, even when burnt, still had value for maintaining bird communities and facilitating their recovery.

The 2019-20 Black Summer mega-fires in the Greater Blue Mountains World Heritage Area had a number of exceptional features: their unprecedented scale, the large area burnt at high to extreme severity, their impact on higher elevation landscapes that are rarely burnt, and their impact on moist vegetation types in gullies that normally play an important role in providing unburnt fire refuges and natural firebreaks. The long-term impact on fauna and flora is of great concern. Gradual recovery is likely if the Black Summer fires were a very rare event that will not recur for many decades. However, a change in the fire regime to more frequent, more extensive, more severe wildfires as a result of climate change has long been predicted (Cary and Banks 2000, Bradstock 2010, Hammill and Tasker 2010, Clarke and Evans 2019). This would make suppression and containment of future wildfires increasingly difficult. If the Black Summer fires are a harbinger of this change, the long-term impact on the Greater Blue Mountains World Heritage Area environment and biota would be catastrophic.

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