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Responding to the biodiversity impacts of a megafire: A case study from south-eastern Australia's Black Summer

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Abstract

Aim: Megafires are increasing in intensity and frequency globally. The impacts of megafires on biodiversity can be severe, so conservation managers must be able to respond rapidly to quantify their impacts, initiate recovery efforts and consider conservation options within and beyond the burned extent. We outline a framework that can be used to guide conservation responses to megafires, using the 1.5 million hectare 2019/2020 megafires in Victoria, Australia, as a case study.

Location: Victoria, Australia.

Methods: Our framework uses a suite of decision support tools, including species attribute databases, ~4,200 species distribution models and a spatially explicit conservation action planning tool to quantify the potential effects of megafires on biodiversity, and identify species-specific and landscape-scale conservation actions that can assist recovery.

Results: Our approach identified 346 species in Victoria that had >40% of their modelled habitat affected by the megafire, including 45 threatened species, and 102 species with >40% of their modelled habitat affected by high severity fire. We then identified 21 candidate recovery actions that are expected to assist the recovery of biodiversity. For relevant landscape-scale actions, we identified locations within and adjacent to the megafire extent that are expected to deliver cost-effective conservation gains.

Main conclusion: The 2019/2020 megafires in south-eastern Australia affected the habitat of many species and plant communities. Our framework identified a range of single-species (e.g., supplementary feeding, translocation) and landscape-scale actions (e.g., protection of refuges, invasive species management) that can help biodiversity recover from megafires. Conservation managers will be increasingly required to rapidly identify conservation actions that can help species recover from megafires, especially under a changing climate. Our approach brings together commonly used datasets (e.g., species distribution maps, trait databases, fire severity mapping) to help guide conservation responses and can be used to help biodiversity recover from future megafires across the world.

KEYWORDS

biodiversity, fire management, fire severity, Megafire, prioritization, spatial conservation action planning, species distribution models, threatened species, wildfire

1 | INTRODUCTION

The 21st century has been termed the age of the megafire—very large, severe wildfires (i.e., hundreds of thousands to millions of hectares) that demand considerable resources to suppress and recover from (Stephens et al., 2014). Recent examples include the 2019 Amazon fires (Barlow et al., 2020; Brando et al., 2020), the 2020 Californian fires and Australia's 2019/2020 'Black Summer' (Nolan et al., 2020). Stoked by climate change (Abatzoglou & Williams, 2016; Bradstock et al., 2014), megafires are expected to become more frequent in coming years (Bowman et al., 2020; Flannigan et al., 2013). Many species thrive in fire-prone landscapes and are able to easily take advantage or recover from fires (Bowman et al., 2020; Fontaine & Kennedy, 2012; Nimmo et al., 2019); however, as megafires increase in frequency across the globe, the relationship between biodiversity and fire is changing (Kelly et al., 2020). Megafires can reshape biodiversity (Williams, 2013) by causing mass mortality and the loss and removal or redistribution of short-term (e.g., food resources, shelter from predators) and long-term (e.g., tree hollows, landscape-scale habitat configuration) resources across vast areas (He et al., 2019). Megafires are significant because their scale and severity can remove access to food and shelter for species across large swathes of habitat including patches that would normally act as fire refuges, increasing the likelihood of burning most of a species' range. Such extensive fires present a clear extinction risk for species already imperilled, those with naturally narrow distributions, and those adapted to ecosystems without a history of regular fire (Ward et al., 2020). Recently, megafires have also threatened species that are historically adapted to, and are able to take advantage of fire disturbed areas (Jones et al., 2016). Altered fire regimes, including the increased incidence of megafires, threaten more than 4,400 species with extinction across almost every continent on the globe (Kelly et al., 2020). Megafires therefore present conservation managers with an important challenge over the coming century (McKenzie et al., 2004).

This century's megafires have, and will, burn across landscapes massively altered by humans (Bowman et al., 2020). Megafires can exacerbate the impact of other stressors (e.g., climate change, land-use change; Kelly et al., 2020), propelling species towards extinction (Ward et al., 2020). For example, invasive mammalian predators—which are responsible for 58% of modern reptile, mammal, and bird extinctions (Doherty et al., 2016)—can exacerbate the biodiversity impacts of fire (Doherty et al., 2015; McGregor et al., 2014). For example, predation by mammalian predators of threatened fauna is intensified post-fire by the reduction of vegetation cover (Conner et al., 2011; Hradsky, 2019) while overgrazing or browsing by introduced herbivores can prevent post-fire vegetation recovery (Forsyth et al., 2012; Midgley et al., 2010). Similarly, the patch-scale effects of megafires can be made worse in fragmented landscapes by limiting recolonization (Cochrane, 2001), which can impede the recovery of species with limited dispersal ability. These effects can also spill over into adjacent unburned refuges (Robinson et al., 2013). Megafires can also cause mass erosion events and debris flow, which may increase stream turbidity and reduce dissolved oxygen in streams within and distant from burned areas, compromising the habitats of aquatic and semiaquatic species (Nyman et al., 2011). The outcomes of these altered interactions at the unprecedented scale of megafires remain largely unknown. Recovery actions following megafires therefore need to address co-occurring threats that could be exacerbated by these large disturbances (Geary et al., 2019), especially in the weeks to months post-fire.

Rapidly quantifying the potential impacts of megafires and enacting conservation responses is emerging as a key action for protecting biodiversity and facilitating recovery in fire-prone ecosystems globally (Kelly et al., 2020). Quickly implementing conservation actions post-megafire can reduce the likelihood of species going locally or globally extinct, as some recovery actions are most needed, and most effective in the weeks to months post-fire (e.g., protection of unburnt patches and invasive species management; Dickman et al., 2020). For instance, the damaging effects of invasive species, such as predators, can be greatest in the weeks post-fire (Leahy et al., 2016). Identifying and enacting rapid megafire response and recovery actions requires analyses that quantify the impact of megafires (e.g., estimating the extent of a species range burnt by fire to identify heavily affected species), and the use of databases to identify and prioritize candidate recovery actions, as well as locations or species that most need these actions. These practices will become increasingly important as traditional fuel management methods are less able to reduce megafire impacts (Clarke et al., 2020). While the true impacts of megafires on biodiversity cannot be known until post-fire surveys are carried out and will be influenced by interactions with future fire regimes, rapid conservation responses will increasingly be required to reduce the likelihood of extinctions. Standardized frameworks that facilitate rapid analysis of impacts and recovery planning in megafire-prone regions across the globe can assist greatly with this (Wintle et al., 2020), particularly given the suite of actions available are likely to be applicable to a range of ecosystems and rapid intervention may be required to maximize success of actions. This can also incentivize governments to invest in responses to biodiversity impacts alongside social and infrastructure impacts. However, no such framework currently exists in the conservation literature (but see Robichaud et al., 2009; White & Long, 2019), despite megafires increasing their effects on biodiversity globally (Kelly et al., 2020).

To address this gap, we outline a framework for quantifying the potential effects of a megafire on a range of biodiversity values and prioritizing a conservation response. We illustrate this with a case study—the biodiversity response and recovery for the 2019/2020 'Black Summer' fire season within the south-eastern Australian state of Victoria. Over 1.5 million ha of largely contiguous native forest, woodland and shrubland burned in this region, much of which provides habitat for rare and/or threatened plant and animal species. We begin by summarizing the extent and severity of the 2019/2020 fire season in Victoria. Next, we measure the extent of overlap of the distribution of ~4,200 taxa and plant communities with the extent of the megafires to identify species whose habitat was heavily affected by fires and are therefore of conservation concern. Then, we identify actions that are important for the recovery of threatened species and communities, and use a spatial conservation action planning tool to identify landscape-scale actions that will contribute most to the post-fire recovery of species. We explain how the outputs of these analyses informed immediate and practical recovery actions for biodiversity, as well as decisions to aid longer-term recovery. Finally we outline how this framework, type of data and information can be used by conservation practitioners to rapidly understand and respond to the biodiversity impacts of future megafires across the globe.

2 | METHODS

2.1 | Study region and the 2019/2020 megafires

The study region for this paper covers the Victorian extent of the 2019/2020 Australian megafires as of 20 April 2020 (~1.5 million ha burn extent; Figure 1). The region has a temperate climate and consists of large tracts of contiguous forest, woodlands and alpine areas interspersed with patches of agricultural land. Wildfire is a regular and periodic disturbance affecting the region, with typical fire return intervals for the region generally varying depending on the part of the region and the forest type considered—from every 5–20 years in lower elevation dry eucalypt forest to a fire return interval

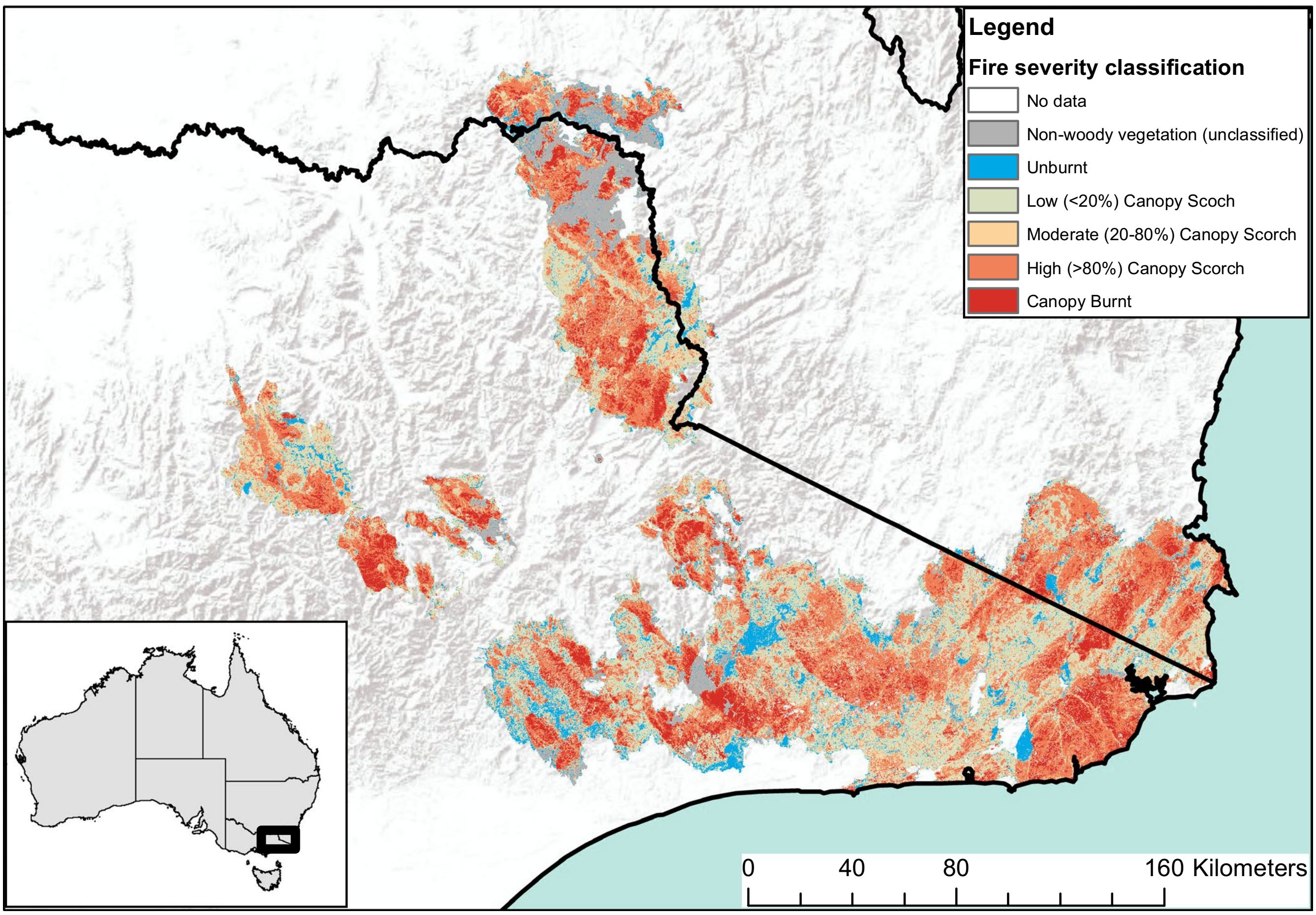

FIGURE 1 Map of the severity of the 2019/2020 eastern Victorian megafires. Five fire severity classes are mapped based on the horizontal coverage of different fire impacts on plant canopies: unburnt (<10% of the understorey burnt); low canopy scorch (<20% scorch); moderate canopy scorch (20%–80% scorch); high canopy scorch (>80% scorch); and canopy burnt (>20% of foliage consumed). Inset: Location of focal area in Victoria, Australia. Base map source: ESRI

over 100 years in more mesic eucalypt and rain forests (Murphy et al., 2013). Prior to 2000, the rolling 20-year average annual wildfire area oscillated around 100,000 ha per year (DELWP, 2020). As of 2020, this has tripled to approximately 300,000 ha (DELWP, 2020). This reflects the substantial amount of fire activity during the 2000–2020 period, during which there was a cumulative total of 6.2 million ha burned across eight major (>150,000 ha) wildfires; a quarter of this 20-year total is represented by the 2019/2020 fire season (DELWP, 2020).

In the summer of 2019/2020, Australia experienced an unprecedented fire season (Collins et al., 2021), with more than 6 million ha of temperate broadleaf forest and woodland burnt across the south-east of the continent (i.e., ~21% of this biome; Boer et al., 2020). Three large wildfire complexes accounted for most (>90%) of the area burnt in Victoria during the 2019/2020 fire season (Figure 1). The initial ignition for the large complex in the east of the state occurred in mid-November, with the two complexes in the north and west of this area igniting in late December (29 and 30, respectively). The fires burnt under a diverse range of weather conditions, including periods of severe—extreme fire weather, reaching a cumulative area of 1.5 million ha in Victoria, before being declared contained in late-March 2020. The fires made some large, rapid runs in native forest (e.g., >10,000 m hr^{-1}) under extreme fire weather conditions.

The megafires that affected eastern Australia were largely caused by record low fuel moisture levels, driven by an extreme and prolonged drought, coupled with regular occurrence of severe fire weather (Nolan et al., 2020). The drought conditions experienced were sufficient to facilitate fire encroachment into moist plant communities that typically provide fire refuge (e.g., rainforest, see Collins et al., 2019). Consequently, severe and potentially irrecoverable impacts are expected for many fire-sensitive plant communities of national and global significance (e.g., Gondwana Rainforest World Heritage Area; Nolan et al., 2020; Gallagher et al., 2021).

To undertake our analyses, we used the mapped fire extent—polygons of each fire boundary—to represent the full extent of the 2019/2020 fires (DELWP, 2020, Table S1). We also used fire severity mapping, generated using Sentinel-2 satellite imagery and a random forest classification procedure implemented in Google Earth Engine (full details of fire severity mapping method are outlined in Collins et al., 2020), to understand the spatial variation in fire effects on biodiversity (Figure 1; Table S1). For the purposes of this paper, we define 'high severity fire' as the two highest fire severity classes, which include areas where the canopy foliage has been either largely consumed or scorched leaving very little green foliage (>80% canopy scorch, Figure 1).

2.2 | Quantifying fire overlap with species distributions

Many species that have had a large proportion of their habitat burnt by a megafire may be at a higher risk of local extinction, particularly those with restricted ranges, and/or are already threatened. To identify the species most affected (i.e., high proportion of their range within the fire extent), we quantified the spatial overlap between the 2019/2020 bushfires and native species habitat. While we recognize that the species in this study have highly variable responses to individual fires and the total regime, and responses are influenced by environmental context (Kelly et al., 2017), we consider this approach, paired with information on species' fire vulnerability, appropriate for rapid identification of species of conservation concern. To do this, we used an existing set of species distribution models across Victoria for ~4,200 taxa of terrestrial vertebrate fauna and vascular plants (Table S1). These species distribution models were built using random forest classification with 26 environmental predictors, including satellite imagery, bioclimatic, terrain and soil-related variables and provide a measure of relative habitat suitability (probability of occurrence of suitable habitat) for each of the taxa (Liu et al., 2013, 2016). These models were previously built to inform various spatial conservation planning decisions in Victoria (Liu et al., 2013). Next, we calculated the percentage of each species' habitat that fell within the boundary of the 2019/2020 bushfires. As the species distribution models provided a measure of relative habitat suitability, we weighted the percentage overlap by modelled habitat quality. We calculated the percentage of each species net habitat that was burned as:

$$\%\ \text{Habitat impacted} = \frac{\sum H_{s,i} \times B_i}{\sum H_{s,i}}$$

where H_{si} is the habitat suitability value in a pixel i, and B_i indicates whether pixel i was burned (1) or not (0). Dividing the net amount of suitable habitat in the fire extent by the state-wide amount gives the proportion of state-wide net habitat burnt by the fire, therefore providing an indication of the level of impact of the fire on each species while accounting for relative suitability of the habitat burnt. Species were then categorized based on their conservation status and broad taxonomic/functional guild (Figure 2). We then repeated this analysis by calculating the proportion of habitat burnt by high severity fire (i.e., where B_i =1 only when a pixel was burnt by high severity fire), which allowed us to assess which species were affected most acutely by the fire (Figure 2). We also explored if species were disproportionally affected in areas of high-suitability habitat by calculating the proportion of habitat burnt by fire using high-threshold habitat distribution models (i.e., applying a new threshold to the habitat distribution models with only pixels with the highest values were retained; Supplementary Material).

2.3 | Identifying species of most immediate concern and candidate recovery actions

We identified species with over 40% of their state-wide modelled distribution within the fire extent to identify which species might require short-term recovery actions immediately post-fire. We used 40% as a threshold because we considered that a species with this much of its distribution affected would likely have experienced a substantial impact due to the megafire. This initial list of species was then appended based on expert advice. This included the addition of species from taxa that did not have distribution models, including freshwater aquatic fauna and terrestrial invertebrates, where fire impact was assessed based on expert knowledge of species' extent and fire sensitivity. In addition, the list of flora species of concern was further filtered using trait databases which included life history information (e.g., germination strategy, generation time, dispersal ability), genetic status (from the Genetic Risk Index developed by Kriesner et al., 2019) and vulnerability to fire (Tables S1 and S3). Species of immediate concern were those that were considered likely to experience local extinctions (indicated by a high proportion of habitat within the fire extent and relatively high vulnerability to fire) and species where those losses would have a strong negative impact on the long-term overall persistence of the species (i.e., those with limited or patchy distributions). See Figure S1 for the detailed criteria and process used.

Next, species trait databases were used to identify a range of short-term (0–6 months post-fire) recovery actions (Tables S1 and S3). Trait data were used to identify the potential mechanisms through which the megafire affected species of concern, and therefore the potential threats faced by these species and the types of interventions potentially required (Table 1). For instance, a trait database on species vulnerable to predation by feral cats and foxes was used to inform which species may be at risk from increased pressure from invasive predators post-fire, and therefore may benefit from fox and cat control. The resulting database outlined the number of species of concern which would potentially benefit from post-fire intervention (Table 1). These data were used to help identify candidate actions that may be required in the short-term post-fire. Where there was spatially explicit information available, actions were included in a spatially-explicit prioritization to inform decisions as to where best to implement them across the landscape.

2.4 | Identifying cost-effective landscape-scale actions within the fire extent

To identify the most cost-effective location-specific actions to undertake within and adjacent to the burned area, we used a modified implementation of a dynamic spatial conservation action planning (SCAP) tool (Thomson et al., 2020). SCAP is a raster-based, landscape-scale tool developed for the State Government of Victoria to inform strategic conservation investment and planning. SCAP combines distribution models for 19 threats and the ~4,200 species (terrestrial fauna and flora), with structured expert elicitation and machine learning techniques to generate species-specific maps of the expected benefits (change in local persistence probabilities) of management actions (single and in combination) across Victoria. Total indicative costs of each action are also calculated at each location over 50 years. These inputs are then integrated in a modified Zonation conservation planning framework (Lehtomäki & Moilanen, 2013) to identify spatially explicit actions that collectively provide the most cost-effective outcome to minimizing the risk of species declines in Victoria over the next 50 years. A priority ranking of actions is produced across the landscape by iteratively removing actions that are the least cost-effective, until all actions have been removed. The last actions to be removed provide the highest return on investment for conservation funding, defined as the *net change in summed persistence probabilities for all species per unit of cost action* (Thomson et al., 2020). For development and implementation details of SCAP, refer to the Supplementary Material for a summary and to Thomson et al. (2020) for the full methods.

Immediately following the 2019/2020 Victorian bushfires, we modified SCAP to incorporate the impacts of fire and aid the state government's biodiversity response by identifying and prioritizing management actions that may benefit surviving or recolonizing native species. Fire impacts were incorporated into SCAP in two ways: (a) by reducing the expected net habitat available to each species in the absence of management actions by the proportion of their statewide habitat burnt by severe fire and (b) by increasing the expected benefits of some actions within the fire extent to all species. The first adjustment effectively assigned greater net benefit to actions that benefit species with proportionally more burnt habitat, on the assumption that these species will have a greater reduction in statewide persistence probability in the absence of management actions. It promoted any actions expected to benefit affected species, including actions outside of fire-affected areas (e.g., in unburnt areas adjacent to burnt areas and the fire perimeter).

The second adjustment was spatially explicit and assumed that many actions became more beneficial (lead to larger absolute increase in local persistence probability) in fire-affected areas than they were pre-fire, but that increase was inversely proportional to fire severity. In unburnt areas within the fire extent, the benefits of relevant actions (habitat protection and all feral animal and weed control actions) were assumed to be 50% higher, on the basis that it was now more beneficial to control threats in potential refugia within the fire extent than in those areas pre-fire. The increased benefit within the fire extent declined linearly with increasing fire severity, with benefits 40%, 30%, 20% and 10% higher in low, moderate, high and very high (canopy burn) severity categories, respectively. The spatial adjustments to expected benefits were applied to all species except hollow-dependent fauna. Expected benefits of post-fire management actions to hollow-dependent fauna were set to zero in severely burnt ash forest (and in clear fell and seed tree timber harvesting coupes), where hollow availability is expected to be severely limited over the next 50 years due to the effects of severe fire (Gibbons et al., 2000; Lindenmayer et al., 2016).

We acknowledge that these adjustments are somewhat arbitrary and that the benefits of post-fire management actions will in reality be highly variable within and among species. Nevertheless, the adjustments represent a general consensus that (a) loss of suitable habitat increases extinction risk (Crooks et al., 2017; Hanski & Gyllenberg, 1997), (b) native species may be particularly vulnerable to the impacts of feral animals (predators or herbivores) and weeds after fire (Hradsky, 2019) and (c) unburnt or less-severely burnt areas within fire-affected areas may be important refugia and sources of recovery following fire. These adjustments allowed a rapid assessment of the areas where post-fire management actions were mostly likely to be beneficial to biodiversity overall, and most cost-effective, accounting for the distributions of thousands of species. More detailed work is underway to refine estimates of the benefits of post-fire management, including more explicit expert elicitation, population modelling and, most importantly, field monitoring of actual outcomes from current actions across the state.

3 | RESULTS

3.1 | Quantifying the overlap of fires with biodiversity values

Our analyses indicate that the megafires overlapped with over 40% of the modelled habitat of 346 species in Victoria, including 45 listed as threatened under the Victorian Flora and Fauna Guarantee (FGG) Act 1988 (Figure 2). One hundred and two of these species had more than 40% of their modelled habitat affected by high severity fire. This included species that had almost all their range burnt, including betka bottlebrush (*Callistemon kenmorrisonii*), which had 93% of its modelled habitat within the fire extent. Although some species had relatively low amounts of modelled habitat in the fire extent, like the spotted tree frog (*Litoria spenceri*; 22% of modelled habitat in fire extent, 13% of which was burnt at high severity), the areas which were burnt included important habitat (e.g., key breeding sites).

For additional descriptions of other biodiversity values affected by the 2019/2020 megafires, such as ecological vegetation classes and areas of high biodiversity value that were not explicitly considered in this framework, refer to the Supplementary Material.

3.2 | Identifying species of immediate concern and candidate actions

Species of immediate concern included 154 flora and 67 vertebrate fauna species, including 38 species listed under the Federal Government's Environment Protection and Biodiversity Conservation (EPBC) Act 1999 and 74 species listed under the Victorian Flora and Fauna Guarantee (FFG) Act 1988.

Our trait analyses for these species identified 11 threats related to the megafire and 21 candidate recovery actions that could be enacted to ameliorate these threats (Table 1). In particular, direct mortality of individuals, loss of critical habitat features and a change in importance of other populations were identified as threats for more than 60 species of concern (Table 1). Similarly, loss of food resources was expected to impact at least 39 species of concern. Impacts of invasive species through predation, herbivory and competition were also identified as important threats requiring action (Table 1).

3.3 | Identifying cost-effective landscape-scale actions within the fire extent

Before the fires, the SCAP identified that controlling deer, predators (feral cats and foxes) and weeds were expected to be highly cost-effective actions across much of the fire-affected region, relative to all other actions across the whole state (Figure 3a,b). Feral horse control also ranked as highly cost-effective in many alpine areas (Figure 3c). Our preliminary post-fire analysis, based on initial expert advice, suggests that these actions have become even more beneficial (and hence cost-effective) in fire-affected regions (Figures 3b and 4), because feral animals and weeds may severely inhibit post-fire recovery for many native species. For example, deer control (~800,000 ha), weed control, cat control and fox control (all ~600,000 ha) and pig control (~500,000 ha) are likely to be cost-effective over large tracts of the burned area. Importantly, SCAP also identifies where within and adjacent to the burned areas these actions are likely to be most cost-effective, depending on where the biodiversity values represented will benefit most per unit cost (Figures 3c and 4). For example, the unburned areas within and adjacent to the megafire extent and low severity burned areas were identified as high priority for action (e.g., deer control, weed control and predator control) according to the analyses.

4 | DISCUSSION

The 2019/2020 south-eastern Australian megafires are likely to have had a considerable effect on biodiversity. By combining data

FIGURE 2 Overlap of 2019/2020 wildfires extent with species modelled habitat. (a) Number of species in each taxonomic group (amphibians, birds, mammals, reptiles and plants) with proportions of modelled habitat of 10% or more within the fire extent for (1) all species and (2) threatened species listed under the Victorian Flora and Fauna Guarantee (FFG) Act 1988. (b) Number of species in each taxonomic group with proportions of modelled habitat of 10% or more within high severity fire extent (two highest fire severity classes that highlight where the vegetation canopy has been either completely burnt or scorched leaving very little green foliage [>80% canopy scorch]) for (1) all species and (2) threatened species listed under the FFG Act. (c) Map of eastern Victoria showing example species distribution models for species affected by the 2019/2020 wildfires overlaid with the fire extent from 20th April 2020 (hashed area). Darker coloured areas indicate areas of relatively higher likelihood of suitable habitat. Example species are all listed under the FFG Act and include endangered Booroolong Tree Frog (*Litoria booroolongensis*), vulnerable Colquhoun Grevillea (*Grevillea celata*), endangered Eastern Bristlebird (*Dasyornis brachypterus*) and endangered Long-footed Potoroo (*Potorous longipes*). Numbers refer to the proportion of habitat burned by the megafire (high severity in brackets). Photo credits: Booroolong Tree Frog: Geoff Heard; Colquhoun Grevillea: Russell Dahms; Long-footed Potoroo: Andy Murray; Eastern Bristlebird: Mick Bramwell

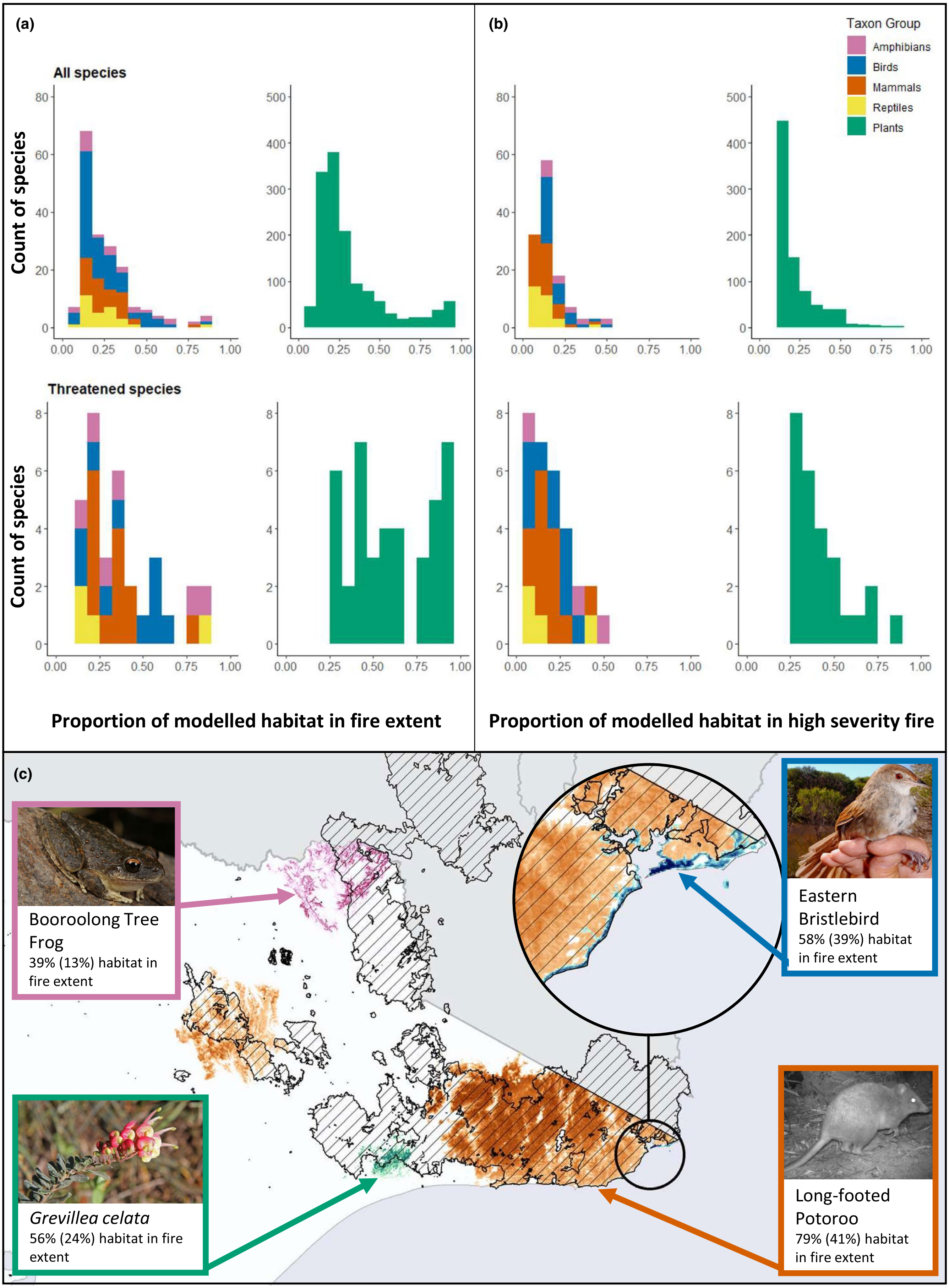
(a)
All species
Count of species
Threatened species
Count of species
Proportion of modelled habitat in fire extent
(b)
Taxon Group
Amphibians
Birds
Mammals
Reptiles
Plants
Proportion of modelled habitat in high severity fire
(c)
Booroolong Tree Frog
39% (13%) habitat in fire extent
Eastern Bristlebird
58% (39%) habitat in fire extent
Grevillea celata
56% (24%) habitat in fire extent
Long-footed Potoroo
79% (41%) habitat in fire extent

TABLE 1 Threats and potential recovery actions identified through matching the traits of species against species of most immediate concern

Threat	Species of concern affected by threat	Candidate recovery actions
Direct mortality of individuals caused by the immediate impacts of the fire	66 species—10 amphibians, 20 mammals, 8 reptiles, 17 aquatic fauna and 11 birds (e.g., all affected freshwater fish; Lyon & O'Connor, 2008)	Emergency extraction and temporary housing of surviving individuals for populations/species with low chance of survival post-fire Manage fire suppression activities to benefit biodiversity (e.g., direct fire suppression to key locations or limit actions that may negatively affect biodiversity, like dropping of chemical retardants)
Loss of food source	39 species—nine amphibians, 12 mammals, six reptiles, three aquatic fauna and nine birds (e.g., Glossy Black Cockatoo; North et al., 2020)	Supplementary feeding Planting of food source trees
Immediate impact of debris flow following fire on survival of individuals	10 species—one amphibian and nine aquatic fauna (e.g., Spotted Tree Frog; Gillespie & West, 2012)	Provide off-stream temporary ponds for amphibians Sediment and erosion control to prevent debris being washed into water bodies Emergency extraction of aquatic species with limited chance of survival post-fire and temporary housing for ongoing conservation
Loss of critical habitat features	67 species—10 amphibians, 20 mammals, eight reptiles, one flora, 17 aquatic fauna and 11 birds (e.g., hollow-dependent fauna; Banks et al., 2011; Lindenmayer et al., 2016)	Protection of key unburnt areas, critical habitat features and populations within the current fire extent Provide artificial habitat for impacted species (e.g., artificial hollows)
Increased predation pressure	41 species—10 amphibians, 12 mammals, 10 reptiles, three aquatic fauna and six birds (e.g., small ground-dwelling mammals including Long-Footed Potoroo; Hradsky, 2019)	Predator (e.g., red fox, feral cat) control within the current fire extent and adjacent areas
Increased competition and grazing pressure from pest herbivores	32 species—three amphibians, two mammals, five reptiles, 15 flora and seven aquatic fauna [e.g.. palatable flora (e.g., *Symplocos thwaitesii*; Davis et al., 2016) and fauna vulnerable to trampling and habitat loss (e.g., guthega skink; Driscoll et al., 2019)]	Herbivore (e.g., feral deer, feral pig, feral goat, feral horse) control within the current fire extent and adjacent areas Fence local populations for protection from pest herbivore species
Multiple wildfires within 20 years	Six species—one amphibian, three mammals and two flora (e.g., *Eucalyptus delegatensis delegatensis*; Fairman et al., 2016)	Collection of seed and ex situ seed banking for key species Reseeding of flora and plant communities in key locations
Increased competition from invasive plants	11 flora (e.g., *Prasophyllum uvidulum*; Duncan & Coates, 2010)	Weed control within the current fire extent and adjacent areas
Small population size effects (inbreeding depression, vulnerability to localized disturbances)	10 species—three amphibians, two mammals, five reptiles, 15 flora and seven aquatic fauna (e.g., Eastern Bristlebird; Clarke & Bramwell, 2016)	Population management—wild to wild translocation of fauna populations, creation of sanctuaries (e.g., fenced reserves), captive breeding to support population growth in wild populations
Disease	10 species—seven amphibians and three mammals (e.g., Alpine Tree Frog; Howard et al., 2011)	Hygiene control in emergency response actions Protection of key areas without disease
Change in importance of other populations	66 species—10 amphibians, 20 mammals, eight reptiles, 17 aquatic fauna and 11 birds (e.g., Southern Brown Bandicoot; Zenger et al., 2005)	Protect and manage key populations of species outside the current fire extent Translocation of important fauna populations Identify and protect ecological refuges (including climate change considerations) Creation of safe haven/sanctuary network

Note: Threats are identified as the potential processes or stressors that may have been exacerbated as a result of the megafire. Candidate recovery actions are those identified as potentially ameliorating the identified threats for each species—although some may not be feasible or beneficial for all species listed. For a full breakdown of species listed against each threat see Table S4).

on species distributions, vulnerability to fire and other threats, and a spatial conservation planning tool, our framework identified a range of conservation actions that may assist recovery from the megafire and other compounding threats. The application of frameworks such as ours will be vital for informing conservation responses into the future as megafires continue to incinerate parts of the globe.

Conservation planning must be adaptable to environmental perturbations, such as disturbances and dynamic threats (Pressey et al., 2007). Fire is regularly incorporated as a threat and/or action in spatial conservation action planning tools (Auerbach et al., 2015; Levin et al., 2013), and there is considerable opportunity to use these tools to inform post-fire conservation decisions. We have demonstrated that spatial conservation action planning tools can also be used to inform conservation responses to large-scale disturbances, such as megafires, by identifying co-occurring threats that can be managed to improve the ability of species to recover from fire. By explicitly integrating fire severity mapping into SCAP by modifying species persistence estimates according to fire severity, we were able to identify conservation actions that target key unburnt refugia, which presents a novel use of spatial conservation planning tools in megafire recovery. Importantly, SCAP can also inform medium and longer-term management priorities for post-fire biodiversity recovery.

4.1 | Application to 2019/2020 Black Summer

At least 346 species had more than 40% of their state-wide habitat burnt, and some of these species had a much higher proportion of their habitat burnt. For example, over 87% of the nationally vulnerable large brown tree frog's (*Litoria littlejohni*) state-wide modelled habitat was burnt, 47% at high severity. The majority of species heavily affected by the megafires were flora, including the nationally endangered betka bottlebrush which had almost all of its state-wide modelled habitat burnt (93%; 71% at high severity). High severity fires have had substantial conservation implications for individual species. For example, a 2014 megafire in California, North America significantly reduced the occupancy of the spotted owl (*Strix occidentalis occidentalis*; Jones et al., 2016). Similarly, a high severity fire in Tasmania initiated the collapse of a population of a long-lived conifer (*Athrotaxis cupressoides*) by triggering recruitment failure (Holz et al., 2015). Therefore, identifying and implementing appropriate short- and long-term conservation responses for heavily affected species is vital to assist their recovery.

We used the impact assessment in conjunction with existing spatial conservation planning tools and threat databases to rapidly identify species-specific actions and landscape-scale actions within and adjacent to burned areas. We identified 21 candidate recovery actions that may reduce the likelihood of extinction for fire-affected species, that ranged from species-specific (e.g., translocation, seed banking) to landscape-scale (e.g., invasive species management, protection of unburned areas). Species-specific actions aimed to both increase survival of populations within the fire area and to spread the risk of future megafires across multiple populations. By using these complementary approaches (SCAP and impact assessment), we were able to ensure the post-megafire needs of all affected species were considered in the planning process.

Some potential species-specific actions, however, required further work to assess the need and feasibility for each identified species. For instance, 66 species were identified as being vulnerable to direct mortality of individuals post-fire, for which emergency extraction of surviving individuals was identified as a potential recovery action. Emergency extraction, however, is a conversation tool only appropriate for species where a large proportion of habitat has been burnt and individuals or populations are unlikely to persist post-fire. Therefore, it is unlikely to be beneficial for the large majority of the 66 species identified. Further assessments were undertaken involving consultation with species experts and land managers to determine if emergency extraction was needed and was undertaken for the eastern bristlebird and multiple freshwater fishes. Some of these species-specific actions have been beneficial in previous megafires. For example, after the 2009 Black Saturday fires in Victoria, a number of freshwater fishes were extracted and placed in temporary housing to prevent the loss of entire populations to post-fire debris flows (Ayres et al., 2012). In North America, over US$3 million is spent annually on emergency reseeding of forest ecosystems following megafires (Peppin et al., 2011). While large conservation gains can be made with actions tailored to species highly affected by megafires, our analyses demonstrate that species-specific actions need to be undertaken in combination with landscape-scale actions that benefit multiple species.

We identified locations within the fire-affected area where invasive species management (deer, red foxes, feral cats, weeds and feral pigs) would be most cost-effective. For instance, deer, horse, weed and predator control were identified as high priority actions in areas which experienced low severity burns or that were adjacent to the fire extent. This is unsurprising as unburned patches or patches burned at low severity are important refuges for fauna post-fire, particularly for species vulnerable to predation by foxes and feral cats or modifications to habitat structure caused by feral deer and horses (Nimmo et al., 2019; Shaw et al., 2021). These landscape-scale actions will be essential to assist recovery of vulnerable native species post-fire and reflect existing literature detailing the importance of invasive species management post-fire (Brown et al., 2016; Hradsky, 2019). In addition to prioritising actions post-fire, the spatial conservation action planning tool guided threat management prior to the fire, which is likely to further increase species' chances of recovery. For example, implementing ongoing landscape-scale predator management programs before fires occur will reduce the risk of predation for vulnerable mammals in burned landscapes, as fewer predators may be present in areas under sustained control (Hradsky, 2019). Similarly, native mammals in northern Australia recovered more quickly from high severity fire where invasive herbivores had been removed (Legge et al., 2011).

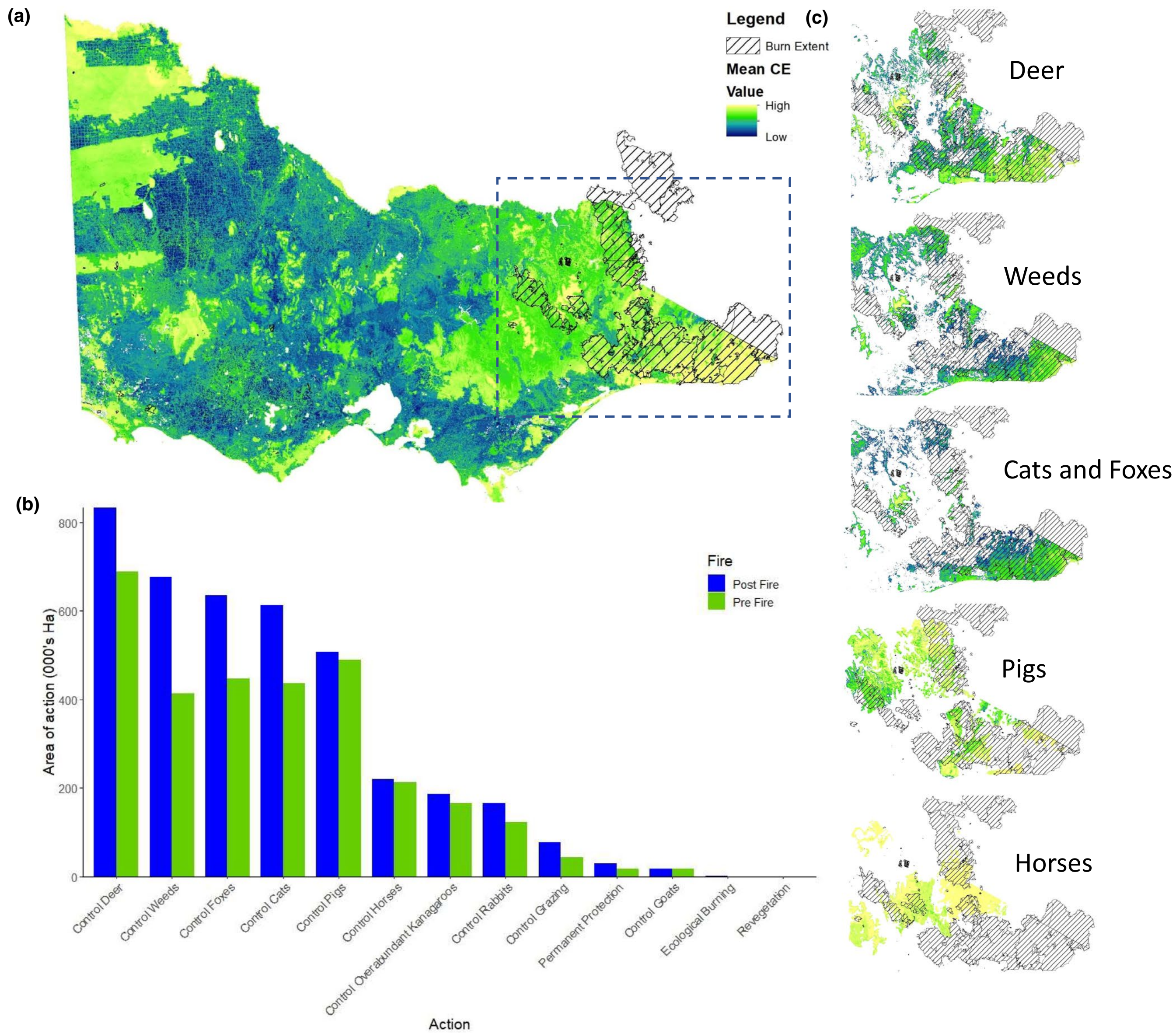

FIGURE 3 (a) Map of Victoria providing a state-wide comparison of the mean cost-effectiveness (CE) rank of all location-specific conservation actions post-fire. Cost-effectiveness is estimated as the expected change in summed persistence probabilities across all species per unit cost associated with a specific action at each location. CE values for each action at each location are ranked against all other location-specific actions. The mean CE shown on the map is the mean rank of all actions at a location and demonstrates that much of the highest benefits to species per unit cost across Victoria are within the megafire zone. (b) The total area (thousands of hectares) of each relevant action in the top 10% of cost-effectiveness scores for all location-specific actions across the state within the total state-wide fire extent for the 2019/2020 wildfire season. This demonstrates that the CE area of most actions increases in the fire zone as these actions become more important for species persistence relative to non-fire-affected areas across the state. (c) The cost-effectiveness rank (relative to all state-wide actions) across eastern Victoria (dashed box in (a)) of the top 5 actions in (b) (Cat and Fox control are combined)

4.2 | Pre- and during-fire planning tools

Maintaining up-to-date, spatially explicit biodiversity data can also help to prioritize species populations for specific management actions before or during extended fire events, and as these priorities evolve. This requires integrating known and estimated genetic, trait and important population data to identify feasible candidates for intensive emergency management or extraction and plan for operational requirements such as access routes, capture and transport methods, and receiving centres. Given these complexities, in future, species could be identified prior to predicted high-risk fire seasons and prioritized for active protection from fire, or potentially extracted earlier to reduce the operational risks. The integration of weather forecasting with forest fuel dynamics and fire behaviour modelling has provided fire suppression agencies with the capacity to model risks to life and property while a wildfire is in progress (Duff et al., 2018). This could be used to also model the risks of ongoing fires to biodiversity and justify targeted fire suppression efforts in high biodiversity value locations and/or identify species that may require emergency extraction.

Climate change means that conservation managers now need to routinely build disturbance into their decision support tools. For example, future decision support products need to explicitly integrate what we know of disturbance history (e.g., previous fire extents and severity, and related disturbances associated with timber harvesting and clearing) when predicting species distributions, population viability or identifying cost-effective actions (Nitschke et al., 2020), especially for actions with costs and benefits that might be different in burned landscapes (e.g., invasive species control).

4.3 | Future development needs

Key to informing rapid analyses of the impact of megafires on biodiversity is having a sound information base from which analyses can be performed, and building this can be done now by conservation managers to better prepare for future megafires. This includes collated spatial information on where biodiversity is distributed (e.g., species distribution models, polygon-based representations or even occurrence records), trait databases that explicitly link fire vulnerability, other proximal threats, and potential management actions, and, where practicable, estimates of the relative effectiveness of conservation actions post-fire. Without these data a priori, quantifying the possible effects of fires on biodiversity and identifying species of concern and candidate management actions is difficult, particularly in an emergency setting. Once collated, these data and information can also be applied to other conservation decisions and challenges. For example, the SCAP tool used in this analysis is applied to a range of decision contexts, including forest management, invasive species control and threatened species conservation. To that end, we outline key datasets and information products that can be built by conservation managers in fire-prone biomes across the globe to assist in preparing conservation responses to future megafires (Table 2). While our framework uses all of these datasets,

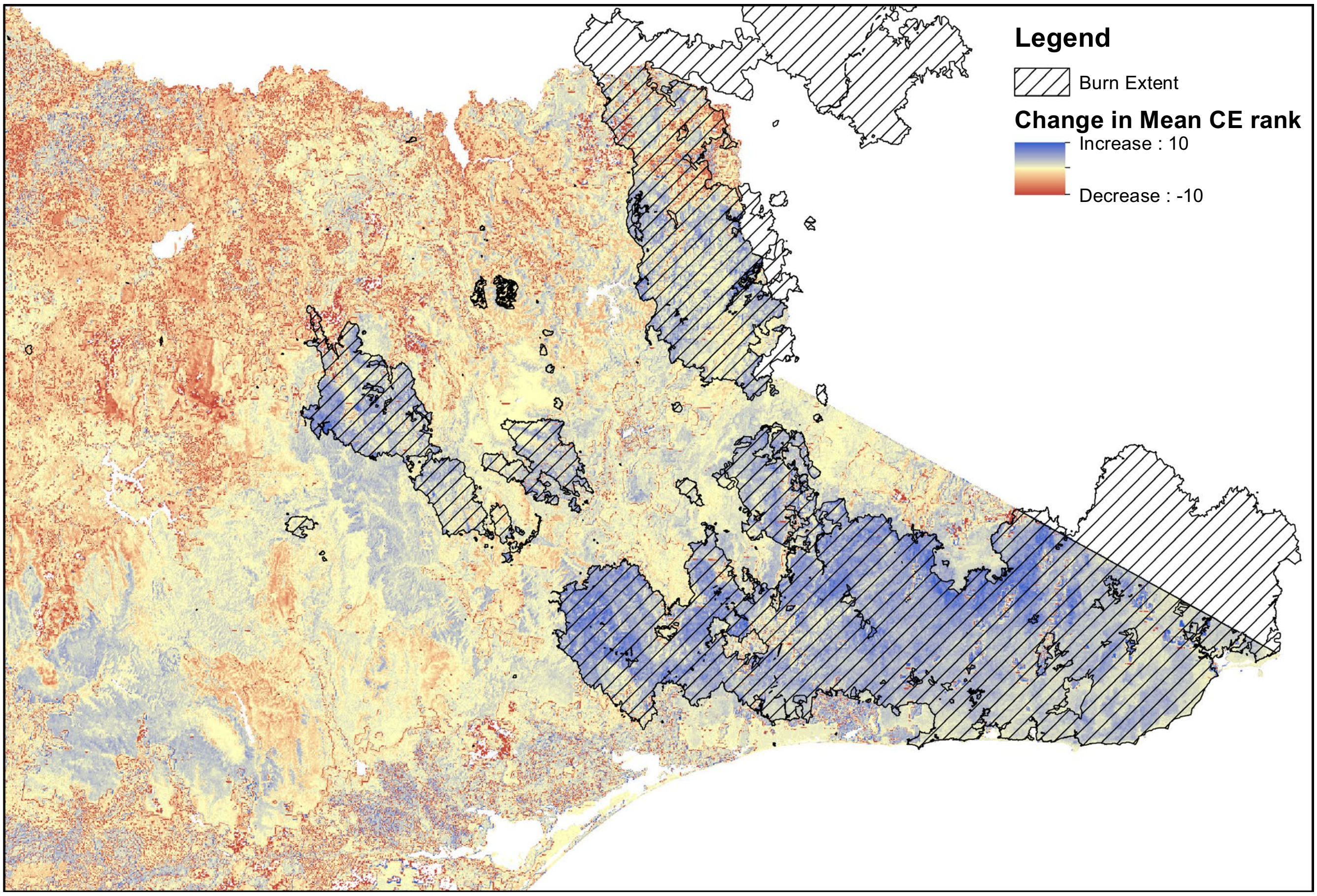

FIGURE 4 Map showing the change in mean cost-effectiveness (CE) rank of all location-specific conservation actions after the modifications to the SCAP tool following the megafire. Cost-effectiveness is estimated as the expected change in summed persistence probabilities across all species per unit cost associated with a specific action at each location. CE values for each action at each location are ranked against all other location-specific actions. The mean CE is the mean rank of all actions at a location and demonstrates that much of the highest benefits to species per unit cost across Victoria are within the megafire zone, and the Change in Mean CE rank is the difference between the pre-fire rank and the post-fire rank. Increases in mean rank of 10 or more are shown in blue on the map, and decreases in mean rank of 10 or more are shown in red. Overlaid on the map is the burn extent of the 2019/20 megafire (black hatching)

TABLE 2 Biodiversity datasets and information sources that can be built to assist land managers to rapidly assess the impacts of megafires and begin to plan conservation responses across the globe, and applied examples of each

Dataset	Description and potential use	Applied examples
Mapped distributions of biodiversity values	Mapped distributions of biodiversity values (e.g., species, plant communities, populations or locations) identified as important for conservation. Ideally, these would be continuous species distribution models, but binary range maps or occurrence records can also be useful. Used to calculate the impact of megafires on species and other biodiversity values	Ward et al. (2020) Baillie et al. (2004)
Fire severity mapping	Modelled, satellite-derived maps of fire severity, which are used to identify places more or less-severely burnt by fire	Collins et al. (2018)
Species attribute/trait data	Trait data for species or other biodiversity values that describe the value's vulnerability to fire, as well as other co-occurring threats and habitat preferences. Can be used to identify candidate recovery actions and values that are especially vulnerable to fire; however, fire response curves are better predictors of species responses to fire	Pausas et al. (2004) Moretti and Legg (2009)
Mapped distributions of threats/pressures to biodiversity	Maps (e.g., distribution models or range maps) of other co-occurring threats (e.g., invasive species, human pressure) that can compound the effects of megafires on vulnerable biodiversity values. Used to identify other threats that may need to be addressed to assist recovery from megafires	Evans et al. (2011) Bowler et al. (2020)
Conservation action planning tools	Conservation action planning tools that integrate and optimize information on the relative costs and benefits of conservation actions targeted at identified biodiversity values. Ideally, these would be spatially explicit so that megafires can be explicitly incorporated, but aspatial conservation action tools are also useful for action planning post-megafire. Used to identify priority conservation actions to be implemented post-megafire	Carwardine et al. (2019) Chadès et al. (2019) Thomson et al. (2020)

application of a subset (e.g., mapped distributions of biodiversity values, trait data) can help to guide conservation responses to megafires and other contexts (Bosso et al., 2018; Legge et al., 2020).

Species' vulnerability to fire and expected responses to conservation actions are important pieces of information for identifying post-megafire actions. To facilitate our approach used here, we had to apply existing fire vulnerability data and generic rules of thumb of the benefit of conservation actions in burnt landscapes, *in lieu* of more robust data. These represent important uncertainties in our approach and avenues for future research; in particular, there are few empirical studies of the relative benefit of conservation actions in burnt landscapes (e.g., invasive species control, supplementary feeding, emergency extraction). The benefit of invasive species control for some species is a key source of uncertainty in the SCAP tool (Thomson et al., 2020) and is likely to be even more uncertain in a post-megafire context. Similarly, species responses to fire can vary substantially depending on context and fire severity (Fontaine & Kennedy, 2012; Kelly et al., 2017), and there are considerable gaps in the knowledge of species' responses to megafires. To address this, we are currently quantifying experts' uncertainties about the benefits of post-fire actions, which will be used in value-of-information analyses to prioritize future research into post-fire management (Thomson et al., 2020). New data currently being collected, including further expert opinion, population modelling results and field monitoring of actual outcomes, will help to provide estimates of species persistence in burnt areas with and without various management actions, accounting for both fire history and predicted future fire regimes.

Our framework will also be further advanced by a better understanding of the costs and benefits of the more bespoke actions in Table 1, which are not currently represented in the SCAP tool. This is an area of active improvement and such estimates will inevitably be uncertain, and those uncertainties should be quantified and incorporated into decision making and research prioritization. Future responses to megafires can be better targeted by addressing these knowledge gaps, and integrated monitoring programs that evaluate the success of post-fire actions for a broad range of species will provide important information in improving conservation responses (Southwell et al., 2019). The dynamic nature of SCAP that allows it to be rapidly updated with new data demonstrates that spatial conservation planning tools are valuable assets for informing responses to megafires, as well as other landscape-scale perturbations.

Moving towards representations of currently occupied habitat or temporally dynamic habitat suitability models, rather than distribution models informed by a-temporal covariate data, will help guide post-fire conservation actions to locations that will have the greatest benefit. This is particularly true for species experiencing ongoing declines and/or whose abundance is mediated by disturbance (Burns et al., 2020), as well as actions that are highly influenced by site-scale disturbance history. These could then be used to inform dynamic maps of important ecological refuges (Reside et al., 2019), with both short-term (e.g., remaining long-unburnt habitat) and long-term (e.g., climate change refuges) considerations to facilitate better-targeted actions.

4.4 | Concluding remarks

Climate change is intensifying multiple stochastic disturbances and threats to biodiversity that overlap in time and space, and altered fire regimes are emerging as a key threatening process for species across the globe (Kelly et al., 2020). Conservation managers increasingly require the capability and capacity to quantify the effects of actions, rapidly re-analyse options, and to redirect operational effort adaptively. Climate change requires managers to balance implementing rapid and reactive emergency responses to significant individual megafires, and considering how the consequences of recent and future events should influence long-term conservation planning. In the face of future megafires, rapid implementation of conservation actions may be required to give biodiversity the best chance of recovery. Standardized frameworks such as ours provide conservation managers with an approach that can be applied to future megafires in any ecosystem globally.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The datasets used in this paper are all Victorian Government datasets. Public access to each of these datasets is detailed in Table S1. The results of the species distribution analyses, which were used to create Figure 2, and the trait data used to identify species of concern are available at Dryad Digital Repository (https://doi.org/10.5061/dryad.3ffbg79hq).

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Biosketch

The authors of this paper worked as a team to analyse the impacts of the 2019–2020 bushfire season on flora and fauna in Victoria, Australia, and support the response and recovery efforts. The team is made up of experts in fire ecology, species distribution modelling, spatial conservation planning, conservation biology and ecological policy.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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