

Impacts of the 2019–2020 Bushfires on New South Wales Biodiversity: A Rapid Assessment of Distribution Data for Selected Invertebrate Taxa

ISABEL T. HYMAN¹, SHANE T. AHYONG^{1,2}, FRANK KÖHLER¹, SHANE F. MCEVEY¹,
GRAHAM MILLEDGE¹, CHRIS A. M. REID¹, JODI J. L. ROWLEY^{1,2}

¹ Australian Museum Research Institute, Australian Museum, 1 William St, Sydney NSW 2010, Australia

² School of Biological, Earth and Environmental Sciences,
University of New South Wales, Kensington, NSW 2052, Australia

ABSTRACT. We analyse expert-confirmed occurrence records from the collection of the Australian Museum of altogether 733 species of invertebrates that exhibit a wide range of life history strategies, dispersal abilities and ecological adaptations (dung beetles, spiny freshwater crayfishes, drosophilid flies, land snails, mygalomorph and archaeid spiders). For 29 species (two dung beetles, four species of spiny freshwater crayfishes, four drosophilid flies, 11 land snails, five mygalomorph and three archaeid spiders), all known occurrences are within the extent of the 2019–2020 bushfires. In addition, the ranges of another 46 species had at least half of their known occurrences completely contained within the fire zone. Given these figures, the conservation status of many NSW species may require revision to recognize the higher level of threat, and active conservation actions will need to be taken to ensure the survival of these and other species.

Introduction

The bushfires that impacted vast areas of eastern Australia from October 2019 to February 2020 were extensive and severe. In New South Wales (NSW) approximately 5.3 million hectares were burnt (7% of the state), including 2.7 million hectares of the state's National Parks (NSW State Government, Department of Planning, Industry and Environment [DPIE], 2020), affecting World Heritage areas such as the Greater Blue Mountains Area and the Gondwana Rainforests of Australia. Fifty-seven national parks and reserves had more than 99% of their area impacted by fire. The most affected ecosystems were rainforests (35% of their state-wide extent), wet sclerophyll forests (41%) and heathlands (53%) (DPIE, 2020). Gondwanan rainforest is not a fire-adapted habitat, with tree-destroying fires only likely to occur at intervals of over 1000 years (Turner, 1984), making this habitat type and the species relying on it extremely vulnerable to fire damage. This habitat type is also likely to recover slowly.

The sheer scale of burnt areas has raised conservation concerns for many species that occur within the impact zone of these fires. Much emphasis has been put on the effects of the bushfires on iconic species such as the koala—*Phascolarctos cinereus* (Goldfuss, 1817)—of which an estimated 6382 individuals (or 15% of NSW's koala population) may have perished in these fires (Lane *et al.*, 2020). Seventy vertebrate species have also been identified as of particular conservation concern since more than 30% of their known distributions were burnt (Ward *et al.*, 2020). Although equally relevant, the conservation impact on lesser-known species is generally poorly understood. We consider any animal species that has a comparatively narrow distribution in eastern Australia and has limited mobility in any of its life stages to be of particular concern.

Almost 1000 plant and animal species are formally listed as threatened under the NSW Biodiversity Conservation Act (2016), and the vast majority of these (estimated 973 species; DPIE, 2020) have at least parts of their distribution within the burnt areas. However, the listed species form only a fraction

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Corresponding author: Isabel T. Hyman Isabel.Hyman@Australian.Museum

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of the total number of species in NSW, an unknown figure that lacks even a reliable estimate. For comparison, there are an estimated 566,398 plant and animal species Australia-wide (Chapman, 2009).

Invertebrates, which according to estimates of Australia's biodiversity make up over 97% of all animal species (Chapman, 2009), play a critical role in ecosystem health and functioning but are generally under-represented in threatened species lists (Taylor *et al.*, 2018). Many invertebrates are narrow-range endemics, increasing their vulnerability to widespread fires. Leaf litter-dwelling species are also known to be particularly vulnerable to bushfires (Buckingham *et al.*, 2019). Many invertebrates are particularly diverse in moist, humid environments such as rainforest, which make up just 3% of the state's forests (ABARES, 2019) but are likely to contain a significant portion of its biodiversity (for example, rainforests make up 2.6% of Australia's forests but contain 60% of all plant species, 60% of butterfly species, 40% of bird species and 35% of mammal species—ABARES, 2019).

After severe bushfires, invertebrate diversity and abundance is reduced (Buckingham *et al.*, 2019). In addition, there are changes to species composition after fires, with a higher proportion of larger invertebrates remaining, as smaller invertebrates may struggle to re-colonize burnt areas due to low vagility and/or greater susceptibility to desiccation under drier conditions (Buckingham *et al.*, 2019). Studies of land snails have shown that snails living in burnt areas have higher mortality than in unburnt areas, indicating that survivors or re-colonizers of burnt areas may struggle to survive (Ray & Bergey, 2015). Rapid weed growth after fires has a negative effect on invertebrates, and also makes these areas more susceptible to future fires (Sands, 2018). The loss of detritivores can result in an increased depth of dry leaf litter, increasing fuel load and also adding to the risk of further fires. Many invertebrates are negatively affected by current fire management regimes (Ray & Bergey, 2015; Sands, 2018), with a need for fuel reduction burning to follow a micro-mosaic patch pattern in order to avoid the loss of overall invertebrate biodiversity (New *et al.*, 2010; Sands, 2018).

The expansive and near simultaneous extent of the NSW bushfires also highlights the potentially underestimated significance of bushfires in assessments of conservation status. If the current NSW fire map (shown in Fig. 1) is correct, numerous native NSW species can be inferred to have been severely impacted, and possibly even made extinct. Therefore, in the immediate term, field surveys must be prioritized to ground truth the extent and granularity of the current NSW fire maps in order to more accurately assess the impacts on these species and inform conservation actions.

In order to strengthen the knowledge base about the potential impacts of these bushfires on the Australian biota, and to better understand future challenges in land management in light of recent events, we have undertaken a preliminary assessment of the potential scale of impacts of these fires on selected groups of invertebrates. Rapid responses are critical in order to manage and direct conservation efforts to the groups in greatest need. These assessments are based on the research collections of the Australian Museum (AM), the single largest repository of biodiversity data in NSW. These collections, and the information that they contain, can play an important role in reconstructing species distributions as well as in detecting changes in distributions over time for a wide range of taxa, from insects to mammals. We analysed the occurrence records for selected groups of invertebrates, whose taxonomy is relatively well-known and whose collections are well-curated, in order to estimate the impact of recent bushfires on the populations of a large number of species that represent different trophic levels and ecological adaptations.

Methods

The model groups used were chosen based on four criteria: (a) well-resolved taxonomy; (b) the group should be well-represented by already databased and expert-identified material in the collections of the AM; (c) the museum records should be considered comprehensive in their geographic coverage in order to best represent the distribution of the group; and (d) the taxa chosen should represent a variety of ecological adaptations and trophic levels, and have low vagility in at least one of their life stages. Based on these criteria, six model groups were chosen: dung beetles, spiny freshwater crayfishes (*Euastacus*), drosophilid flies, land snails, mygalomorph spiders and archaeid spiders.

For each group, all NSW records (excluding Lord Howe Island and Norfolk Island) from the AM were checked by a taxonomic specialist for each model taxon. Undescribed species were, in most cases, deleted, since these species are generally not well-known and their taxonomy is poorly understood. Imprecise records with large errors in coordinates (> 10 km) were also deleted, as were records with obvious errors in taxonomy or occurrence. Duplicate records (with identical coordinates) were removed to avoid skewing the results based on multiple records at a single site. We also investigated the effect of limiting records to the past 50 years (1970–2020), in order to best reflect the current distribution. Some selected species were not limited to NSW. The final datasets used for analysis are published separately by Ahyong (2020), Köhler & Hyman (2020), McEvey (2020a), Milledge (2020), and Reid (2020).

All statistical analyses were conducted in R ver. 3.6.2 (R Core Team, 2019). We used two different sources of data on the Australian fires. The NSW Bushfire map (Fig. 1) indicated whether or not the site had burnt, and the Google Earth Engine Burnt Area Map (GEEBAM, 2020) indicated the impact of the fire on vegetation. For each taxonomic dataset we removed records with latitude or longitude values of zero and filtered records to the state of NSW (GADM database www.gadm.org, version 2.5, July 2015). We then assigned each record with each fire layer, allowing determination of the mapped burn status of each record. Species with ranges outside NSW were included, but are discussed individually under the sections for each taxon in the Discussion.

Results

From a total of 733 species studied, more than half (399 species) had some parts of their range contained within the fire zone. For 174 species, at least 25% of their known occurrence was in the fire zone; for 75 of these species, at least half of their known occurrence was in the fire zone; 36 species had 75% of their known occurrence burnt; and for 29 species their entire known range was burnt (see Table 1).

From a total of 92 dung beetle species, 54 were impacted by the bushfires and two species had their known ranges entirely contained within the fire zone (Fig. 2A; Tables 1, 2). Most of these impacted species are flightless or restricted to wetter forests. For the two most heavily impacted species, 75–100% of the burnt sites were in the high to very high GEEBAM categories (Fig. 3A, Table 3).

From a total of 38 species of spiny freshwater crayfishes, 21 species were impacted by the bushfires and for ten species, 50% of their ranges were burnt. Four species had their known ranges completely contained within the fire zone (Fig. 2B; Tables 1, 2). For the four most heavily impacted species,

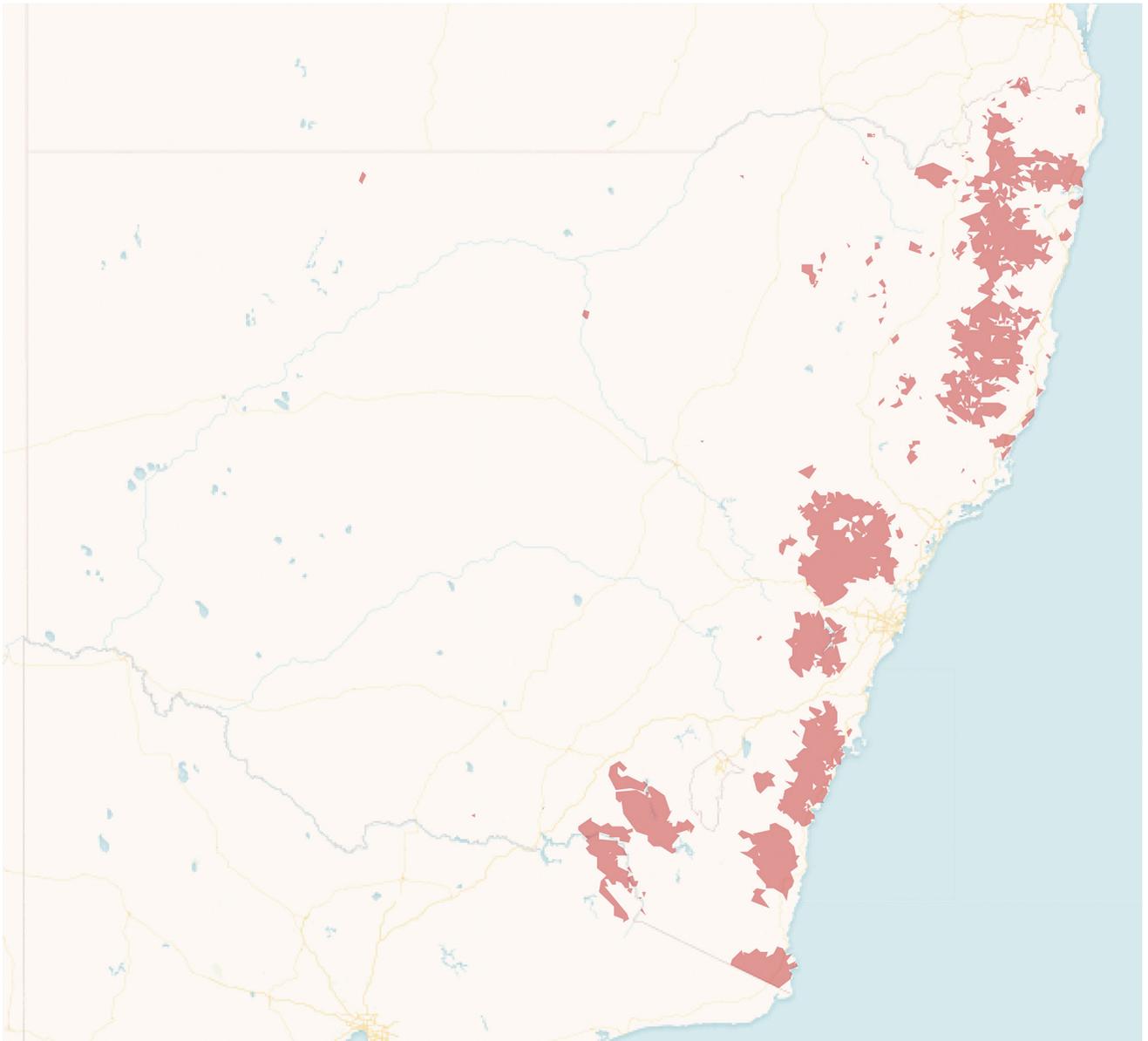


Figure 1. The NSW Bushfire map, showing areas that were burnt in the 2019–2020 bushfires. [Online source accessed April 2020]
https://services9.arcgis.com/ZFllzBMHgtgl0EYj/arcgis/rest/services/NSW_Bushfire_Burnt_Areas_2019_and_2020/FeatureServer/0

79–100% of the burnt sites were in the high to very high GEEBAM categories (Fig. 3B, Table 4).

From a total of 123 species of drosophilid flies, 75 were impacted by the bushfires and four species had their known ranges completely contained within the fire zone (Fig. 2C; Tables 1, 2). For three of the four most heavily impacted species, 100% of the burnt sites were in the high to very high GEEBAM categories, while for the fourth, 100% of the burnt sites were in the low GEEBAM category (Fig. 3C, Table 5).

From a total of 341 species of land snails, 206 were impacted by the bushfires and 11 species had their known ranges completely contained within the fire zone (Fig. 2D; Tables 1, 2). For one of the 11 most heavily impacted species, 100% of the burnt sites were in the very high GEEBAM categories; for another four species 33–50% of the burnt sites were in the high to very high GEEBAM categories;

and for the last six species the burnt sites were primarily in the low, medium or non-native GEEBAM categories (Fig. 3D, Table 6).

From a total of 126 species of mygalomorph spiders, 36 were impacted by the bushfires and five species had their known ranges completely contained within the fire zone (Fig. 2E; Tables 1, 2). For two of the five most heavily impacted species, 100% of the burnt sites were in the high GEEBAM category; for one species, 45% of the burnt sites were in the very high GEEBAM category; while for the remaining two species 100% of the burnt sites were in the low GEEBAM category (Fig. 3E, Table 7).

From a total of ten species of archaeid spiders, three were impacted by the bushfires, all having their known ranges completely contained within the fire zone (Fig. 2F; Tables 1, 2).

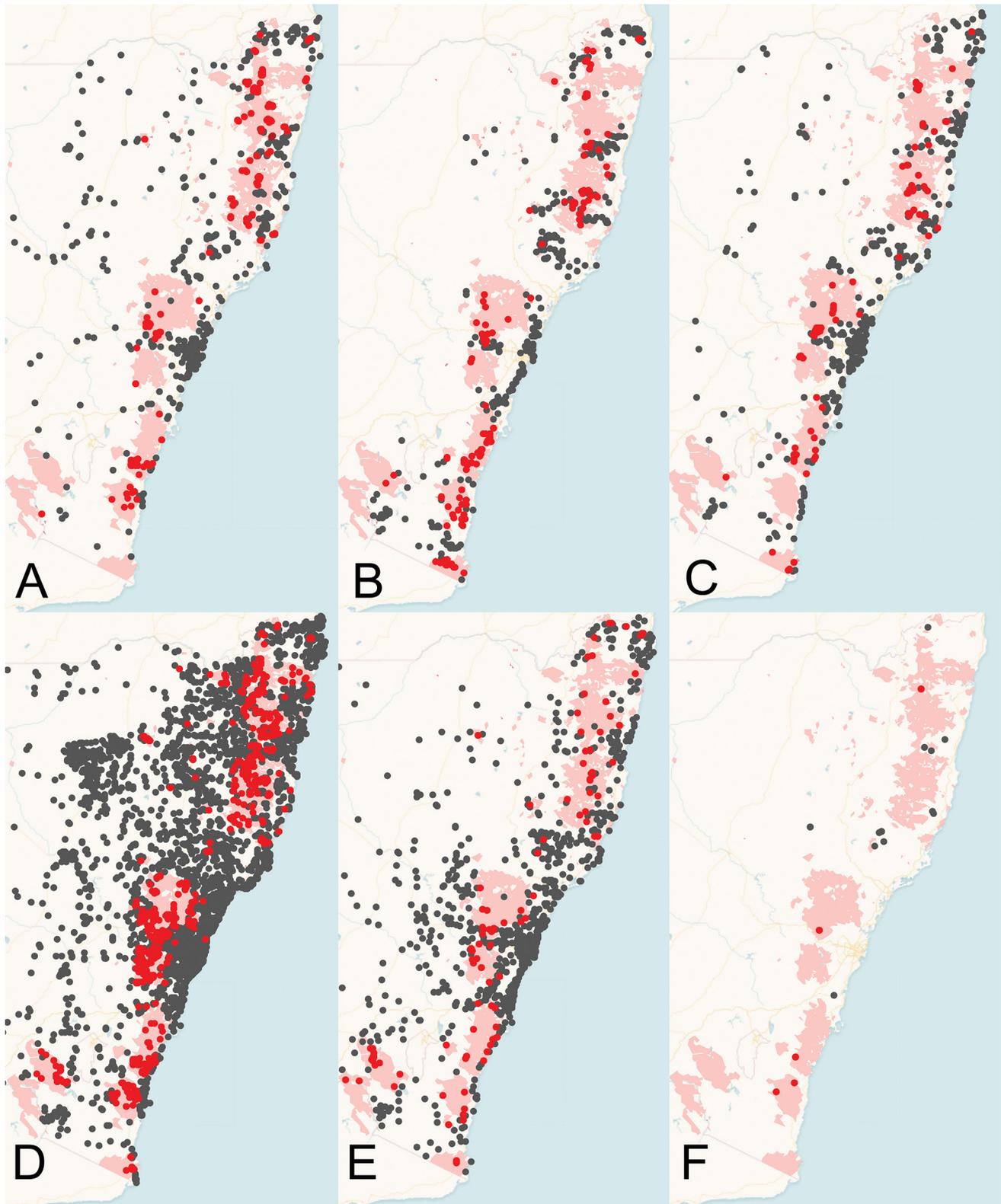


Figure 2. Mapped species records for each of the taxonomic groups, showing records from burnt sites in red and records from unburnt sites in black. The extent of the bushfires is marked in pink. (A) Dung beetles; (B) spiny freshwater crayfishes; (C) drosophilid flies; (D) land snails; (E) mygalomorph spiders; and (F) archaeid spiders.

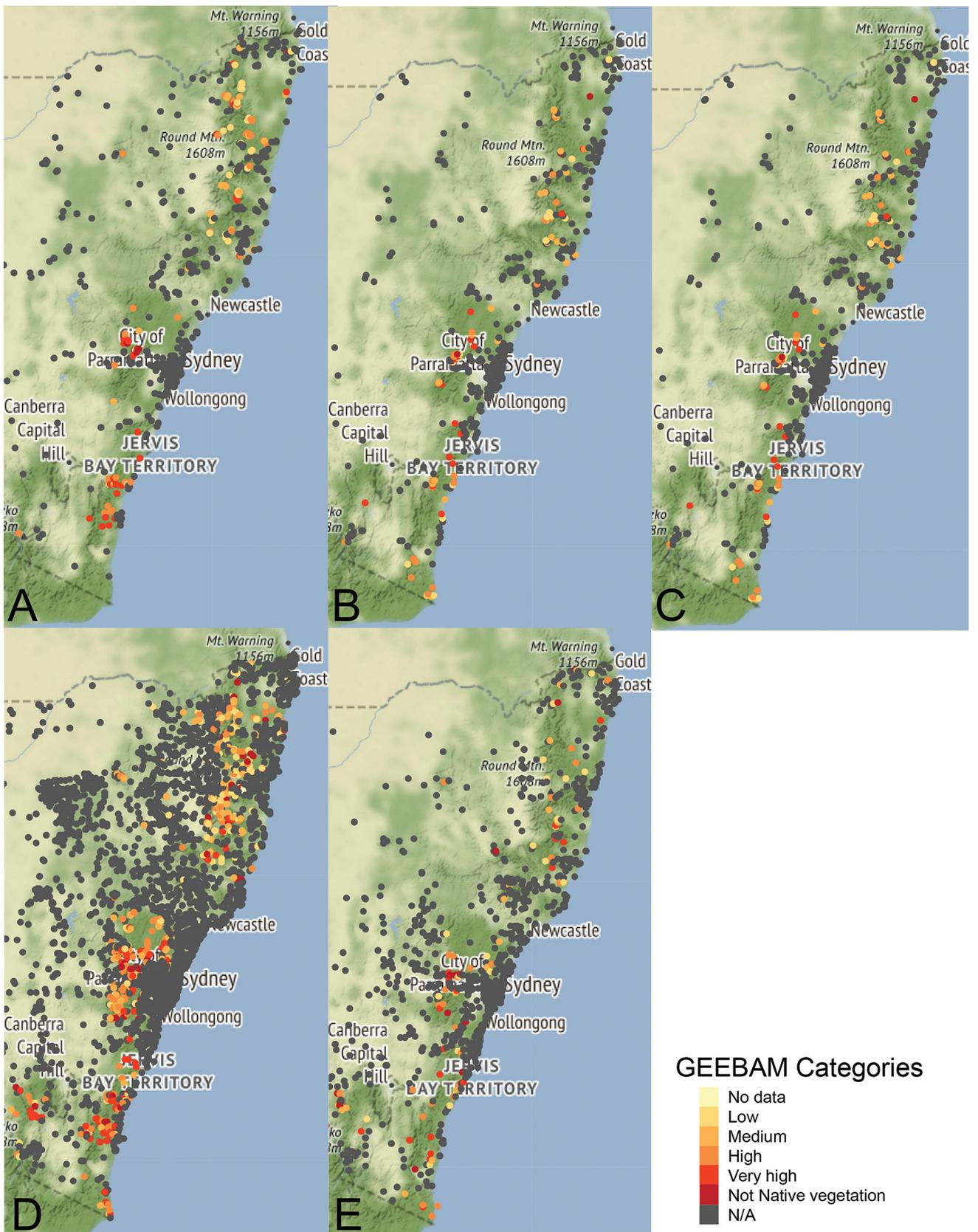


Figure 3. Mapped species records for each of the taxonomic groups, using the Google Earth Engine Burnt Area Map (GEEBAM) to show the impact of the fire on vegetation at each site. (A) Dung beetles; (B) spiny freshwater crayfishes; (C) drosophilid flies; (D) land snails; and (E) spiders.

Table 1. Overall number of species and number of species affected by the bushfires in each taxonomic group. Duplicate records (with identical coordinates) have been removed. For each group (dung beetles, spiny freshwater crayfishes, drosophilid flies, land snails, and mygalomorph (*m*) and archaetid (*a*) spiders), all records are shown in the first column (*all*), and records for the last 50 years (1970 to 2020) are shown in the second column (*1970*).

	beetles		crayfishes		flies		snails		spiders (m)		spiders (a)		total	
	all	1970	all	1970	all	1970	all	1970	all	1970	all	1970	all	1970
number of species	95	94	38	37	123	119	341	329	126	116	10	10	733	705
species with any habitat burned	57	55	21	20	75	71	206	201	36	34	3	3	398	384
species with at least 25% burned	32	32	12	13	23	28	88	105	16	14	3	3	174	195
species with at least 50% burned	15	15	9	9	8	9	28	37	12	10	3	3	75	83
species with at least 75% burned	5	6	5	5	5	5	13	15	5	6	3	3	36	40
species with 100% burned	2	3	4	4	4	4	11	12	5	6	3	3	29	32

Table 2. A list of species that had 25% or more of their known occurrence burnt in the 2019–2020 bushfires. Species identified in the current study as priority species for immediate conservation management are marked with a hash symbol (#); while species similarly identified in two recent Australian Government reports (DAWE, 2020a; Legge *et al.*, 2020) are marked with an asterisk (*).

Species with 100% of their known occurrences burnt		% burnt
beetles	<i>Onthophagus weringerong</i> Storey & Weir, 1990	100%
	<i>Thyregeis kershawi</i> Blackburn, 1904	100%
crayfishes	<i>Euastacus bidawalus</i> Morgan, 1986 *	100%
	<i>Euastacus guwinus</i> Morgan, 1997 *#	100%
	<i>Euastacus "spinifer" #</i>	100%
flies	<i>Euastacus vesper</i> McCormack & Ahyong, 2017 #	100%
	<i>Acletoxenus formosus</i> (Leow, 1864)	100%
	<i>Leucophenga subpollinosa</i> Huang, Su & Chen, 2017	100%
	<i>Scaptodrosophila eluta</i> (Wheeler & Takada, 1964)	100%
snails	<i>Scaptodrosophila jackeyi</i> (Bock, 1982)	100%
	<i>Austrochloritis kippara</i> Stanistic, 2010 *#	100%
	<i>Coricudgia wollemiana</i> Stanistic, 2005 *#	100%
	<i>Egilodonta bendethera</i> Stanistic, 2005 *#	100%
	<i>Egilomen sebastopol</i> Stanistic, 2010 *#	100%
	<i>Gyrocochlea janetwaterhouseae</i> Shea, Colgan & Stanistic 2012 *#	100%
	<i>Hedleyropa yarrangobillyensis</i> Stanistic, 2005 *#	100%
	<i>Letomola lanalittleae</i> Stanistic, 2005 *#	100%
	<i>Macrophallikoropa stenoumbilicata</i> Stanistic, 2005 *#	100%
	<i>Planorbacochlea dandahra</i> Shea, Colgan & Stanistic 2012 #	100%
spiders	<i>Rhophodon palethorpei</i> Stanistic, 2005 *#	100%
	<i>Sigaloeista gracilis</i> Köhler, 2019 #	100%
	<i>Aname caeruleomontana</i> Raven, 1984 #	100%
	<i>Arbanitis helensmithae</i> (Wishart & Rowell, 2008) #	100%
	<i>Arbanitis horsemanae</i> (Wishart, 2011) #	100%
	<i>Arbanitis macei</i> (Wishart & Rowell, 2008) #	100%
	<i>Carraia afoveolata</i> Raven, 1984 #	100%
	<i>Austrarchaea mcguiganae</i> Rix & Harvey, 2011 #	100%
	<i>Austrarchaea monteithi</i> Rix & Harvey, 2011 #	100%
	<i>Austrarchaea smithae</i> Rix & Harvey, 2011 #	100%
Species with 75–99% of their known occurrences burnt		
beetles	<i>Matthewsius illawarrensis</i> Matthews, 1974 *#	92%
	<i>Onthophagus squalidus</i> Lea, 1923	75%
	<i>Matthewsius rossi</i> (Matthews, 1974) *#	75%
crayfishes	<i>Euastacus clarkae</i> Morgan, 1997 *#	80%
flies	<i>Scaptodrosophila ehrmanae</i> (Parsons & Bock, 1977) #	80%
snails	<i>Austrochloritis seaviewensis</i> Stanistic & Potter, 2010 *#	78%
	<i>Austrochloritis marksandersi</i> Stanistic, 2010 *#	75%

continued ...

Table 2 (continued).

Species with 50–74% of their known occurrences burnt			
beetles	<i>Diorygopyx duplodontatus</i> Matthews, 1974 *#	67%	
	<i>Aulacopris reichei</i> White, 1859 *	60%	
	<i>Onthophagus</i> msp cbc3-001 #	60%	
	<i>Amphistomus trispiculatus</i> Matthews, 1974	59%	
	<i>Onthophagus rubicundulus</i> Macleay, 1871	58%	
	<i>Aulacopris maximus</i> Matthews, 1974	52%	
	<i>Lepanus</i> msp NSW-2	50%	
	<i>Lepanus</i> nr <i>pisoniae</i> Lea, 1923 *	50%	
	<i>Lepanus ustulatus</i> (Lansberg, 1874)	50%	
	<i>Onthophagus kokereka</i> Matthews, 1972	50%	
	crayfishes	<i>Euastacus pilosus</i> Coughran & Leckie, 2007 *#	73%
		<i>Euastacus girummulayn</i> Coughran, 2005 *#	67%
		<i>Euastacus yanga</i> Morgan, 1997 #	61%
		<i>Euastacus claytoni</i> Riek, 1969 #	50%
flies	<i>Leucophenga domanda</i> Bock, 1984	50%	
	<i>Scaptodrosophila anthemion</i> (Bock, 1976)	50%	
	<i>Scaptodrosophila insolita</i> (Bock, 1976) #	50%	
snails	<i>Austrochloritis wollemiensis</i> Shea & Griffiths, 2010 *#	71%	
	<i>Vitellidelos kaputarensis</i> Shea & Griffiths, 2010 *#	71%	
	<i>Gyrocochlea gibraltar</i> Stanisic, 2010 *#	67%	
	<i>Meredithena marysvillensis</i> (Gabriel, 1947) #	67%	
	<i>Protorugosa alpica</i> (Iredale, 1943) #	67%	
	<i>Austrochloritis kaputarensis</i> Stanisic, 2010 *#	60%	
	<i>Prolesophanta occlusa</i> Shea & Griffiths, 2010 #	57%	
	<i>Austrochloritis abrotonus</i> Shea & Griffiths, 2010 *#	56%	
	<i>Pommerhelix monacha</i> (Pfeiffer, 1859) *#	55%	
	<i>Oreomava canfluviatilus</i> (Gabriel, 1929) #	53%	
	<i>Austrochloritis paucisetosa</i> Stanisic, 2010 *#	50%	
	<i>Kandoschloritis pustulosus</i> Shea & Griffiths, 2010 #	50%	
	<i>Macleayropa boonanghi</i> Stanisic, 2010 *#	50%	
	<i>Planorbacochlea manningensis</i> Shea, Colgan & Stanisic, 2012 #	50%	
<i>Rhophodon kempseyensis</i> Stanisic, 2005 *#	50%		
spiders	<i>Ixamatus fischeri</i> Raven, 1982 #	67%	
	<i>Paraembolides boydi</i> (Raven, 1978) #	67%	
	<i>Arbanitis paulaskewi</i> (Wishart, 2011) #	50%	
	<i>Cethegus barraba</i> Raven, 1984 #	50%	
	<i>Hadronyche emmalizae</i> Gray, 2010 #	50%	
	<i>Ixamatus musgravei</i> Raven, 1982 #	50%	
	<i>Atrax yorkmainorum</i> Gray, 2010 #	50%	
	Species with 25–49% of their known occurrences burnt		
beetles	<i>Diorygopyx niger</i> Matthews, 1974	43%	
	<i>Amphistomus specularifer</i> Matthews, 1974	42%	
	<i>Diorygopyx incrassatus</i> Matthews, 1974 *	40%	
	<i>Onthophagus kiambram</i> Storey, 1977	40%	
	<i>Diorygopyx incomptus</i> Matthews, 1974	36%	
	<i>Lepanus bidentatus</i> (Wilson, 1922)	36%	
	<i>Cephalodesmius armiger</i> Westwood, 1842	34%	
	<i>Diorygopyx tibialis</i> (Macleay, 1871)	33%	
	<i>Onthophagus hoplocerus</i> Lea, 1923	33%	
	<i>Onthophagus tweedensis</i> Blackburn, 1903	33%	
	<i>Onthophagus yourula</i> Storey & Weir, 1990	33%	
	<i>Onthophagus blackburni</i> Shipp, 1895	30%	
	<i>Diorygopyx simpliciclunis</i> Matthews, 1974	29%	
	<i>Onthophagus longipes</i> Paulian, 1937	29%	
	<i>Onthophagus pugnax</i> Harold, 1868	29%	
	<i>Onthophagus incornutus</i> Macleay, 1871	25%	
	<i>Onthophagus nurubuan</i> Matthews, 1972	25%	

continued ...

Table 2 (continued).

Species with 25–49% of their known occurrences burnt (continued)		% burnt
crayfishes	<i>Euastacus suttoni</i> Clark, 1941 *	38%
	<i>Euastacus simplex</i> Riek, 1956 *	31%
	<i>Euastacus spinichelatus</i> Morgan, 1997 *	30%
flies	<i>Microdrosophila discrepantia</i> Bock, 1982	43%
	<i>Microdrosophila pleurolineata</i> Wheeler & Takada, 1964	40%
	<i>Scaptodrosophila novamaculosa</i> (Mather, 1956)	40%
	<i>Leucophenga cyanorosa</i> Bock, 1979 #	38%
	<i>Scaptodrosophila garnetensis</i> (Bock, 1984)	36%
	<i>Mycodrosophila marksae</i> Bock, 1980	33%
	<i>Scaptodrosophila rhabdote</i> (Bock, 1976)	33%
	<i>Scaptodrosophila collessi</i> (Bock, 1976)	32%
	<i>Scaptodrosophila minnamurrae</i> (Bock, 1976) #	30%
	<i>Scaptodrosophila cancellata</i> (Mather, 1955)	29%
	<i>Scaptodrosophila megagenys</i> (Bock, 1976)	29%
	<i>Scaptodrosophila inornata</i> (Malloch, 1923)	28%
	<i>Hirtodrosophila donaldi</i> (Wheeler, 1981)	25%
	<i>Microdrosophila hasta</i> Bock, 1982	25%
	<i>Scaptodrosophila vindicta</i> (Parsons & Bock in Bock, 1982) #	25%
	snails	<i>Austrorhytida nandewarensis</i> Shea & Griffiths, 2010 *
<i>Austrochloritis kanangra</i> Shea & Griffiths, 2010 *		48%
<i>Austrochloritis speculoris</i> Shea & Griffiths, 2010		47%
<i>Pommerhelix mastersi</i> (Cox, 1864) *		47%
<i>Austrorhytida harriettae</i> (Cox, 1868)		46%
<i>Annabellia assimilans</i> (Cox, 1864)		44%
<i>Sigaloeista rubra</i> Stanistic, 2010		44%
<i>Vitellidelos dorrigoensis</i> Shea & Griffiths, 2010 *		44%
<i>Diphyoropa macleayana</i> Stanistic, 2005 *		43%
<i>Macrophallikoropa depressispira</i> Stanistic, 2005 *		43%
<i>Terrycarlessia turbinata</i> Stanistic, 2010		41%
<i>Pommerhelix depressa</i> (Hedley, 1901) *		41%
<i>Elsothera grossa</i> Stanistic, 2010		41%
<i>Nitor wiangariensis</i> Hyman, 2007		40%
<i>Planorbacochlea reticulata</i> Shea, Colgan & Stanistic, 2012		40%
<i>Sigaloeista dorrigo</i> Köhler, 2019		40%
<i>Helicarion cuvieri</i> Férussac, 1821		38%
<i>Brevisentis kaputarensis</i> Shea & Griffiths, 2010 *		38%
<i>Montidelos macquariensis</i> (Cox, 1872)		38%
<i>Paralaoma annabelli</i> Shea & Griffiths, 2010 *		38%
<i>Comboynea conferta</i> (Hedley, 1924)		37%
<i>Egilodonta bairnsdalensis</i> (Gabriel, 1930)		36%
<i>Cystopelta astra</i> Iredale, 1937		36%
<i>Meridolum jervisensis</i> (Quoy & Gaimard, 1832) *		35%
<i>Parmavitrina megastoma</i> (Cox, 1868)		35%
<i>Coenocharopa multiradiata</i> Stanistic, 1990		34%
<i>Austrochloritis abbotti</i> Stanistic, 2010		33%
<i>Cralopa kaputarensis</i> Stanistic, 1990		33%
<i>Excellaoma retipora</i> (Cox, 1867)		33%
<i>Gyrocochlea notiala</i> Stanistic, 2010		33%
<i>Macleayropa carraiensis</i> Stanistic, 2010 *		33%
<i>Scelidoropa nandewar</i> Stanistic, 2005 *		33%
<i>Austrochloritis nambucca</i> Iredale, 1943	33%	
<i>Brazieresta larreyi</i> (Brazier, 1871)	32%	
<i>Ponderconcha gilberti</i> (Pfeiffer, 1846)	32%	
<i>Pupisoma evada</i> (Iredale, 1944)	31%	
<i>Planorbacochlea yessabahensis</i> Shea, Colgan & Stanistic, 2012	31%	
<i>Pommerhelix exocarpi</i> (Cox, 1868)	30%	
<i>Austrochloritis stanisici</i> Shea & Griffiths, 2010	30%	
<i>Diphyoropa illustra</i> (Gabriel, 1947) *	30%	
<i>Austrorhytida glaciamans</i> (Iredale, 1938) *	30%	
<i>Scelidoropa sarahjaneae</i> Stanistic, 2005	29%	
<i>Flammulops excelsior</i> (Hedley, 1896)	29%	
<i>Tarocystis glenrockensis</i> (Hyman, 2007)	28%	
<i>Elsothera kyliestumkatae</i> Stanistic, 2010 *	27%	

continued ...

Table 2 (continued).

Species with 25–49% of their known occurrences burnt (continued)		% burnt
	<i>Meridistes woolnoughi</i> Stanistic, 2010	27%
	<i>Austrochloritis kosciuszkoensis</i> Shea & Griffiths, 2010 *	27%
	<i>Atopos australis</i> (Heynemann, 1876)	27%
	<i>Pseudiotula euryisiana</i> Stanistic, 2010	26%
	<i>Mysticarion porrectus</i> (Iredale, 1941) *	25%
	<i>Helicarion mastersi</i> (Cox, 1868)	25%
	<i>Dictyoropa eurythma</i> (Hedley, 1924)	25%
	<i>Gyrocochlea hawkesburyana</i> Stanistic, 2010	25%
	<i>Pommerhelix duralensis</i> (Cox, 1868)	25%
	<i>Montidelos exiguus</i> Shea & Griffiths, 2010	25%
	<i>Mysticarion hyalinus</i> (Pfeiffer, 1855)	25%
	<i>Omegapilla australis</i> (Angas, 1864)	25%
	<i>Ventopelita leucocheilus</i> (Cox, 1868)	25%
	<i>Triboniophorus graeffei</i> Humbert, 1863	25%
	<i>Thersites novaehollandiae</i> (Gray, 1834)	25%
spiders	<i>Arbanitis mascordi</i> (Wishart, 1992)	40%
	<i>Hadronyche meridiana</i> Hogg, 1901	40%
	<i>Atrax sutherlandi</i> Gray, 2010	32%
	<i>Cataxia pulleinei</i> (Rainbow, 1914)	25%

Discussion

General conservation implications

The effects of the 2019–2020 bushfires on invertebrates are manifold. Primarily, the fires have caused the immediate deaths of a large, yet unquantifiable number of individuals (i.e., fire caused decreases in population size). Any species which has experienced a reversible population reduction of more than 50% due to a known threat that has ceased to exist (i.e., the 2019–2020 bushfires) is assessed as threatened according to IUCN Red List criterion A1 (IUCN, 2012). Our study revealed that 10.7% of all analysed species had 50% or more of their known occurrences burnt. If the proportion of affected occurrence records can be used as an estimator for the reduction in population size, these species may fall in one of the Red List Categories simply due to the immediate reduction in population size caused by the bushfires. Whether there is a correlation between proportion of burnt occurrences and reduction in population size is arguable and depends on the survival rates in burnt areas and the representativeness of the available distribution data.

The impacts of the bushfires, however, go beyond the immediate mortality of individuals in burnt areas. In addition, the bushfires are likely to cause increased mortality for some time after the fires have been extinguished due to the changed habitat conditions that burnt areas provide in comparison with unburnt sites (e.g., Ray & Bergery, 2015). The bushfires have certainly caused at least the temporary loss of swathes of suitable habitat by converting close canopy forests with undergrowth and leaf litter that harbour an intricate ecosystem with complex species interactions, into more open and exposed landscapes that have lost parts of their former species inventory and provide new selective arenas. Such altered habitat structures may have cascading ecological impacts that may benefit the advent of competitors, predators, or invasive species at the detriment of indigenous species (Fahrig, 2003; Hewitt *et al.*, 2005; Lawton *et al.*, 1998; Sands, 2018). While these indirect impacts of bushfires are even harder to quantify, they are likely to cause medium to long-term reductions in the extent of occurrence (EOO), area of occupancy (AOO) and population trend of species,

in addition to the above-mentioned population reduction. The combined effects are likely to trigger additional IUCN Red List criteria and have the potential to inflate the list of species that are eligible for a formal listing as threatened.

Thirdly, the direct and indirect impacts of bushfires are likely to exacerbate any pre-existing threats to native species and may accelerate any pre-existing declines in the extent of the distributional range of species and their genetic diversity as well as to promote population fragmentation.

The long-term effects of the 2019–2020 bushfires on species depend on a number of intrinsic variables, which require detailed assessments. As detailed single-species assessments are time consuming, it is prudent to prioritize those species for assessments that have large parts of their known distribution in burnt areas. Such species would be those with comparatively small ranges, comparatively low fecundity and/or dispersal ability, and species that inhabit habitats that normally do not experience bushfires, such as rainforests.

Dung beetles

There are at least 450 species of true dung beetle (Coleoptera: Scarabaeidae: Scarabaeinae) in Australia (Gunter *et al.*, 2019) of which approximately 120 occur in NSW (Harris & Reid, 2016; Gunter *et al.*, 2019). In this discussion the introduced fauna (25 species; Edwards *et al.*, 2015) is ignored, as it is exotic and entirely associated with open habitats, particularly pastures (Gollan *et al.*, 2011). Overall the greatest diversity of native dung beetles in NSW is in more mesic habitats along the coastal side of the Great Dividing Range. However, the dung beetles of NSW are best considered as two groups, separated phylogenetically and generally also by habitat and vagility.

The genus *Onthophagus* includes about 70 species in NSW, all but one fully winged and active fliers, which are mostly widespread in distribution and in drier forests. Most species are generalists, feeding on a wide range of animal faeces but also rotting fungi and other mushy pabula (Matthews, 1972; Ebert *et al.*, 2019). One species of *Onthophagus*, *O. weringerong* Storey & Weir, 1990, was identified in our study as critically impacted by the fires,

Table 3. The impact of the fire, measured using GEEBAM categories, on all dung beetle species that had 50% or more of their known occurrence burnt.

Beetles	2	3	4	5	6	4 + 5
	low	medium	high	very high	not native vegetation	total high+very high
<i>Thyregeis kershawi</i>	0%	0%	0%	100%	0%	100%
<i>Matthewsius illawarrensis</i>	13%	0%	50%	33%	3%	83%
<i>Lepanus nr pisoniae</i>	0%	0%	75%	0%	0%	75%
<i>Onthophagus weringerong</i>	0%	25%	75%	0%	0%	75%
<i>Diorygopyx duplodentatus</i>	0%	0%	33%	33%	0%	67%
<i>Aulacopris reichei</i>	0%	0%	25%	25%	0%	50%
<i>Matthewsius rossi</i>	0%	0%	0%	50%	14%	50%
<i>Onthophagus squalidus</i>	20%	20%	40%	0%	0%	40%
<i>Onthophagus msp cbc3-001</i>	0%	0%	25%	13%	0%	38%
<i>Amphistomus trispiculatus</i>	41%	2%	16%	10%	2%	25%
<i>Onthophagus rubicundulus</i>	21%	0%	21%	0%	0%	21%
<i>Aulacopris maximus</i>	25%	3%	9%	6%	0%	16%
<i>Lepanus msp NSW-2</i>	29%	5%	5%	6%	0%	11%
<i>Lepanus ustulatus</i>	67%	0%	0%	0%	0%	0%
<i>Onthophagus kokoreka</i>	0%	20%	0%	0%	0%	0%

50–74%
 75–99%
 100% burnt

with 100% of the NSW range affected, and one species, *O. squalidus* Lea, 1923 had 75% of its range impacted. Three species, *O. rubicundulus* Macleay, 1871, *O. kokoreka* Matthews, 1972, and an undescribed species coded *O. CBCR* species 1, had 50–60% of their ranges impacted. However, when compared with the Australian database of Scarabaeinae on the *Atlas of Living Australia* (Anonymous, 2020a), none of the described *Onthophagus* species noted above are restricted to NSW and so none can be considered threatened by the fires of 2019–2020, although their ranges may have been reduced. The only threatened species of *Onthophagus* is the most unusual, as it is the only flightless species of *Onthophagus* in Australia (*O. CBCR* species 1). This species is only known from eight specimens, all collected in 1993 from three wet forest sites within 100 km of each other, and it urgently needs to be formally described and registered as threatened.

The remaining native dung beetles include approximately 50 species in 10 relatively small genera (Matthews, 1974, 1976; Gunter *et al.*, 2019). In contrast to *Onthophagus*, these are often flightless, generally restricted to mesic forests and have small ranges. Ten species were found to be impacted in at least 50% of their NSW ranges. Three are species of *Lepanus*, a genus in the process of being revised (Gunter & Weir, 2019). For this reason they are not discussed further, except to note that *L. ustulatus* (Lansberge, 1874), with 50% of its NSW range impacted, is a volant and common species in wetter forests of southeast Queensland. The remaining seven species are flightless. These species and the estimated ranges impacted in NSW are: *Thyregeis kershawi* Blackburn, 1904 (100%), *Matthewsius illawarrensis* (Matthews, 1974) (92%), *M. rossi* (Matthews, 1974) (75%), *Diorygopyx duplodentatus* Matthews, 1974 (67%), *Aulacopris reichei* White, 1859 (60%), *A. maximus* Matthews, 1974 (52%) and *Amphistomus trispiculatus* Matthews, 1974 (59%). Of these, four species also have several records in neighbouring states: *T. kershawi* is rare in NSW but common in central Victoria (Matthews, 1976; Anonymous, 2020a), *A. reichei* is widespread from

central NSW to central Victoria (Matthews, 1974; Anonymous, 2020a), *A. maximus* occurs from central NSW to southeast Queensland (Matthews, 1974; Anonymous, 2020a) and *A. trispiculatus* is restricted to northeast NSW and southeast Queensland (Matthews, 1974; Anonymous, 2020a). Their populations in NSW may have been threatened but they appear to be secure elsewhere. *Matthewsius illawarrensis* and *M. rossi* are only known from three rainforest localities in and around the Sydney Basin area (Gunter & Weir, 2017) and must be regarded as Critically Endangered (IUCN, 2012) by the impacts of fire (and climate change). *Diorygopyx duplodentatus* is a rarely collected species endemic to tall forests on high elevation ridges of the Great Dividing Range in northern NSW, with just four known localities. This species also should be regarded as Critically Endangered (IUCN, 2012).

Spiny freshwater crayfishes

All Australian freshwater crayfishes belong to the Southern Hemisphere family Parastacidae. Australia is the world centre of parastacid crayfish diversity, and includes the three largest and second smallest known species of freshwater crayfish (Ahyong, 2014). The modern distribution of Australian freshwater crayfishes, being in many respects relictual, reflects the increasing aridity of Australia since the mid-Miocene (Martin, 2006). The highest diversity is in the moist southeast of the continent, with comparatively few in the south-western corner and wet tropics of the northeast.

Euastacus, the largest parastacid genus, ranges from northern Queensland south to Victoria and eastern South Australia (McCormack, 2012; Ahyong, 2014). Most species of the genus favour cool, aerated, flowing water in lowland and high altitude habitats having forest cover or native riparian vegetation, usually with different species occupying different altitudinal ranges (Coughran, 2008). Consequently, the highest diversity is in the eastern drainages of southern NSW (38 species) (Ahyong, 2014; Crandall & De Grave, 2017), substantially coinciding with the fire zone. Most species occupy narrow ranges, usually in the vegetated upper

Table 4. The impact of the fire, measured using GEEBAM categories, on all spiny freshwater crayfish species that had 50% or more of their known occurrence burnt.

Crustaceans	2	3	4	5	6	4 + 5
	low	medium	high	very high	not native vegetation	total high+very high
<i>Euastacus bidawalus</i>	0%	0%	100%	0%	0%	100%
<i>Euastacus guwinus</i>	0%	0%	0%	100%	0%	100%
<i>Euastacus vesper</i>	0%	20%	80%	0%	0%	80%
<i>Euastacus "spinifex"</i>	7%	0%	36%	43%	0%	79%
<i>Euastacus claytoni</i>	0%	0%	29%	21%	7%	50%
<i>Euastacus yanga</i>	7%	4%	30%	15%	5%	45%
<i>Euastacus clarkae</i>	45%	9%	27%	0%	0%	27%
<i>Euastacus girurmulayn</i>	50%	0%	0%	25%	0%	25%
<i>Euastacus pilosus</i>	38%	8%	15%	0%	8%	15%

□ 50–74% □ 75–99% □ 100% burnt

reaches of single catchments, and as such the majority are Endangered or Critically Endangered under IUCN Red List criteria (Coughran & Furse, 2010).

The ranges of 21 of 38 NSW species of *Euastacus* were impacted by the fires. Of these, the entire ranges of three species (*E. "spinifer"*, *E. guwinus* and *E. vesper*) were burnt. *Euastacus guwinus* and *E. vesper* both have isolated distributions in the Shoalhaven and Cudgegong river catchments, respectively (Morgan, 1997; McCormack & Ahyong, 2017). *Euastacus "spinifer"* has a wider range than the former two species, ranging from the Southern Highlands to the vicinity of Batemans Bay, Clyde River catchment. Although *Euastacus spinifer* is currently considered a wide-ranging species in NSW (McCormack, 2012), population analyses indicate that the southern population of *E. spinifer*, herein referred to as *E. "spinifer"*, is a separate species, currently under detailed evaluation (Van De Wal, 2020). For these three highly impacted species, 79–100% of the burnt sites were also in the high to very high GEEBAM categories (Fig. 3B, Table 4), suggesting high fire intensities in these areas. The mosaic nature of burn impacts within the fire zone provides at least a degree of hope that not all species will have been equally affected. In this vein, the range of the Critically Endangered Fitzroy Falls spiny crayfish (*Euastacus dharawalus*) (McCormack, 2013), which is endemic to a small area in the vicinity of Fitzroy Falls, Southern Highlands, was surprisingly but fortunately not affected by fire. For a fourth species, *E. bidawalus*, the entire NSW range was within the fire zone, but that species ranges into unburnt areas of Victoria as well.

Although the most direct impacts of fire are on terrestrial habitats, degradation of stream water quality within and downstream of burnt areas can be expected to have significant effects on the aquatic fauna, especially spiny crayfishes. These fire impacts are likely to have been accentuated by the effects of the preceding years of extended drought on the small streams and creeks occupied by *Euastacus*. Even if temporary elevation of water temperatures can be avoided by retreat into deep burrows, subsequent exposure to toxins released by burning, eutrophication and anoxia caused by excessive organic deposition and runoff can nevertheless be detrimental (New, 2014; Emelko *et al.*, 2016; Harper *et al.*, 2019). Although some aquatic crustaceans have demonstrated resilience to habitat burning (Driessen, 2019), little is known about fire resilience of crayfishes, such as *Euastacus*, which typically

favour cool, well-oxygenated, oligotrophic waters. In addition, species of *Euastacus* regularly leave the stream to forage. Therefore, for spiny crayfishes, fire has probably not only affected the immediate aquatic environment, but also important terrestrial food sources. Going forward, finely granular ground-truthing of the extent of fire in the catchments of spiny crayfishes, together with population assessments, are required to evaluate the fire impacts on NSW species of *Euastacus*.

Drosophilid flies

Australian drosophilid flies are largely restricted to a narrow band of wet or humid forest habitats along the eastern side of the continent from northern Queensland to Victoria and Tasmania. Species diversity attenuates southwards (McEvey, 2020b). New Guinea has an estimated 1000 species and the Australian drosophilid fauna (281 species) can best be understood as a subset of that, with limited secondary radiations in the subtropical rainforests of southern Queensland and north-eastern NSW (McEvey, 2020a). New South Wales has 130 species, 123 of which have been filtered out for study using the criteria given in Methods. Low humidity and desiccation stress are significant in defining the limits of species distribution (Kellermann *et al.*, 2020). In montane forests, flies descend (compelled by positive hydrotropism, positive geotaxis, and negative phototaxis) to damp gullies during periods of high wind and low humidity, conditions which precede bushfire events. Indeed, many species are never found away from damp gullies. Mycophagous species, for example, which comprise about 40% of the fauna, occur only in close association with fleshy, soft fungal growths—such growths are also dependent on high humidity and low solar radiation levels. Consequently, many drosophilid species in the AM collection have been collected in autumn, in gullies on fungi. Many species are absent in fly collections at other times of the year, or in collections from sclerophyll or xeric habitats. Vagility is very low, so active movement over distances exceeding several hundred metres is very unlikely (Coyne *et al.*, 1982). When adult flies are present at any one locality during warm humid conditions, the questions arise: (a) were they present throughout the year in arrested diapause? (b) have they arrived by active migration? or (c) have they arrived by passive and random dispersal, for example, by wind? Most evidence (Dobzhansky, 1973) suggests that they are locally

Table 5. The impact of the fire, measured using GEEBAM categories, on all drosophilid fly species that had 50% or more of their known occurrence burnt.

Flies	2	3	4	5	6	4 + 5
	low	medium	high	very high	not native vegetation	total high+very high
<i>Acletoxenus formosus</i>	0%	0%	0%	100%	0%	100%
<i>Leucophenga subpollinosa</i>	0%	0%	100%	0%	0%	100%
<i>Scaptodrosophila eluta</i>	0%	0%	100%	0%	0%	100%
<i>Scaptodrosophila ehrmanae</i>	0%	20%	40%	20%	0%	60%
<i>Scaptodrosophila anthemon</i>	0%	0%	0%	50%	0%	50%
<i>Scaptodrosophila insolita</i>	25%	25%	0%	25%	0%	25%
<i>Leucophenga domanda</i>	50%	0%	0%	0%	0%	0%
<i>Scaptodrosophila jackeyi</i>	100%	0%	0%	0%	0%	0%

50–74%
 75–99%
 100% burnt

permanent (or sedentary) and that their abundance fluctuates from undetectable lows (almost absent) to high frequency abundance (frequently encountered by collectors).

During the recent fires, NSW humid forest habitats have been unusually impacted because of coincident drought conditions. At many localities, habitats normally offering suitable protection from desiccation stress were burnt, opening the forest canopy to unusually high levels of sunlight, heat and air flow. Among the drosophilid flies in this study, 75 species have distributions in areas impacted by the bushfires. Figure 2C and Tables 1 and 2 show that four species had their known ranges in NSW completely burnt. However, all four are widespread species common in Queensland and elsewhere, but rare in NSW. These species will perhaps be absent in NSW collections for some decades, or perhaps be discovered in adjacent suitable localities. Of the remaining 71 species, 66 are known to occur in localities that were burnt to varying extent in NSW. These 66 species also have distributions extending outside NSW into Queensland or Victoria or elsewhere and are therefore not facing the threat of extinction. Five remaining species are noteworthy because they have small ranges, not extending outside NSW, and large parts of those ranges have been damaged by fire.

Scaptodrosophila ehrmanae is a cool-adapted species of fern gullies of Victoria and NSW, 80% of the known localities in NSW have been burnt. *Scaptodrosophila insolita*, on the other hand, is rare in collections; only five specimens are known, all are from NSW (McEvey, 2020a), and 50% of its known range has been burnt. *Scaptodrosophila minnamurrae* is not uncommon, it is apparently found only in NSW at numerous localities, 30% of which have been fire-affected. *Scaptodrosophila vindicta* is a species of the rainforests of Barrington Tops and nearby lowland rainforests (McEvey, 2020a), 25% of those localities have been burnt. *Leucophenga cyanorosa* is a very striking species with patterned wings (McEvey, 2018), restricted to NSW montane wet temperate forests of the Blue Mountains, Barrington Top and further north (McEvey, 2020a); fire has affected 38% of the localities where it is known.

Land snails

Australia harbours approximately 1600 currently accepted species of terrestrial snails, many of them poorly known. In addition, there are claims of several hundred undescribed species (Stanisic *et al.*, 2010). The need to conserve water is a major driving factor in land snail behaviour

and distribution (Solem, 1978), and in eastern Australia, the largest diversity of land snails is found in rainforests where there is high rainfall and humidity (Smith & Stanisic, 1998). Only a relatively small proportion of the fauna has made the transition to dry eucalypt forests. Dry rainforest (including auricularian vine forest, semi-evergreen vine thicket and coastal thickets) and limestone outcrops also form an important habitat type for many land snails, acting as moisture-retaining refugia often surrounded by less hospitable dry sclerophyll forest (Smith & Stanisic, 1998; Stanisic *et al.*, 2010). The snail fauna found in these isolated areas tends to show high levels of endemism (Stanisic, 2005; Stanisic *et al.*, 2010).

There are 856 land snails recorded from NSW in the AM collections, including presumably undescribed candidate species referred to by code-names. These were cleaned and filtered to 341 species for the purposes of this analysis (as described in Methods; specifically undescribed candidate taxa have been removed from the dataset). Over 60% of these species were affected by the recent bushfires. The 11 species that had their known ranges completely contained in the fire zone are all restricted species with narrow ranges, each with fewer than 10 records in the AM collections (and in most cases, with only one or two records). The majority (nine species) are rainforest or limestone-associated species belonging to the family Charopidae. Charopids are a very diverse group of small to minute snails, with most Australian species fewer than 5 mm in shell diameter (Stanisic *et al.*, 2010). They number over 200 species in Australia, with an estimated 300+ undescribed species (Stanisic, 1998; Shea *et al.*, 2012). Most charopids have narrow distributions, but are often under-represented in collections due to their small size. An additional six charopid species had up to 50% of their known ranges burnt.

Another group of snails heavily affected by the fires is the genus *Austrochloritis* (family Camaenidae), one of the most speciose genera in eastern Australia, currently numbering 34 accepted species (Shea & Köhler, 2019). One *Austrochloritis* species has had all of its known range burnt, while another six *Austrochloritis* species and two other closely related camaenids have had up to 50% of their known ranges burnt. There are also likely to be additional, undescribed species of *Austrochloritis* within the burnt regions (Shea & Köhler, 2019). Camaenids are Australia's largest group of land snails, with an estimated 700–800 species (Solem, 1998). Camaenid species have narrow ranges and many have adapted to drier environments, with a great diversity of species known from

Table 6. The impact of the fire, measured using GEEBAM categories, on all land snail species that had 50% or more of their known occurrence burnt.

Snails	2	3	4	5	6	4 + 5
	low	medium	high	very high	not native vegetation	total high+very high
<i>Egilodonta bendethera</i>	0%	0%	0%	100%	0%	100%
<i>Meredithena marysvillensis</i>	33%	0%	67%	0%	0%	67%
<i>Hedleyropa yarrangobillyensis</i>	25%	0%	0%	50%	25%	50%
<i>Macleayropa boonanghi</i>	0%	0%	50%	0%	0%	50%
<i>Oreomava cannfluviatilus</i>	6%	6%	13%	38%	0%	50%
<i>Planorbacochlea dandahra</i>	50%	0%	50%	0%	0%	50%
<i>Vitellidelos kaputarensis</i>	0%	11%	47%	0%	5%	47%
<i>Gyrococchlea janetwaterhouseae</i>	43%	14%	29%	14%	0%	43%
<i>Austrochloritis abrotonus</i>	8%	4%	20%	22%	5%	42%
<i>Gyrococchlea gibraltar</i>	33%	0%	33%	0%	0%	33%
<i>Macrophallikoropa stenoumbilicata</i>	0%	67%	0%	33%	0%	33%
<i>Protorugosa alpica</i>	44%	0%	33%	0%	0%	33%
<i>Austrochloritis kaputarensis</i>	6%	24%	12%	18%	0%	29%
<i>Austrochloritis seaviewensis</i>	0%	44%	25%	0%	6%	25%
<i>Pommerhelix monacha</i>	2%	8%	14%	9%	19%	23%
<i>Austrochloritis marksandersi</i>	46%	0%	0%	15%	8%	15%
<i>Austrochloritis wollemiensis</i>	8%	6%	8%	4%	50%	13%
<i>Planorbacochlea manningensis</i>	0%	60%	0%	10%	0%	10%
<i>Rhophodon kempseyensis</i>	10%	30%	0%	10%	0%	10%
<i>Kandoschloritis pustulosus</i>	36%	9%	9%	0%	9%	9%
<i>Austrochloritis kippara</i>	0%	50%	0%	0%	50%	0%
<i>Austrochloritis paucisetosa</i>	57%	0%	0%	0%	0%	0%
<i>Coricudgia wollemiana</i>	0%	100%	0%	0%	0%	0%
<i>Egilomen sebastopol</i>	0%	100%	0%	0%	0%	0%
<i>Letomola lanalittleae</i>	0%	0%	0%	0%	100%	0%
<i>Prolesophanta oclusa</i>	29%	0%	0%	0%	29%	0%
<i>Rhophodon palethorpei</i>	0%	0%	0%	0%	100%	0%
<i>Sigaloeista gracilis</i>	100%	0%	0%	0%	0%	0%

50–74%
 75–99%
 100% burnt

semi-arid habitats in central and Western Australia (Solem, 1998). Many species of *Austrochloritis* inhabit dry woodland and heath as well as rainforest (Stanisic *et al.*, 2010), thus increasing their susceptibility to bushfires.

Two other groups affected by the bushfires are the families Helicarionidae and Rhytididae. Helicarionid species *Sigaloeista gracilis* is only represented in our analysis by a single site in Gibraltar Range National Park, which was burnt in the 2019–2020 fires. However, the species is also recorded from Richmond Range National Park (Köhler, 2019), an area that was not burnt. Helicarionids are primarily rainforest-dwelling species, with most of their diversity in southeastern Queensland. Many of the species present in the burnt areas of NSW have relatively broad ranges as currently defined (Hyman *et al.*, 2017; Köhler, 2018a,b). However, the widespread helicarionid semislug *Helicarion cuvieri* has numerous genetically distinct clades that may prove to be recently diverged, geographically restricted species (Köhler, 2018a), several of which are likely to have been negatively impacted by the bushfires.

There were no rhytidid species that suffered 100% habitat destruction as a result of the bushfires, but three species had 57–71% of their known distribution burnt. Rhytidids are carnivorous snails found primarily in wet forest areas (Smith, 1998). The majority of species prey upon other native snails.

Among the most heavily affected species, a high proportion live exclusively in rainforest or in limestone-associated woodland, regions that will recover slowly from the bushfires. This category also contains a disproportionate number of minute species with a shell diameter of less than 5 mm. These species are difficult to find and are often under-represented in surveys, giving hope that they may be present in other unburnt areas. Follow-up surveys will require specialists and special techniques for targeting minute snails.

Spiders

Mygalomorph spiders are long-lived, reside in burrows and are highly sedentary (Raven & Wishart, 2006). Owing to their subterranean lifestyle, it might be assumed that they are relatively immune to the effects of bushfires. However, a recent study of high-intensity and low-intensity fires in urban areas in Western Australia found high mortality of burrowing mygalomorph spiders after high-intensity fires (100% mortality after a year) (Mason *et al.*, 2019). Mortality was much lower for low-intensity fires. Many mygalomorph spiders have narrow ranges and thus may be vulnerable to extinction from high-intensity fires.

Three of the five mygalomorph species with 100% of their known ranges burnt belong to the genus *Arbanitis*

Table 7. The impact of the fire, measured using GEEBAM categories, on all mygalomorph and archaeid spider species that had 50% or more of their known occurrence burnt.

Spiders	2	3	4	5	6	4 + 5
	low	medium	high	very high	not native vegetation	total high+very high
<i>Aname caeruleomontana</i>	0%	0%	100%	0%	0%	100%
<i>Arbanitis macei</i>	0%	0%	100%	0%	0%	100%
<i>Ixamatus fischeri</i>	0%	0%	0%	86%	0%	86%
<i>Cethegus barraba</i>	0%	0%	50%	0%	0%	50%
<i>Paraembolides boydi</i>	4%	0%	39%	9%	4%	48%
<i>Carrai afoveolata</i>	36%	18%	0%	45%	0%	45%
<i>Arbanitis mascordi</i>	14%	0%	14%	0%	0%	14%
<i>Atrax yorkmainorum</i>	2%	2%	5%	0%	58%	5%
<i>Arbanitis helensmithae</i>	100%	0%	0%	0%	0%	0%
<i>Arbanitis horsemanae</i>	100%	0%	0%	0%	0%	0%
<i>Hadronyche emmalizae</i>	0%	14%	0%	0%	57%	0%
<i>Ixamatus musgravei</i>	0%	50%	0%	0%	0%	0%

□ 50–74% □ 75–99% ■ 100% burnt

(Idiopidae). *Arbanitis* is widely distributed in eastern and southeastern Australia (Rix *et al.*, 2017) and most species appear to have limited ranges (Wishart & Rowell, 2008). Similarly, the other two species concerned, *Carrai afoveolata* (Euagridae) and *Chenistonion caeruleomontana* (Anamidae) are only known from their type localities and must be assumed to be vulnerable to extinction. Follow-up surveys would need to include pitfall trapping as adult males are usually needed for species identification of mygalomorph spiders.

Archaeid spiders are litter dwellers with narrow species distributions and could be expected to be severely impacted by high-intensity fires. The Australian endemic genus *Austrarchaea* includes a number of relictual, largely short-range endemic species (Rix & Harvey, 2011).

The three species with 100% of their known ranges burnt are *A. monteithi*, known only from the type locality; *A. smithae*, known with certainty only from Mount Wilson in the Blue Mountains; and *A. mcguiganae*, known only from Monga National Park. All of the specimens of these species that were directly collected came from sifting elevated leaf litter, suggesting they would be particularly susceptible to intense fires.

Comparisons and limitations

A list of priority invertebrate species for urgent management intervention has been released by the Australian Government, using similar techniques to the current study but sourcing species distribution data from the *Atlas of Living Australia* (ALA) (DAWE, 2020a). Species were included on the list if more than 30% of their known range was burnt, with the exception of the land snails, where only those species with more than 50% of their known habitat burnt were listed. The compilation of such a list is always hampered by the lack of information available on many poorly known taxonomic groups. Consequently, our study has revealed some additional species that should be considered a priority for management intervention.

We identified an additional seven species of land snails with more than 50% of their known NSW range burnt, as well as an extra 27 species of dung beetles, three freshwater crayfishes, 17 drosophilid flies, 27 land snails and 19 spiders with more than 30% of their known range in NSW burnt (see Table 2). These species included two beetles, two freshwater crayfishes, four flies, two land snails and eight spiders falling in the 100% burnt category that had not previously been identified as high priority.

Directly comparing the results of our study with the existing priority list revealed some of the limitations of the study method. It was apparent that the use of differing methods and datasets affected results. For example, comparing the land snails listed as priority based on ALA records (DAWE, 2020a) to the current study based on AM collection data shows that while the majority of species were found in both studies, each study identified some species that the other did not. Our study failed to identify species that are not present in the AM collections but are held in other Australian museums, while the Australian Government's priority list did not identify a number of species described in the last 10 years that are not listed on the *Atlas of Living Australia*.

There were also considerable differences in the estimation of the percentage of habitat burnt for some species. For species where records are very scant, the addition or removal of a single extra site can change the categorization substantially. The data were also sensitive to the removal of older records and the removal of duplicate sites, all of which may have contributed to discrepancies between the two studies.

Finally, a limitation of both studies lies in the assumption that collection records reflect the current distribution. In the majority of cases collections records probably under-represent the actual range (especially for small or very cryptic species), but in the case of declining populations it may also be an over-estimation. It is now vital that distributions are confirmed with on-ground surveys in order to assess the current status of species identified as highest risk.

Outcomes and consequences

The bushfires that raged through eastern Australia in 2019–2020 are part of a growing number of large-scale fires seen around the world in recent years, linked to human-induced climate change (Mantgem *et al.*, 2014; Jolly *et al.*, 2015; Fonesca *et al.*, 2017) as well as other factors, such as land use and logging (Lindenmayer *et al.*, 2020). Changes to land management and action on climate change are being called for (Lindenmayer *et al.*, 2020; *Nature Climate Change* editorial—Anonymous, 2020b), but it is likely that the risk of extensive fires will remain high.

There is now an urgent need for field studies assessing the impact of these bushfires, both in the short- and long-term. The Australian Government has released reports listing priority species of vertebrates, invertebrates and plants that require management intervention (Legge *et al.*, 2020; DAWE, 2020a,b). Recommendations include immediate on-ground assessment and protection of adjacent unburnt areas. The current study has confirmed the placement of 41 species on this list and added an additional 103 species that are recorded as having 30% or more of their habitat burnt.

The impacts of the bushfires are likely to have been more severe on species that inhabit forest types that are normally not prone to fires (e.g., rainforests) than those inhabiting forest types which experience fires more regularly (e.g., dry sclerophyll forests). Furthermore, the consequences of local extinctions and declines are more critical for the survival of species with comparatively low fecundity, low dispersal ability and/or narrow distributional ranges. Thousands of species of invertebrates meet these criteria, many of them likely to be undescribed, and the risk of a wave of extinctions is very real. Prioritizing assessment of the species that data suggests are the most vulnerable, and monitoring the response and recovery of our native fauna, will be critical in understanding and mitigating the short-term and long-term impact of mega-bushfires.

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